HYDROLOGICAL PROCESSES
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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\ _ne!sediment transport\ bed material transport and river morphology and numerical modelling of ~uvial landscape development[

Research on sediment yield and denudation has con_rmed that Canadian rivers are often dominated by riparian sediment sources[Studies of the e}ects of forestry on erosion\ in!stream sedimentation and habitat are prominent\ including major _eld experimental studies in coastal and central British Columbia[Studies of _ne!sediment transport mechanisms have focused on the composition of particles and the dynamics of ~oc!culation[In ~uvial dynamics there have been important contributions to problems of turbulence!scale ~ow structure and entrainment processes\ and the characteristics of bedload transport in gravel!bed rivers[Although

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addressing broader environmental concerns[However\ large reductions in programme funding for water resources in Canada in the 0889s "Pearce and Quinn\ 0885# have had severe consequences for long!term sediment monitoring programmes[Monitoring is now reduced to about 199 stations\ most of which are in Ontario\ Alberta and British Columbia\ and only about 09) of stations have a full regular monitoring programme[The remaining 89) 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 0888#[

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 con! tributing little to the sediment load and landscape denudation "Ashmore and Day\ 0877^ Church *e a* [\ 0878^ Ashmore\ 0882#[This pattern of erosion can also be shown by using sediment particle characteristics rather than sediment yields and budgets "De Boer and Crosby\ 0885#[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\ 0885#[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\ 0885#[The downstream change in suspended solids characteristics is explained by the increased contribution to the sediment load of reworked glacial\ glacio~uvial and glaciolacustrine deposits on the main valley ~oor[

Where uplands are erosionally connected to the stream system\ the e}ect of di}ering sur_cial "glacial# deposits on sediment yield may be detected[Stone and Saunderson "0885# investigated the regional patterns of ~uvial sediment yield in the low relief\ largely agricultural\ tributaries to the lower Great Lakes using Water Survey of Canada data for 81 tributaries[The average speci_c sediment yield of the drainage basins of the Great Lakes and Lake St Clair ranged from 10=6 to 76=2 t km 1 year 0\ but the highest speci_c sediment yields " 499 t km 1 year 0# were found in sub!basins with agricultural and industrial land use on _ne!grained glacio!lacustrine parent materials[However\ these results are di . cult to reconcile with soil loss observations on the Prairies "Pennock *e a* [\ 0884# showing that the highest rates of soil loss were found in glacial till landscapes "29 t ha 0 year 0 2999 t km 1 year 0# whereas the lowest rates were found in silty glaciolacustrine and aeolian landscapes and in _ne sandy loam glacio~uvial lacustrine landscapes "01 t ha 0 year 0 0199 t km

year

example\ recent research in southern Manitoba "Hargrave and Shaykewich\ 0886# 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 runo}\ rather than rainfall\ is the major agent of erosion in many parts of Canada "McConkey *e a* [\ 0886^ Edwards *e a* [\ 0887^ Gill *e a* [\ 0887#[This is consistent with the high sediment concentrations observed during spring runo} 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 _eld "Edwards *e a* [\ 0887#[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\ 0885# indicates that the parameters of sediment transport in sheet! wash equations for agricultural _elds are applicable over slopes only between 3 and 44 m[

E \ ed e a a d ea ab a e ec e a ▾e g

Fluvial processes have an important e}ect on in!stream biological habitats[The e}ects of timber harvesting on erosion and in!stream sedimentation are particularly prominent in research on watersheds in coastal British Columbia "Hogan *e a* [\ 0887a#\ 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 "*O c c e a*# as well as other species of _sh "Macdonald and Herunter\ 0887#[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 a}ect variation in the structure\ stability and distribution of _sh habitat "Tschaplinski\ 0887#[Baseline "pre!harvesting# studies of snow hydrology\ groundwater in~u! ences and road!related sediment sources were undertaken for 4 years prior to any harvesting activity "Heinonen\ 0887#[Suspended sediment loads in three of the streams have been monitored since 0881 "Beaudry\ 0887# and indicate that the pre!harvested watersheds have very low annual suspended sediment yields compared with other British Columbia watersheds[Approximately 84) of the annual yield is delivered in a 0 month period during snowmelt "Beaudry\ 0887#[Hogan *e a* ["0887b# 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 pro_les of these natural streams[If harvesting causes the long pro_le to become less variable\ as suggested in coastal watershed studies\ the e}ects will be detectable statistically "Hogan *e a* [\ 0887b#[Abundant natural large woody debris is present in all the channels and is generally very stable[Hogan *e a* ["0887b# indicate that the source of the woody debris is the upstream reaches\ which necessitates protection of both the _sh habitat in the lower reaches and the woody debris sources upstream[

