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Recent (1995–1998) Canadian research on contemporary processes of river erosion and sedimentation, and river mechanics

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Abstract:

Canadian research on contemporary erosion and sedimentation processes covers a wide range of scales, processes, approaches and environmental problems. This review of recent research focuses on the themes of sediment yield, land-use impact, fine-sediment transport, bed material transport and river morphology and numerical modelling of fluvial landscape development.

Research on sediment yield and denudation has confirmed that Canadian rivers are often dominated by riparian sediment sources. Studies of the effects of forestry on erosion, in-stream sedimentation and habitat are prominent, including major field experimental studies in coastal and central British Columbia. Studies of fine-sediment transport mechanisms have focused on the composition of particles and the dynamics of flocculation. In fluvial dynamics there have been important contributions to problems of turbulence-scale flow structure and entrainment processes, and the characteristics of bedload transport in gravel-bed rivers. Although much of the work has been empirical and field-based, results of numerical modelling of denudational processes and landscape development also have begun to appear.

The nature of research in Canada is driven by the progress of the science internationally, but also by the nature of the Canadian landscape, its history and resource exploitation. Yet knowledge of Canadian rivers is still limited, and problems of, for example, large pristine rivers or rivers in cold climates, remain unexplored. Research on larger scale issues of sediment transfer or the effects of hydrological change is now hampered by reductions in national monitoring programmes. This also will make it difficult to test theory and assess modelling results. Monitoring has been replaced by project- and issues-based research, which has yielded some valuable information on river system processes and opened opportunities for fluvial scientists. However, future contributions will depend on our ability to continue with fundamental fluvial science while fulfilling the management agenda.

INTRODUCTION

In the Canadian landscape dominated by the effects of Pleistocene glaciation it is easy to ignore the significant contemporary role of fluvial processes in erosion, transfer and deposition of sediment, and in shaping the land surface. These processes range over time-scales from seconds to millions of years and on spatial scales from single grains to continents, and incorporate diverse environmental problems. Scientific investigation

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of these problems requires a wide array of techniques, challenging the understanding, measurement and modelling of physical processes, from fluid turbulence and flocculation to continental dynamics. The range of scales, diversity of approaches, and sophistication of instrumentation, have never been greater (Church, 1996). Canadian scientists have contributed to understanding across the full range of these problems and processes, yielding information and perspectives influenced by the nature and variety of the Canadian landscape and its use and management, and by the size and geomorphological history of the land mass.

Scope

The review forms part of the Canadian quadrennial report to the International Association of Hydrological Sciences (IAHS). It focuses on a limited number of themes on the science and management of sediment dynamics in rivers and river systems and is restricted to work published between 1995 and 1998. The thematic coverage was chosen to be of interest to the hydrological sciences in general and to relate to the areas of activity covered by the IAHS International Commission on Continental Erosion. The themes were also chosen to cover the range of scales and types of investigation characteristic of Canadian fluvial science and to deliberately include information and developments from government monitoring and management projects, as well as academic scientists. The emphasis is on contemporary processes and related environmental issues, and the approach is to synthesize results from a limited number of topics in some detail, rather than to present an exhaustive account of all work. We have focused on contemporary river processes with some direct relation to hydrology and hydraulics. This leaves out much useful Canadian work on deltaic and lacustrine sedimentation and the sedimentology of recent fluvial deposits, as well as subglacial fluvial erosion and sedimentation processes.

The major topic areas include sediment yield and land-use effects; in-stream fine-grained sedimentation and contaminant transport; channel-scale sediment transport, hydraulics and river morphology; and numerical modelling of fluvial landscape development. Technical developments associated with these topics are covered in the final section of the review.

SEDIMENT SOURCES, SEDIMENT YIELD AND THE EFFECTS OF LAND USE

Traditional interest in drainage basin sediment yield focused on measurement of sediment loads for water resources engineering and estimates of rates of continental denudation. In recent years the rationale for studies of sediment yield has extended to the recognition that contaminant fluxes are closely tied to fine sediment transfer. At the same time there is a need to assess the impacts of land use and environmental change on sediment fluxes and landform development. This shift has necessitated the study and modelling of sediment budgets (source, transfer and sinks of sediment) and processes and rates of transfer within drainage basins, rather than simply the output signal. Recent research in Canada has shown how conditions in the Canadian landscape produce spatial patterns of sediment yield contrary to standard expectations and explanations (Ashmore, 1993), with direct effects on the composition of fine sediment and contaminant fluxes. Canada is also distinctive for its large, remote and pristine northern river basins for which even basic knowledge of sediment yields and budgets is severely limited, yet for which understanding of environmental impacts is increasingly important, particularly to aboriginals. Although agricultural land-use remains an important theme in research on land-use impacts, Canadian research is dominated by work on the impact of forest harvesting on stream sedimentation and morphology, and on the sustainability of fish habitat.

Basin-scale sediment yield

Much of the understanding of basin-scale sediment fluxes in Canada is derived from an extensive network of sediment monitoring stations, established initially for river engineering studies in the 1960s and 1970s and synthesized in a large number of technical and research reports (Winkler and Cashman, 1991). Rationalization of the original monitoring programme began during the 1980s (Day, 1986, 1992) along with similar efforts in the USA and Mexico (Osterkamp and Parker, 1991; Osterkamp *et al*., 1992) with the intent of addressing broader environmental concerns. However, large reductions in programme funding for water resources in Canada in the 1990s (Pearce and Quinn, 1996) have had severe consequences for long-term sediment monitoring programmes. Monitoring is now reduced to about 200 stations, most of which are in Ontario, Alberta and British Columbia, and only about 10% of stations have a full regular monitoring programme. The remaining 90% are either based on occasional sampling to establish rating curves (in Alberta) or use monitoring only during spring freshet or major storm events (data and information based on personal communication from Environment Canada personnel P. Zyrmiak, B. Smith and T. Yuzyk, March 1999).

Previous studies, based mainly on Federal Government sediment load data, have shown that sediment loads in the glaciated landscape of Canada are often dominated by riparian sources, with uplands contributing little to the sediment load and landscape denudation (Ashmore and Day, 1988; Church *et al.*, 1989; Ashmore, 1993). This pattern of erosion can also be shown by using sediment particle characteristics rather than sediment yields and budgets (De Boer and Crosby, 1996). For example, sediment sources in the Assiniboine–Whitesand River system in Saskatchewan are de-coupled so that sediment generated in the headwater portion of the basin is not transported downstream, but instead is deposited within the system. The sediment carried in the downstream reaches is derived locally from the areas directly adjacent to the mainstream (De Boer and Crosby, 1996). Analysis by SEM/EDS has been used to demonstrate that suspended solids in the upstream portions of the basin consist predominantly of planktonic diatoms, with small numbers of composite particles comprised of mineral grains cemented together with clay and organic matter. In the downstream portions of the basin, suspended solids consist of composite particles cemented together with clay minerals, and few diatoms are present (Crosby and De Boer, 1996). The downstream change in suspended solids characteristics is explained by the increased contribution to the sediment load of reworked glacial, glaciofluvial and glaciolacustrine deposits on the main valley floor.

Where uplands are erosionally connected to the stream system, the effect of differing surficial (glacial) deposits on sediment yield may be detected. Stone and Saunderson (1996) investigated the regional patterns of fluvial sediment yield in the low relief, largely agricultural, tributaries to the lower Great Lakes using Water Survey of Canada data for 92 tributaries. The average specific sediment yield of the drainage basins of the Great Lakes and Lake St Clair ranged from 21·7 to 87·3 t km^{-2} $year^{-1}$, but the highest specific sediment yields (> 500 t km^{-2} $year^{-1}$) were found in sub-basins with agricultural and industrial land use on fine-grained glacio-lacustrine parent materials. However, these results are difficult to reconcile with soil loss observations on the Prairies (Pennock *et al.*, 1995) showing that the highest rates of soil loss were found in glacial till landscapes (30 t ha^{-1} $year^{-1}$ = 3000 t km^{-2} $year^{-1}$) whereas the lowest rates were found in silty glaciolacustrine and aeolian landscapes and in fine sandy loam glaciofluvial–lacustrine landscapes (12 t ha^{-1} $year^{-1}$ = 1200 t km^{-2} $year^{-1}$).

Federal funds for monitoring have helped to improve knowledge of sediment transport in very large northern river basins, with important baseline and background information for environmental impact assessment. For example, NOGAP (Northern Oil and Gas Action Program) projects have directly improved the understanding of sediment movement in the Mackenzie River and Delta (Carson *et al.*, 1998, 1999). The mean annual contribution of sediment at the head of the Mackenzie Delta from the upstream basin is about 128 Mt, with 107 Mt from the Mackenzie River and 21 Mt from the Peel River. The net sedimentation in the delta is estimated to be 34% of the mean input to the delta head. Point bar sedimentation is balanced by channel bank erosion throughout the delta, but the sediment exchange between various erosion and deposition sites is not accounted for in the net sedimentation. The intra delta sediment exchange is important for sediment dilution and the residence time of sediment-borne contaminants. Current levels of contaminants in the delta are quite low although concentrations of some anthropogenic compounds have been increasing since the 1950s (Pannatier, 1998).

Erosion in agricultural landscapes

Soil erosion in agricultural landscapes is important for farming practice and soil conservation, but it also affects the overall sources and routing of sediment, nutrients and contaminants through fluvial systems. For example, recent research in southern Manitoba (Hargrave and Shaykewich, 1997) shows that the bulk of nutrient (N, P) losses are associated with sediment rather than soil water. The timing of loss is also important and there is increasing evidence that snow melt runoff, rather than rainfall, is the major agent of erosion in many parts of Canada (McConkey *et al*., 1997; Edwards *et al*., 1998; Gill *et al*., 1998). This is consistent with the high sediment concentrations observed during spring runoff events in streams. However, high erosion rates vary with land treatment and high erosion rates also may be accompanied by high rates of redeposition within the field (Edwards *et al*., 1998). The redeposition process also calls into question the reliability of soil-loss equations calibrated on very short (a few metres) erosion plots. Evidence from sheet-wash experiments (Mathier and Roy, 1996) indicates that the parameters of sediment transport in sheet-wash equations for agricultural fields are applicable over slopes only between 4 and 55 m.

Erosion, sedimentation and stream habitat effects of forest harvesting

Fluvial processes have an important effect on in-stream biological habitats. The effects of timber harvesting on erosion and in-stream sedimentation are particularly prominent in research on watersheds in coastal British Columbia (Hogan *et al*., 1998a), but the concerns extend to many other areas of the country.

In British Columbia attention now has been focused also on interior areas through an interdisciplinary study of six experimental watersheds in the Stuart–Takla region. The basins are in the Hogem Range of the Omineca mountains at the northern end of the sub-boreal spruce biogeoclimatic zone forming the most northern extent of the Fraser River basin. The streams support both early and late run sockeye salmon (*Oncorhynchus nerka*) as well as other species of fish (Macdonald and Herunter, 1998). One of the major goals of the project is to determine how forestry-associated changes in the thermal, hydrological and geomorphological regimes in these watersheds affect variation in the structure, stability and distribution of fish habitat (Tschaplinski, 1998). Baseline (pre-harvesting) studies of snow hydrology, groundwater influences and road-related sediment sources were undertaken for 5 years prior to any harvesting activity (Heinonen, 1998). Suspended sediment loads in three of the streams have been monitored since 1992 (Beaudry, 1998) and indicate that the pre-harvested watersheds have very low annual suspended sediment yields compared with other British Columbia watersheds. Approximately 95% of the annual yield is delivered in a 1 month period during snowmelt (Beaudry, 1998). Hogan *et al*. (1998b) have mapped the channel morphology of three streams in early autumn for each year of the study to evaluate changes associated with hydrological regime and large woody debris positioning. Pre-harvest data show large variability in the longitudinal profiles of these natural streams. If harvesting causes the long profile to become less variable, as suggested in coastal watershed studies, the effects will be detectable statistically (Hogan *et al*., 1998b). Abundant natural large woody debris is present in all the channels and is generally very stable. Hogan *et al*. (1998b) indicate that the source of the woody debris is the upstream reaches, which necessitates protection of both the fish habitat in the lower reaches and the woody debris sources upstream.

There are similar forestry concerns in eastern Canada. The Copper Lake buffer zone study, in the boreal forest near Cornerbrook, Newfoundland, has been assessing the impact of forest harvesting on brook trout (*Salvelinus fontinalis*) populations and habitat since 1993 (Scruton *et al*., 1995). Clarke and Scruton (1997) evaluated the fine-sediment yields in two streams upstream and downstream of road construction using the Wesche method of sediment trapping (partially buried sediment box traps filled with gravels) for evaluating statistical differences in fine-sediment storage. Seasonal differences in sediment storage, and also spatial effects due to bridge and culvert construction, were observed. Riparian buffers also significantly affect the accumulation of fine sediment during summer low flows (Clarke *et al*., in press). Control streams exhibited little seasonal variation in fine sediment accumulation, whereas streams with zero or narrow (20 m) buffers had significantly increased accumulations of fines during summer low flows.

At the Catamaran Brook watershed in New Brunswick a long term (15 year) interdisciplinary project is evaluating hydrological and sediment effects from forestry activities on biological habitats. Sites downstream of logging roads show elevated (by 5–10%) Freddle indexes (indicative of increased burial of gravel by fine sediment), which is estimated to cause a potential decline in alevin emergence from 95% to 68% (St-Hilare *et al.*, 1997). The absence of any apparent impact of logging roads at other sites may be explained by a lack of significant hydrological events between construction and sampling.