There are similar forestry concerns in eastern Canada[The Copper Lake bu}er zone study\ in the boreal forest near Cornerbrook\ Newfoundland\ has been assessing the impact of forest harvesting on brook trout "*Sa ▾e a* # populations and habitat since 0882 "Scruton *e a* [\ 0884#[Clarke and Scruton "0886# evaluated the _ne!sediment yields in two streams upstream and downstream of road construction using the Wesche method of sediment trapping "partially buried sediment box traps _lled with gravels# for evaluating statistical di}erences in _ne!sediment storage[Seasonal di}erences in sediment storage\ and also spatial *e a* [\ 0886#[The absence of any apparent impact of logging roads at other sites may be explained by a lack of signi_cant 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 ~ocs\ ~oc morphology and the e}ects of ~occulation on sediment transport[

F cc a a d ed e a

It is well established that _ne sediment in streams is transported as ~ocs rather than as individual particles\ yet there is much to be learned about the formation and structure of ~ocs and the implications for sediment

F c g . Fractal dimensions may be used to quantify changes in the morphology of ~ocs "De Boer\ 0886#[Images of ~ocs from a small prairie stream were analysed\ and fractal dimensions of the ~oc population were determined from the relationships between ~oc area\ perimeter and length[The changes in the morphology of the ~ocs resulting from algal bloom could be quanti_ed with the fractal dimension derived from the area perimeter relationship[The change in fractal dimension from 0=15 to 0=31 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 "0887# to describe the e}ect of bu}er strips on ~oc morphology in two contrasting drainage basins in southern Ontario prior to\ and during\ snowmelt[In the Strawberry Creek basin\ the narrow\ ine}ective riparian bu}er zones resulted in an in~ux of sediment!laden overland ~ow from farmland[As a result\ during snowmelt\ sediment concentrations increased by a factor of 29 compared with pre!melt conditions\ and an increase in the fractal dimension from 0=13 to 0=24 re~ected the change in ~oc shape resulting from the input of _nes and organic matter from topsoil[Conversely\ in the Cedar Creek basin the extensive riparian bu}er zones prevented an in~ux of particles during snowmelt\ resulting in little change in sediment concentrations and fractal dimensions[

C a a a

It is now recognized that much contaminant transport in rivers is associated with _ne!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\ 0885^ Gray and Tuominen\ 0887#\ with a focus on anthropogenic e}ects and the impact of sediment!borne contaminants on the entire ecosystem "Ouellett\ 0886^ Cary and Cordiero\ 0886#[

It is apparent that the signi_cance of sediment!borne contaminants depends on both the nature of the contaminants and the in!stream sediments[Stone *e a*["0884# showed that phosphate release from _ne! grained bed sediment depends on both the sorption characteristics of the individual particle size fractions and the particle size distribution as a whole[Di}erent contaminants also show di}ering size!fraction a . nities "Stone and Droppo\ 0885#[For example\ in southern Ontario streams\ concentrations of Zn and Pb were greatest in the smallest " 7μm# fraction\ whereas Cu concentrations were greatest in the 7 to 01 μm fraction[Overall\ 79) of the load of Pb\ Cu and Zn is associated with particles 20 μm\ which illustrates the important role of _nes in metal transport[Trace!metal studies in the St Lawrence River "Quemerais *e a*[\ 0885# showed that Co\ Mn and Fe are transported predominantly in the particulate phase\ whereas a signi_cant proportion of Cd and Cu "45 and 37) \ respectively# is transported in the dissolved phase[Quemerais and Lum "0886# 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 in~ux 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 "0885# 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 e}ect on water quality during runo} 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