TRANSPORT AND FLOCCULATION OF FINE SEDIMENT: PROCESSES AND IMPACTS

Fine-sediment processes are the dominant agents of physical erosion in watersheds and an important transfer mechanism of contaminants. These processes are a complex interaction of physical, chemical and biological processes in streams and much of the recent work has focused on the details of these mechanisms, especially the formation and destruction of flocs, floc morphology and the effects of flocculation on sediment transport.

Flocculation and sedimentation

It is well established that fine sediment in streams is transported as flocs rather than as individual particles, yet there is much to be learned about the formation and structure of flocs and the implications for sediment and contaminant transport. Flocs behave very differently from the solid sphere that has long been the standard model of a sediment particle. The internal structure of flocs affects not only their physical properties (density and settling velocity), but also their chemical (adsorption of contaminants and nutrients) and biological properties.

Floc structure, size and settling velocity. Flocs have a complex internal structure dominated by a three-dimensional matrix of fibrillar material formed by microbial organisms and this intricate pore structure allows water to form an important bound component of the floc (Droppo *et al.*, 1997). Earlier work on flocculation in streams in southern Ontario (Droppo and Stone, 1994; Stone and Saunderson, 1992) has been followed by studies in the Mackenzie Delta (Droppo *et al.*, 1998a). In the Mackenzie Delta, suspended sediment is transported predominantly as flocs with sizes that, at times, exceed those found in the earlier studies in southern Ontario. *In situ* or effective particle-size analysis reveals two populations. The primary particles have fractal dimension D_{50} between 5 and 5·7 μm, whereas the flocs have D_{50} between 11 and 16 μm, producing an effective particle-size distribution that is bimodal, with a gap in the 7 to 10 μm range.

Settling velocity increases linearly with floc size but velocities are much less than predicted by Stokes' law for solid spherical particles of the same size. Floc density varies inversely with floc size, and for the larger flocs approaches the density of water (Droppo *et al.*, 1998b). Settling velocities during the rising limb are lower than during the falling limb of the spring melt hydrograph for flocs of the same size. The difference in settling velocities is probably due to the difference in the contribution of sediment sources during the event, with in-channel biofilms possibly contributing suspended matter during the rising limb, whereas on the falling limb this source would be exhausted. Stream contamination from pulp mills appears to have no effect on floc size (Petticrew and Bickert, 1998). In addition to floc density, porosity and size, floc shape strongly affects settling velocity. Elongated flocs tend to settle more slowly than more-spherical flocs.

The settling of flocs may have a direct effect on stream habitat. In small, mountain streams in British Columbia, Petticrew (1996) observed that the primary particles, with diameters between 5 and 50 μ, do not settle, but the formation of flocs up to 1290 μm in length allows settling to occur. The direct consequence is siltation of spawning gravels. Petticrew (1996) also draws attention to the possible role of bacterial activity in facilitating flocculation in these streams.

Stone and Krishnappan (1997, 1998) investigated experimentally, the effect of shear stress on floc size, using a 5 m diameter rotating circular flume, and a Malvern Particle Size Analyzer to measure effective particle-size distributions. For a sample from agricultural tile drains, D_{50} of the flocs reached a maximum value at a shear stress of 0·169 N m^{-2}. The D_{50} of flocs in suspension decreased at low shear stress because of settling of the coarser fraction and decreased at higher shear stress because of floc break-up. Seasonal decrease in floc size from February to May in the Fraser River at Prince George may be a result of the increased shear velocity associated with the spring freshet (Petticrew and Bickert, 1998).

Floc morphology. Fractal dimensions may be used to quantify changes in the morphology of flocs (De Boer, 1997). Images of flocs from a small prairie stream were analysed, and fractal dimensions of the floc population were determined from the relationships between floc area, perimeter and length. The changes in the morphology of the flocs resulting from algal bloom could be quantified with the fractal dimension derived from the area–perimeter relationship. The change in fractal dimension from 1·26 to 1·42 represents the formation of large particles with intricate shapes and large perimeters during the algal bloom. Fractal dimensions were also used by De Boer and Stone (1998) to describe the effect of buffer strips on floc morphology in two contrasting drainage basins in southern Ontario prior to, and during, snowmelt. In the Strawberry Creek basin, the narrow, ineffective riparian buffer zones resulted in an influx of sediment-laden overland flow from farmland. As a result, during snowmelt, sediment concentrations increased by a factor of 30 compared with pre-melt conditions, and an increase in the fractal dimension from 1·24 to 1·35 reflected the change in floc shape resulting from the input of fines and organic matter from topsoil. Conversely, in the Cedar Creek basin the extensive riparian buffer zones prevented an influx of particles during snowmelt, resulting in little change in sediment concentrations and fractal dimensions.

Contaminant transport

It is now recognized that much contaminant transport in rivers is associated with fine-grained sediments. In Canada this has led to both basic research and management initiatives on major river systems such as the Fraser, the St Lawrence and the Peace and Athabasca (NRBS, 1996; Gray and Tuominen, 1998), with a focus on anthropogenic effects and the impact of sediment-borne contaminants on the entire ecosystem (Ouellett, 1997; Cary and Cordiero, 1997).

It is apparent that the significance of sediment-borne contaminants depends on both the nature of the contaminants and the in-stream sediments. Stone *et al*. (1995) showed that phosphate release from fine-grained bed sediment depends on both the sorption characteristics of the individual particle size fractions and the particle size distribution as a whole. Different contaminants also show differing size-fraction affinities (Stone and Droppo, 1996). For example, in southern Ontario streams, concentrations of Zn and Pb were greatest in the smallest ($<8\mu m$) fraction, whereas Cu concentrations were greatest in the 8 to 12 μm fraction. Overall, 80% of the load of Pb, Cu and Zn is associated with particles <31 μm, which illustrates the important role of fines in metal transport. Trace-metal studies in the St Lawrence River (Quémerais *et al*., 1996) showed that Co, Mn and Fe are transported predominantly in the particulate phase, whereas a significant proportion of Cd and Cu (56 and 48%, respectively) is transported in the dissolved phase. Quémerais and Lum (1997) report that particular Cd concentrations in the St Lawrence River showed a positive correlation with particular organic mater and Mn, and a negative correlation with suspended solids concentration. The latter was explained by the influx of relatively coarse suspended sediment, with a low ability to adsorb trace elements, by the Quebec tributaries during high discharge events.

Transfer of heavy metals on street sand is an important concern in urban areas. Stone and Marsalek (1996) investigated the trace element composition and partitioning of street sediment collected in Sault Ste Marie, Ontario and found that a large portion of the heavy metals are potentially bioavailable. The elevated levels of Cd, Pb, Cu, Zn, Mn and Cr in the exchangeable and/or soluble phases indicate that street sediment has a potentially adverse effect on water quality during runoff and snowmelt. Nevertheless, a large proportion of the total metal load was associated with coarser particles, which have little potential for downstream transport.

TURBULENT FLOW STRUCTURE, SEDIMENT TRANSPORT AND BEDFORMS

Context

Increasing interest in the study of small-scale processes in rivers parallels an international trend apparent since the 1980s (for example, recent symposium volumes include Clifford *et al*., 1993; Ashworth *et al*., 1996; Carling and Dawson, 1996). Further impetus for the study of turbulence in sedimentology and geomorphology has come from the discovery of quasi-periodic structure in boundary layer flows and their potential role in the development of alluvial bedforms (Leeder, 1983). Small-scale flow structures 'are centrally implicated in sediment transport' (Church, 1996, p. 154), although it is debatable whether short-lived (a few seconds) structures are of sufficient duration to directly affect the development of fluvial landforms. Overall turbulent characteristics of the flow may be more relevant to fluvial geomorphology than are individual flow structures. Recent work has focused on the overall changes in flow turbulence produced by specific bed morphology, on the detection and characterization of intermittent flow structures both in space and time, and on the detection and description of the particle-scale bed structures in gravel-bed streams. These studies cover small-scale flow processes in a wide range of contexts (bedrock channels, gravel-bed rivers) and morphologies (river confluence, pebble clusters), with a dominant interest in gravel-bed rives. Only a few have successfully addressed the issue of fluvial landform development as a consequence of the interactions between flow, turbulence and sediment transport.

Bed structure in gravel-bed rivers

Particle clusters are a common mode of particle organization on gravel-bed streams, but more recently Church *et al.* (1998) have shown that larger scale organization and particle-size segregation may occur. Their field observations are corroborated by laboratory study. The most common structures are stone cells that develop at low bed-material transport and are constructed by the displacement of particles from less stable to more stable configurations. Intermediate stages in the development of stone cells include pebble clusters and stone lines. The overall structure increases the stability of the bed.

Structure of turbulent flow in gravel-bed rivers

Structures in turbulent flows are central to turbulence production and to the exchange of momentum yet '... the phenomenological picture over rough boundaries remains decidedly murky...' (Church, 1996, p. 154). Recent work has penetrated the murk. Using techniques to detect 'bursts' and to quantify the scales of the structure present in turbulent flow over a gravel-bed, Roy *et al.* (1996) have shown that the near-bed region is characterized by large flow structure similar to those found in the outer flow region. The inference is that large-scale flow structures extend through the entire water column with a scale two to three times larger than the flow depth. Ferguson *et al.* (1996) used a probabilistic approach to characterize the changes of velocity over the entire water column. They identified the presence of recurrent sequences of intermittent high- and low-speed wedges, with leading edges inclined downstream. A satisfactory explanation of these wedges has not yet been formulated, but eddy shedding from the lee of the largest particles on the bed may play a critical role in the development and enhancement of the wedges. They should also play a critical role in the entrainment of particles at the bed.

Pebble clusters are the dominant micro topographic features of gravel-bed rivers. Their presence drastically modifies both the average velocity vectors and the turbulence characteristics of the flow field. Buffin-Belanger and Roy (1998) made detailed flow measurements upstream and downstream of a pebble cluster and used mean velocity and turbulence statistics to delineate several flow regions. These regions are highly dynamic and their size and relative locations vary in time and space. Two separate zones of vortex shedding and of fluid upwelling occur in the lee of the obstacle. These zones are often amalgamated but they have clearly distinct properties. The presence of strong intermittent sweeps moving across the shedding and up welling regions also complicates the general flow structure behind a pebble cluster. There are strong similarities with the flow structures associated with dunes. Abrupt downstream transitions in bed roughness are common in gravel-bed streams. Robert *et al.* (1996) have concluded that the passage from an armoured bed to a zone with pebble clusters and isolated large particles results in an overall increase in turbulence intensities and in a change in the types of structures seen in the flow. An inner zone develops between the bed and the top of the protruding clasts in which there is intense eddying and strong downward flow component. Eddy shedding from the larger particles dominates the flow structure.

Flow structure at river confluences

Because of their critical role in the routing of flow and sediment, river confluences have been the subject of much research in the last decade. Recently, it has become apparent that flow structure at confluences is strongly affected by the (common) discordance of the confluent beds. Laboratory experiments have clearly shown the effects of bed discordance for parallel channels (Best and Roy, 1991) and the structures are now known for confluences with a 30° angle (Biron *et al*., 1996a,b). One of the main effects of bed discordance is distortion of the mixing layer between the two flows. The width of the mixing layer increases rapidly near the apex of the confluence and some fluid from the deeper channel is entrained under that of the shallower channel in such a way that upwelling occurs near the bank on the side of the shallower channel. The entrainment of fluid in the lee of the step is probably due to the low pressure zone that develops there. As a result, the separation zone usually occurs on the side of the tributary as it enters the confluence and is much smaller when the beds are discordant than when they are concordant. Field study in a sand-bed confluence also shows that bed discordance affects the three-dimensional flow structure and the intensity of the turbulence generated in the shear layer, and distorts the mixing layer (De Serres *et al*., 1999). The back-to-back secondary flow cells often reported at symmetrical confluences were not observed at this site. These results are beginning to be corroborated by three-dimensional numerical flow models (Bradbrook *et al*., 1998). Although this work is directed primarily towards understanding the physical processes of river confluences, it has important environmental applications. For example, bed discordance enhances mixing intensity and reduces the mixing length downstream of confluences (Gaudet and Roy, 1995), indicating that bed morphology is a primary factor to consider in the environmental management of river confluences.

Turbulence, suspension and dunes in sand-bed streams

Suspension of sandy bed material is also strongly controlled by turbulent flow structures. Direct and simultaneous measurement of turbulent eddies (using electro magnetic flow meters) and local suspended-sediment concentration (using optical back-scatter sensors) make it possible to study the intermittent nature of suspension 'events' and the influence of mean flow conditions (Lapointe, 1996). In a river about 100 m wide and 2·5 m deep, turbulent momentum exchange is highly variable, and exchange levels 10 times the mean occur up to 5% of the time but account for up to 70% of the stress. Vertical sediment flux 10 times the mean rate occurs up to 5% of the time, but accounts for up to 90% of the net suspension and is more frequent in deeper flows, perhaps related to dune development. The overall frequency distributions are similar to those found in much larger rivers, suggesting the occurrence of a general frequency distribution for vertical mixing. Suspension appears to be dominated by eddies with length scales one to five times flow depth.

Dunes in the Fraser River estuary channels (Kostaschuk and Villard, 1996) are of two types: symmetrical with rounded crests and low angles ($<8°$) and asymmetrical with steep lee side (around 19°) An important feature of these dunes is the absence of lee-side flow separation, although it may be present intermittently in the lee of asymmetrical dunes. Round-crested dunes are characterized by higher sediment transport rates than the asymmetrical dunes because of higher near-bed flow velocity. Asymmetrical dunes represent a transitional morphology between the large symmetrical dunes and smaller dunes. The low transport rate on their stoss side is caused by the presence of smaller dunes superimposed on the larger form, and lead to lower deposition rates on the lee side. The Fraser estuary dunes fit in the upper-stage plane bed region of standard bedform domain diagrams, which leads to the conclusion that these diagrams, derived from experimental flume data, may be inapplicable for large-scale forms in rivers.