C e

Increasing interest in the study of small!scale processes in rivers parallels an international trend apparent since the 0879s "for example\ recent symposium volumes include Cli}ord *e a*[\ 0882^ Ashworth *e a*[\ 0885^ Carling and Dawson\ 0885#[Further impetus for the study of turbulence in sedimentology and geomorphology has come from the discovery of quasi!periodic structure in boundary layer ~ows and their potential role in the development of alluvial bedforms "Leeder\ 0872#[Small!scale ~ow structures {are centrally implicated in sediment transport| "Church\ 0885\ p[043#\ although it is debatable whether short! lived "a few seconds# structures are of su . cient duration to directly a}ect the development of ~uvial landforms[Overall turbulent characteristics of the ~ow may be more relevant to ~uvial geomorphology than are individual ~ow structures[Recent work has focused on the overall changes in ~ow turbulence produced by speci_c bed morphology\ on the detection and characterization of intermittent ~ow 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 ~ow processes in a wide range of contexts "bedrock channels\ gravel! bed rivers# and morphologies "river con~uence\ pebble clusters#\ with a dominant interest in gravel!bed rives[Only a few have successfully addressed the issue of ~uvial landform development as a consequence of the interactions between ~ow\ turbulence and sediment transport[

Bed c e g ave-bed ve

Particle clusters are a common mode of particle organization on gravel!bed streams\ but more recently Church *e a* ["0887# have shown that larger scale organization and particle!size segregation may occur[Their _eld observations are corroborated by laboratory study[The most common structures are stone cells that

F\ c e a ve c e ce

Because of their critical role in the routing of ~ow and sediment\ river con~uences have been the subject of much research in the last decade[Recently\ it has become apparent that ~ow structure at con~uences is strongly a}ected by the "common# discordance of the con~uent beds[Laboratory experiments have clearly shown the e}ects of bed discordance for parallel channels "Best and Roy\ 0880# and the structures are now known for con~uences with a 29> angle "Biron *e a*[\ 0885a\b#[One of the main e}ects of bed discordance is distortion of the mixing layer between the two ~ows[The width of the mixing layer increases rapidly near the apex of the con~uence and some ~uid 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 ~uid 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 con~uence and is much smaller when the beds are discordant than when they are concordant[Field study in a sand!bed con~uence also shows that bed discordance a}ects the three!dimensional ~ow structure and the intensity of the turbulence generated in the shear layer\ and distorts the mixing layer "De Serres *e a*[\ 0888#[The back!to! back secondary ~ow cells often reported at symmetrical con~uences were not observed at this site[These results are beginning to be corroborated by three!dimensional numerical ~ow models "Bradbrook *e a*[\ 0887#[Although this work is directed primarily towards understanding the physical processes of river con~uences\ it has important environmental applications[For example\ bed discordance enhances mixing intensity and reduces the mixing length downstream of con~uences "Gaudet and Roy\ 0884#\ indicating that bed morphology is a primary factor to consider in the environmental management of river con~uences[

T b e ce\ e a d d e a d-bed ea

Suspension of sandy bed material is also strongly controlled by turbulent ~ow structures[Direct and simultaneous measurement of turbulent eddies "using electro magnetic ~ow meters# and local suspended! sediment concentration "using optical back!scatter sensors# make it possible to study the intermittent nature of suspension {events| and the in~uence of mean ~ow conditions "Lapointe\ 0885#[In a river about 099 m wide and 1=4 m deep\ turbulent momentum exchange is highly variable\ and exchange levels 09 times the mean occur up to 4) of the time but account for up to 69) of the stress[Vertical sediment ~ux 09 times the mean rate occurs up to 4) of the time\ but accounts for up to 89) of the net suspension and is more frequent in deeper ~ows\ 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 _ve times ~ow depth[

Dunes in the Fraser River estuary channels "Kostaschuk and Villard\ 0885# are of two types] symmetrical with rounded crests and low angles " 7># and asymmetrical with steep lee side "around 08># An important feature of these dunes is the absence of lee!side ~ow 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 ~ow 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 _t in the upper!stage plane bed region of

The critical state can be maintained only by substantial increases in ~ow resistance\ which Tinkler "0886a# argues comes mainly from intense vorticity and shearing between the zone of critical ~ow and the surrounding ~ow[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\ 0887#[Turbulent ~ow processes and structures are also important for ~uvial erosion of bedrock and the micro morphology of bedrock channels[Erosion marks\ ~utes and ripples often found in bedrock channels are caused by the mechanical action of suspended sediment and the most intense erosion is associated with ~ow separation eddies around protrusions and large vortices developed in the mixing layer between high velocity layers and stagnation zones "Tinkler\ 0886b^ Hanckock *e a* [\ 0887#[

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 thepartic!sticoneplaopmeson of which bedload1-290(transpord)]TJ T * 5(is4
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channel change and bed material transport rates[For example\ on the Vedder River\ British Columbia "Martin and Church\ 0884# 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 ~ood magnitudes[

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 ~uvial

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