Bedrock channels

There has been a revival of interest in fluvial processes and morphology of bedrock channels, exemplified by the recent publication of the research paper collection *Rivers Over Rock* (Tinkler and Wohl, 1998). Critical flow may be very common and extensive during high flow in rock-bed channels. (Tinkler, 1997a).

The critical state can be maintained only by substantial increases in flow resistance, which Tinkler (1997a) argues comes mainly from intense vorticity and shearing between the zone of critical flow and the surrounding flow. The initiation of bedload transport may also contribute to the increase in roughness and initial motion of boulders may take place beneath standing waves (Carling and Tinkler, 1998). Turbulent flow processes and structures are also important for fluvial erosion of bedrock and the micro morphology of bedrock channels. Erosion marks, flutes and ripples often found in bedrock channels are caused by the mechanical action of suspended sediment and the most intense erosion is associated with flow separation eddies around protrusions and large vortices developed in the mixing layer between high velocity layers and stagnation zones (Tinkler, 1997b; Hanckock *et al*., 1998).

BED LOAD TRANSPORT, SEDIMENT SORTING AND CHANNEL MORPHOLOGY

Although bedload is often a very small component of the total sediment load of most rivers, it is critical to the development of river morphology. Recent Canadian research has tackled three major issues related to the processes of bedload transport in gravel-bed streams: the actual downstream changes in particle size in relation to terrain and tributary characteristics; the relationship between river morphology and bedload transport processes; and description of the individual particle-scale displacements of which bedload transport is comprised. At the same time there are important applications of this understanding to the effect of environmental change in rivers and the relationship between bedload transport and stream habitat.

Processes

Downstream fining of bed sediment. The progressive downstream diminution of bed-sediment particle-size in alluvial rivers is a well-known phenomenon, although the relative importance of particle abrasion versus particle sorting and exchange is still not known. In many streams there are occasional inputs of sediment from tributaries or lateral sources (such as mass movements). These lateral inputs may be of sediment with a completely different size-distribution from that of the main stream and, if sufficient in quantity, may cause an abrupt change in bed-sediment sizes that 'resets' the diminution curve to a new value. On two gravel-bed rivers in British Columbia (Rice and Church, 1998), a series of 'sedimentary links' are identified statistically, within which there is rapid downstream diminution of bed sediment size, but at each node the particle size is reset by the tributary sediment source. There may be no overall trend in grain size over the entire length of river. Thus, the particle size at a point is a function of the cumulative effects of abrasion and sorting on material from each 'significant' source, weighted by the contribution to the sediment mixture at the point. This pattern can be described properly only with sufficient attention to sample size and representativeness (Rice and Church, 1998). In very small headwater streams the frequent tributary and lateral inputs, plus in-channel debris dams, may disturb the downstream sorting pattern so much that the effect is to produce an essentially random process (Rice and Church, 1996a). The combination of these studies will produce a basin-scale model of changes in bed-material particle size. Patterns of downstream fining can be deduced from morphological variables for tributaries such as link magnitude, basin area and basin slope used to predict the occurrence of tributaries having a significant effect on main-stem particle size (Rice, 1998).

Bed material transport and river morphology. Standard approaches to measuring, describing and predicting bedload at a point or cross-section and as equilibrium hydraulic functions (as in traditional engineering approaches) for 'conveyor belt' transport, fail to address the relationship between bedload and morphology. Morphological methods for estimating bed-material transport rates (see discussion in the section 'Techniques for Research and Monitoring') can explicitly address the spatial variation in transport rate in relation to river morphology (Martin and Church, 1995; Ashmore and Church, 1998; Haschenburger and Church, 1998). Direct measurement of change in river morphology (volumes of erosion and deposition) before and after significant flow events can yield information on the reach-average and downstream pattern of bed material transport. This makes it possible to observe directly the relationship between channel morphology, channel change and bed material transport rates. For example, on the Vedder River, British Columbia (Martin and Church, 1995) it is apparent that depositional zones (downstream decrease in transport rate) are wider and more braided than the single-channel 'transport zones'. This reach-scale pattern is persistent over several years, although there are some changes in reach behaviour over time and depending on flood magnitudes.

The Fraser River also shows persistent patterns of sediment transfer. The wandering channel pattern is characterized by specific points of erosional attack coupled with well-defined depositional zones, whereas the main thalweg of the river functions as a transfer zone within which exchange of bed material and moving particles are apparently minimal (Ashmore and Church, 1998). This erosion–deposition cell style of transfer is also observed in braided rivers and may be used as the basis for local transport-rate estimates between coupled cells. Transport rate varies substantially over very short distances, and rapid morphological change is necessarily accompanied by rapid temporal changes in transport rate. In proglacial meltwater flow regimes the downstream pattern of transport seldom remains the same from one day to the next. The result is that there is considerable scatter in the overall positive relation between discharge and transport rate that can be related to specific episodes of morphological change (Ashmore and Church, 1998). In the case of average for the event transport rates, there is some scatter in the relation between peak discharge and bedload transport rate because of differing event hydrograph shapes between autumn/winter and spring/summer snow melt floods (Martin and Church, 1995). This is not likely to be a problem when the flow generation mechanism is the same in all cases, such as diurnal summer melt events in proglacial streams.

Channel cross-section geometry. The variation in mean cross-section depth, width and velocity at a cross-section with changing flow stage is often referred to as 'at-a-station' hydraulic geometry. Knowledge of these relationships between width, depth, velocity and discharge are important for channel hydraulics and sediment transport calculations. In many cases the relationships can be approximated from the known channel geometry and the appropriate resistance function. It is known that the resistance function or the channel shape may cause these basic relationships to be more complicated than the simple power functions that are usually used. Hickin (1995) shows that the relationships also may be affected by channel scour at flows above the entrainment threshold. This causes abrupt breaks in the hydraulic geometry relationships around the threshold discharge, which is especially noticeable in the velocity–discharge curve.

Particle displacement and local scour and fill. The nature of individual gravel-particle displacements is important for an understanding of the development of fluvial morphology. It also can be used for the measurement of the volumetric flux of bed-material transport obtained by multiplying 'virtual velocity' (distance moved per transport event) by the active cross-section area (see discussion in the section 'Techniques for Research and Monitoring') (Haschenburger and Church, 1998). Gottesfeld (1998) tracked over 1400 magnetized bedload clasts (8000 records) for distance moved and depth of burial following nival floods, spawning season and autumn storms as part of the Stuart–Takla experimental watersheds study. Nival storms are the dominant gravel-displacement events, with a mean 'step length' of 16·8 m, and a maximum of 343 m. Exponential decay relationships between the depth of clast burial and distance downstream were observed. Reworking of the bed materials by floods facilitates the ease of bedload mobility for the salmon arriving to spawn three months later, although the extensive reworking of the bed by the salmon nine months before the more powerful nival events may aid in ensuring efficiency of bedload transport.

Tracer experiments can also provide information on the process of bedload transport. In Carnation Creek, British Columbia (Haschenburger and Church, 1998) tracers moved from pool to pool and there was no apparent influence of starting position (e.g. pool versus bar) on tracer mobility. Active depth, active width (estimated from tracer burial and from scour chains), virtual velocity and estimated transport rate all increase with increasing stream power. Mean maximum active depth is about twice D_{90}, and active width is often substantially less than wetted width.

Impact of floods, flow regulation and engineering

Against a background of very limited knowledge of Canadian rivers in general, fluvial geomorphologists and engineers have begun to build a picture of how rivers respond to large floods and to changes in flow regimes. This contributes to the international effort but also may reveal whether there are aspects of river behaviour characteristic of rivers in cold climates and in glaciated terrain. The results will help to anticipate future effects of land-use and climatic change.

Floods. River channel morphology is known to be transient, even under long-term equilibrium, and sensitive to both occasional large floods and long-term changes in flow conditions or sediment delivery. All flows above the bed–sediment entrainment threshold may cause modification of channel form, and extreme flood events may cause long-term changes to channel form. Canada is not a landscape of extreme floods and catastrophic fluvial events in comparison with some parts of the world, and the sensitivity of channels to large floods is not well known because of a dearth of cases. However, these is some expectation that sensitivity may be low in many cases because of the prevalent non-alluvial conditions.

The disastrous Saguenay region floods of July 1996 presented a rare opportunity in Canada to observe catastrophic flood effects in detail. Geomorphological impacts are described by Brooks and Lawrence (1998) and Lapointe *et al*. (1998). Flows on Ha!Ha! River, estimated at eight times the 100 year flood, produced two major avulsions and retrogressive headcuts in glacial sediments and massive sedimentation downstream (Lapointe *et al*., 1998). Threshold stream power for major valley-floor scouring is of the order of 300 W m^{-2}. More generally in the region, geomorphological impacts were less severe and generally associated with bridges and dams and local channel incision.

Flow regulations. Canadian rivers are heavily developed and regulated for water resource development. The impacts of this on channel morphology and sediment transport have not been documented over the long term. However, studies on rivers in western Canada (Church, 1995) provide information on the long-term adjustment to both flow regulation and flow enhancement. It is apparent from these cases that the morphological response of rivers to flow regulation may be complex and contingent on local conditions and flow history.

In the Peace River, the effect of flow regulation (a 50% reduction in peak discharge) independent of sediment supply can be documented because the major sediment sources occur downstream of the hydropower dam. The gravel-bed reaches immediately below the dam have stabilized and channel incision is not possible. Tributary mouths are areas of substantial sediment accumulation that is gradually creating a step-like channel long profile. Sand-bed reaches further downstream are showing evidence of aggradation and channel narrowing via vegetation encroachment and fine-channel accretion on bars and in side channels (Church, 1995; Prowse and Conly, 1996). At the same time the former floodplain has been abandoned and a new floodplain level is forming 2 or 3 m lower. The time-scale for adjustment appears to be hundreds of years. The effects extend all the way to the Slave River Delta 1500 km downstream from the point of regulation. Flow regulation effects to the Slave River Delta have been manifest in the reduced rates of growth on cleavage bars along the outer portions of the delta and the sedimentation characteristics within and along the distributary channels of the delta (Prowse and Conly 1996; English *et al*., 1997).

The Kemano River, British Columbia, is the receiving stream in a flow diversion project. Mean flow has increased three fold, which was accommodated initially by passive filling of existing side channels and channel widening (Church, 1995). However, the expected incision and gradient reduction occurred only after a large flood disrupted the bed armour.

Changes to channel morphology and channel behaviour may also be induced by engineering modification of rivers and by gravel extraction. Aggrading, gravel-bed braided streams present substantial problems when there is pressure to encroach on the channel zone, constrict and control the channel, or mine gravel from the channel (Galay *et al*., 1998). Although Galay *et al*. (1998) have suggested guidelines for interference in braided or wandering streams, which take account of approximate gravel transport rates and other aspects of stream dynamics, Church (1998) urges caution in all respects, pointing out that the guidelines and solutions are not necessarily effective for all rivers and that it is necessary to consider the impact on river habitat and the overall desirability of river control strategies within a complete management policy. Gravel extraction should at least be informed by the known downstream pattern of gravel transport rate.

Bedload, channel morphology and stream habitat

Channel processes and morphology are also important for stream habitat and attention is focused frequently on spawning and rearing habitat for fish. Alluvial channel form, on its own, is a primary determinant of habitat availability (Payne and Lapointe, 1997). Depending on planform (which includes braid-like, stable and tightly curved unstable reaches) Payne and Lapointe (1997) found a fivefold difference in usable habitat for fish fry, and a threefold difference in usable habitat for par. Unstable reaches, often thought of as unsuitable for fish habitat, provide rearing habitat for juvenile salmonids.

Fluvial morphology is often deliberately structurally modified for enhancement of stream habitat but the stability of these structures (weirs, groynes, revetments and boulders) is seldom monitored. Pattenden *et al.* (1998) evaluated the efficacy of 351, 2 to 7-year-old in-stream structures that had been placed in south-western Alberta streams to enhance the quality and quantity of deepwater refuge habitat for adult trout. They assessed the performance of the structures in the context of fish habitat, fluvial setting and hydraulic conditions. Many (*c.* 35%) of the structures neither maintained their physical stability nor provided suitable habitat in periods of minor flood discharges, and the major flood (greater than 100 year return period) of 1995 damaged or destroyed 81% of structures. Losses were greatest in unstable streams with high bedload and also in higher sinuosity channels. Miles (1998) reaches very similar conclusions from studies in southern British Columbia and other high energy environments. Success rates decrease with time and many structures suffer serious damage from moderate floods. Miles (1998) argues that the solution lies in focusing on restoring the conditions and processes in the river, valley and drainage basin that create habitat, rather than in costly (in the long term) artificial in-channel structures.

Basic studies of channel morphology and hydraulics also provide insight into the effects on stream habitat. On the Sainte Marguerite River, Quebec, significant net scour and/or fill occurred during a large summer flood event in 1996. The severity of impact of the flood on channel morphology was highest downstream of reaches with bank protection (Eaton, 1997). Dion (1997) developed two models to estimate the usable habitat area for juvenile salmon. The first model utilized the wetted width, water surface slope and discharge, whereas the second used the riffle–pool amplitude, bed slope and discharge. The first (hydraulic) model provided better estimates of usage area than the second (morphological model) but it requires more effort to obtain the input data required. An increase in habitat for fry and par resulted from riffle sedimentation during a major flood.

Bed stability may be assessed using measurement of hydraulic conditions and applying tractive-force criteria. At sites in Catamaran Brook watershed (New Brunswick), calculated stability varied little over time at depositional sites compared with erosional sites, but even in unstable locations immobile particles provided 'hydraulic refugia' for some organisms (Giberson and Caissie, 1998). Spawning activity also contributes to bed instability and downstream displacement of gravel particles (Gottesfeld, 1998) and modification of substrate grain size. Scrivener and Macdonald (1998) used freeze cores of gravel in redds and outside of redds to show that there was significantly less fine sediment ($<1{\cdot}18$ mm) in the redds compared with surrounding gravel. This cleaning or reduction of sand-sized particles improves the porosity of the gravel encouraging oxygen flow and egg survival. Petticrew (1998) found that after salmon spawning the gravel did not store large masses of fines, but the particles in the silt and clay fractions (<63 μm) were aggregated into particles that were up to 1200 μm in diameter. Petticrew and Droppo (in press) provide fall velocities for these dense aggregates, which indicate that downstream movement of these particles will be reduced during periods of low flow, such as when spawning occurs. Fine-grained aggregates with the same particle-size spectra as those in the stream gravels are also identified in downstream lake delta deposits, indicating that the material moves as cohesive aggregates along the stream length.

MODELLING LANDSCAPE EVOLUTION

Context

Knowledge of the physics of erosional processes in the landscape is essential to the understanding of long-term landscape evolution, which has been a central component of the study of geomorphology from its inception. Classic nineteenth century work (e.g. Davis, 1899) was conceptual, with little foundation in the numerical definition of geophysical processes. The 1960s and 1970s brought new approaches based on mathematical models of surficial (denudational) processes (e.g. Kirkby, 1971). The surficial processes models were the precursor to contemporary models of landscape evolution that take advantage of recent increases in computing power, and combine both tectonic and denudational processes (e.g. Anderson, 1994; Kooi and Beaumont, 1994; Tucker and Slingerland, 1994). Numerical models of landscape evolution can now combine endogenic and exogenic processes over time scales of 10^3 to 10^6 years, and include rigorous sensitivity analysis. The recent international upsurge in landscape modelling is perhaps best exemplified by a special issue of *Journal of Geophysical Research* (1994, Vol. 99), demonstrating that the problem is of broad geophysical concern extending beyond the issues of landscape evolution alone to those of Earth system interactions (Molnar and England, 1990).

Canadian contributions

Recent Canadian contributions to landscape modelling focus on coupled tectonic–surface process models (e.g. Kooi and Beaumont, 1994, 1996), and on modelling of the geomorphological component of landscape evolution in isolation from tectonic impacts (Martin, 1998), so as to better specify the geomorphological (exogenic) processes. Kooi and Beaumont (1996) used a coupled model to explore some of the classic and modern conceptual frameworks of geomorphology that are seldom tested explicitly. The geomorphological component of their model adopts a generalized physics approach (Martin, 1998) to process specifications used in recent landscape evolution models (e.g. Anderson, 1994; Tucker and Slingerland, 1994). Process equations are generalized at a level of detail that is appropriate and resolvable at the large scale. Processes actually may be variable in rate or occurrence, but are assumed to act continuously over sufficiently long time periods. Furthermore, details of actual process operation, such as the exact location of erosion and deposition, are assumed to 'average-out' such that they can be represented by relatively simple relationships. In their model, Kooi and Beaumont (1996) use a diffusion equation to simulate hillslope processes and a stream power relation to simulate fluvial transport. Beaumont *et al.* (2000) emphasized that research defining the surface processes component of coupled landscape evolution models is still in its early stages. Much further research is required regarding how to best parameterize geomorphological process operation over large time and space scales. Beaumont *et al.* (2000) explain that denudational forcing may be as important as mantle forcing in orogenesis at convergent plate boundaries. In addition, coupling of tectonic and denudation processes occurs at divergent plate boundaries.

Martin (1998) argues that geomorphological processes and rates need to be better specified in existing models of evolution. The work focuses on hillslope and channel sediment transport processes typical of coastal regions of British Columbia. A generalized physics approach was applied to process definition, and equations were calibrated using large field databases to correct the shortcoming of earlier models in which equations defined often were not rigorously evaluated using field data. The standard hillslope transport laws based on linear diffusion, which are used frequently in numerical models, may be better represented by non-linear rules (Martin and Church, 1997). A stream power relation was defined to estimate fluvial transport, and calibrated using a large database of transport rates. The hillslope and fluvial model components were run in isolation and in combination and results were evaluated to assess whether the equations, if combined within a surface model, simulated landscape evolution realistically.

There has been an increasing interest in the study of large-scale geomorphology in recent years. The numerical modelling of landscape evolution is an approach that has been adopted to address the operation of the geomorphological component of landscape evolution, both in isolation and in combination with tectonics. However, Canadian contributions are few in an area of growing international significance, leading to an obvious need for increased activity of this kind in Canadian geomorphology and geophysics.

DEVELOPMENT OF TECHNIQUES FOR RESEARCH AND MONITORING

In the course of research on fluvial erosion and sedimentation Canadian scientists have made substantial contributions to methods and techniques. These are dealt with separately to emphasize the scope and significance of the contributions.

Flocs and contaminants

The monitoring of sediment-associated contaminants requires both appropriate sampling methods and suitable monitoring design. Temporal and spatial variability of contaminant transport requires that monitoring programmes for contaminant fluxes should incorporate knowledge about the transport regime at the sampling site, about the desired end-product of the sampling programme, and about the accuracy needed to meet programme needs (Droppo and Jaskot, 1995).

Investigation of flocs has involved the development of new laboratory and field techniques for stabilization of flocs in preparation for detailed analysis of the floc structure. Droppo *et al*. (1996) use sampling of flocs from a settling chamber and embedding the settled flocs in agarose. This technique minimizes floc dehydration and deformation, and the details of the architecture of the embedded floc can be studied with conventional optical microscopy (COM), transmission electron microscopy (TEM), and scanning confocal laser microscopy (SCLM) (Liss *et al*., 1996). The different techniques are used to provide information on floc structure at different scales. The COM technique provides information on the overall shape of the floc, and estimates of floc size, shape and volume. At the other end of the scale, the high-resolution TEM images reveal complex networks of polymeric fibrils, with a diameter of 4 to 5 μm, connecting the inorganic and organic components of flocs. This increases the surface area of flocs available for sorption of contaminants and draws attention to the similarities of flocs and biofilms (Liss *et al*., 1996).

Assessment of instream sedimentation for forest harvesting

In British Columbia the enforcement of the forest practices code has resulted in provision of methods to evaluate the success of watershed restoration techniques. Sedimentation traps have been evaluated for estimating differences in in-stream sedimentation on systems affected by forest harvesting (Larkin and Slaney, 1996; Larkin *et al*., 1998). Traps may be lost at high flow and results are highly variable, but there is potential for relative assessment of sedimentation effects. A new techniques manual (Rex and Carmichael, 1999) provides a comparison and statistical evaluation of nine methods that can be used to measure changes in bed composition. The document also provides guidelines for establishing sites and monitoring programmes.

Turbulent flow structure

Although the measurement of turbulence both in the laboratory and in the field is now easier to carry out, one of the key issues is data quality and analysis. For instance, several different sensors are now available and currently used. This introduces new issues in the comparability of the data obtained from different instruments. It is therefore necessary to assess the properties of each type of sensor. In recent years, significant contributions have established procedures to examine velocity measurements obtained from laser–Doppler anemometers (Biron *et al*., 1995), acoustic Doppler velocimeters (Lane *et al*., 1998) and electromagnetic current meters (Roy *et al*., 1996, 1997). Of particular concern in the analysis of turbulent velocity data is that of filtering. Electromagnetic current meters have electronic filters that vary from one type of sensor to the other. These filters do not only reduce the variances of the velocity signals but also affect the structural features of the signal itself. It has been shown that filtering a signal increases the dependency of one value to the next, thus increasing its apparent coherence (Roy *et al*., 1997). This is most important when assessing the average size of structures in turbulent flows from autocorrelation techniques.

Grain size and bed morphology in gravel

The characterization of the grain-size distribution and of the spatial arrangements of structure and morphological features in a gravel-bed river is a difficult problem. For instance, the determination of the important statistics of the grain-size distribution should require a very large number of clast measurements. The exercise is further complicated by the fact that we do not know the theoretical distribution of the grain sizes and therefore cannot estimate the reliability of a measurement. Rice and Church (1996b) have applied boot-strapping to estimate the variability standard errors of various statistics with sample size. The technique provides an estimate of the standard errors of the centile diameter (D_5, D_{16}, D_{50}, etc.) of the grain-size distribution by subsampling of clasts. Their work has important practical implications: they show that 400 particles represent a reasonable sample size for estimating the diameter percentiles.

Bedload transport

Direct measurements of bedload transport using portable traps are often unreliable. This represents a severe limitation in the study of alluvial dynamics and of morphological changes in a reach. Martin and Church (1995) and Ashmore and Church (1998) have investigated morphological or 'inverse' methods for assessing bedload transport, arguing that they are simpler and superior to point sampling for understanding spatial and temporal patterns of transport in relation to evolving stream morphology. The method uses the continuity principle in conjunction with morphological evidence of changes either from cross-sections (Martin and Church, 1995) or from digital elevation models (Ashmore and Church, 1998). Deposition and erosion volumes are computed over a reach to assess the transfer of material. This can be done using either an estimate of mean sediment transfer distance to give a reach-averaged rate, or by using net changes in bed elevation to compute the downstream change in bed material transport rate and hence the spatial and temporal pattern of cross-section averaged transport rate. The morphological method also has the advantage of making the direct connection between the spatial and temporal patterns of bed material transport rate and the associated development of stream bed morphology (Ashmore and Church, 1998; Haschenburger and Church, 1998).

However, the morphological technique has not been tested against the 'true' transport rate and there are several potential sources of error and bias in the estimates (Ashmore and Church, 1998). Testing of the method under controlled conditions in which both input and output to the control reach are known, can be done with small-scale physical models (Stojic *et al*., 1998). Digital photogrammetry was used to derive a time sequence of very high resolution digital elevation models from which the complete pattern of erosion and deposition can be quantified for a given time interval. These can be used to derive spatial patterns of transport and to estimate errors in the morphological method.

Resurvey of bed topography to derive morphological transport rates is only of value in rivers in which the overall pattern of river development is a series of discrete and persistent zones of net scour and net disposition. In other cases the method requires the use of scour chains and particle tracing to yield the active cross-section area, and the 'virtual velocity' of gravel particles, which when multiplied and adjusted for porosity or bulk density yield a mean 'event' bed material transport rate (Haschenburger and Church, 1988). Virtual velocity is defined as the total distance travelled by a particle over the total time during which flows were competent to transport the material. Haschenburger and Church (1988) have applied this method to multiple flood events of differing magnitudes to demonstrate the feasibility of the method. With a small number of events the sampling errors remain large relative to calculated transport rates, especially because of large errors in virtual velocity estimates. The results are also sensitive to the choice of critical discharge for entrainment and deposition because this affects the time base for the particle velocity estimates. Tracers are slightly less precise than scour chains for estimating active area, but are preferred for practical reasons — the tracer particles are already needed for virtual velocity estimates.

RETROSPECT AND PROSPECT

The characteristics of the Canadian landscape and environment have always conditioned and guided fluvial research, yet this review shows that the small community of fluvial scientists have also contributed to the general progress on fundamental problems in fluvial science in general. Fundamental research has been coupled to the development of new techniques across the entire range of scales of interest. Recent work has been marked by an interest in 'application' to environmental problems, and an increasing recognition of the connection between physical and biological processes. There is obvious strength in field-based empirical science, but theoretical developments and application of numerical modelling are weak by comparison, despite the fact that areas of traditional strength (e.g. landscape development, erosion and sediment transport mechanics, and turbulence) are ripe for this type of modelling. Significant progress is likely only when fluvial scientists develop those tools and skills themselves or are able to entrain the necessary expertise interested in the types of geophysical problems that will further our insight into fluvial processes.

Despite significant progress on several fronts we should also ask how much we know about Canadian river systems. This review outlines progress in several areas: the glacial conditioning of fluvial erosion in 'wild' landscapes, the effects of timber harvesting on sediment transfer and stream characteristics, and the empirical description of the processes of sediment transport in gravel-bed rivers that are common throughout the country. However, we know little about our large rivers (with basin areas up to 10^6 km^2) in both settled and pristine environments, we know little about the non-alluvial rivers, large and small, that dominate the landscape, and we have done little to incorporate our knowledge of river ice and permafrost into our understanding of sediment transfer, river mechanics and fluvial landscapes. Canadian fluvial science has tended to follow the path to smaller and smaller scales of interest, which increasingly divorces the work from the landscape from which the initial inspiration is derived, leading us away from the unique character of Canadian river systems. Although some areas of hydrology and geomorphology have expanded in scope to consider regional landforms and processes, and Earth systems in general, river scientists remain resolutely local in focus.

Management-based science on some of the larger river systems (e.g. Northern River Basins Study) have perhaps been useful in indirectly providing knowledge of Canadian rivers. This type of government-initiated work has replaced much of the effort and resources that previously were devoted to national hydrological monitoring networks and programmes. These monitoring programmes provided data that have helped us understand the nature of landscape development and sediment transfer in Canadian rivers, but the job is unfinished. We still know little about fundamental issues such as the time-scale of sediment transfers in large basins, and the response of rivers to environmental change, for which the basic data and baseline conditions provided by monitoring are essential. Fluvial science has been helped to some extent by the recognition of its value for river system management. However, a focus on management expedience may detract from basic science and produce a plethora of issues-related case studies from which generalization, synthesis and theory testing will be difficult. The current mix, however, is attracting an increasing number of researchers and practitioners and this is the key to a healthy future.

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