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Bed configuration and microscale processes in alluvial channels

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Abstract: Numerous recent studies on fluvial processes, both in Canada and internationally, have focused on small-scale phenomena. Investigations on the characterization of surface roughness in coarse-grained channels and its links with flow resistance and sediment transport processes have been a dominant field of research. Closely related is a second major area of investigation on turbulent flow structures in boundary layers over both sand and gravel beds and their relations with the transport of bed material. Phenomena potentially related to 'bursting' have been shown to control bedload transport processes and the concentration of sediment in suspension. Detailed investigations have also been conducted on the links between flow turbulence, bed material movement, and bed morphology at channel junctions. Finally, selective entrainment and transport of individual coarse particles have been studied from field measurements and laboratory experiments. Emphasis has been put on bed microtopography, surface structure and texture, and on a probabilistic approach to bedload transport.

Key words: fluvial processes, surface roughness, turbulent structure, entrainment, bedload, confluence.

I Introduction

Part of the recent research in fluvial geomorphology, hydraulic engineering and fluid mechanics has focused on detailed, small-scale phenomena, and a reductionist approach has dominated the field during the last few years. Some major areas of research have been established, almost all being related to the 'trilogy' sediment transport, turbulent flow, bedform development. Three recent research themes on fluvial forms and processes will be discussed. I will also indicate some research directions which appear to be particularly relevant for further understanding of forms and processes in alluvial channels.

The first area of research to be discussed is the characterization of surface roughness in coarse-grained channels. Although this has long been a major research topic in the engineering literature on sand-bedded rivers, recent emphasis on gravel-bedded rivers (Hey *et al.*, 1982; Thorne *et al.*, 1987; Billi *et al.*, 1992) and related detailed investigations on the transport of gravel-bed material and its surface texture, structure, and geometric properties represent a subtle shift in emphasis. Interestingly, there has been a sustained interest in gravel-bed rivers in Canada during the last two decades with which the recent international concern on coarse-grained channels could be associated.

A second major area of recent interest is the characterization of turbulent structures in both sand- and gravel-bed channels and their links with sediment transport processes. Early studies in the fluid mechanics literature (e.g., Grass, 1971; Jackson, 1976) have clearly inspired contemporary investigations of fluvial hydraulics and sedimentology (Leeder, 1983).

Flow competence and the threshold of motion represent the third major component of recent research. Numerous studies illustrate clearly the links between surface micro-topography, flow turbulence and the onset of sediment motion. The 'equal mobility' hypothesis of Parker and associates (Parker and Klingeman, 1982; Parker *et al.*, 1982a; 1982b) has generated a debate and numerous contributions have been put forward which illustrate the complex properties of bedload movement in gravel-bed rivers. Associated with these questions of selective entrainment or equal mobility is a recent and renewed interest into bedload transport processes as determined from the movement of individual clasts. Also significant are some recent contributions on bed material transport using flow visualization techniques and/or measurements at a temporal resolution similar to that utilized for the study of turbulent flow structures.

II Surface roughness

Despite the early investigation of Laronne and Carson (1976), the effects of small-scale topographic variations and microform bed roughness elements on flow and sediment transport remain largely unknown. Surface roughness in gravel-bed rivers is complex and difficult to characterize (Robert, 1990a; 1990b). A number of spatial scales of boundary feature can be distinguished, conveniently divided into different categories (Robert, 1990a; Hassan and Church, 1992), i.e., grain sizes and shapes, microtopographic features (imbrication, clusters, etc.), and large-scale bed undulations such as riffles, pools and channel bars. Each of these scales exerts a significant control on some flow properties and sediment transport processes.

1 Bed morphology

As opposed to sand-bed channels in which morphological properties of the bed and their relation with bed material size and flow intensity are well-known, the geometrical properties of gravel-bed surfaces have not been thoroughly investigated. Microtopographic profiles show the complexity of natural gravel-bed surfaces. Perhaps their most consistent characteristic is the presence of two distinct scales of irregularity: one which corresponds to the texture of individual grains and a second which seems to correspond to obstacles and clusters of grains along the bed surface (Robert, 1988; 1991). Statistical analysis of these microtopographic profiles, or more specifically, analysis of bed elevation series using fractal ideas (Mandelbrot, 1982) suggests that natural gravel-bed surfaces are highly irregular at a spatial scale corresponding to the spacing of the largest particles on the bed and associated imbricated pebbles and cluster bedforms (Robert, 1988; 1991). Bed material sorting also appears to control the statistical properties derived from those topographic profiles (Robert, 1991).

Series of bed elevations measured at a very small sampling interval depart, however, from the fractal models and Brownian motion traces. That is, self-similarity is observed over only a narrow range of scales (Robert, 1988; 1991) and frequency distributions of increments of bed elevation series (or local slopes) are not characterized by a Gaussian-normal distribution (which is a basic characteristic of fractional Brownian models; Kirchner *et al.*, 1990). These preliminary studies nevertheless suggest the usefulness of a detailed picture of the bed configuration at different spatial scales and how the surface roughness properties may interact with the flow and determine hydraulic resistance processes (e.g., Clifford *et al.*, 1992a; 1992b).

Finally, characterization of grain size (and shape) distribution is also of paramount interest. In recognition of the importance of a reliable and statistically meaningful estimate of a given grain size index (for flow resistance estimates, for instance), more attention should perhaps be devoted to sampling problems and adequate representation of bed material (surface and subsurface) distributions (Church *et al.*, 1987; Wolcott and Church, 1991).

2 Flow resistance

Flow resistance processes and their links with grain sizes and the bed configurations can be studied from two complementary perspectives. The first approach involves prediction of mean flow velocity (or mean flow depth) at a cross-section or along a given reach as a function of cross-section size and shape and bed material size (e.g., Bray, 1980). A second approach deals with the local and detailed investigation of velocity profile characteristics as a function of local bed surface conditions (Nowell and Church, 1979; Wiberg and Smith, 1991; Robert *et al.*, 1992).

The prediction of mean flow velocity from bed roughness characteristics has been thoroughly studied in sand-bed channels. The seminal paper of Simons and Richardson (1966) and many subsequent studies clearly illustrated the dominant role played by bedforms in increasing flow resistance and boundary shear stress, but also the difficulties involved in predicting flow discharge since the bed roughness conditions in turn depend on flow stage, sediment transport rate and bed shear stress. In gravel-bed rivers, it has long been assumed that similar considerations are not relevant since bedload transport occurs infrequently and bedforms are in many cases poorly developed (despite early considerations on shear stress partitioning as, for example in the Meyer-Peter and Muller bedload equation). However, many studies during the last decade suggest that gravel bedforms at different spatial scales do have significant effects on mean flow resistance and boundary shear stress and that similar procedures should be considered (Parker and Peterson, 1980).

One basic problem which remains to be solved is the partition of bed shear stress into components pertaining to grain stress and form drag (Robert, 1990b). This would greatly enhance the estimation of mean flow velocity corresponding to a given discharge and also the prediction of bedload transport rates from that part of the shear stress related to the grain component (Carson, 1987). In addition to large-scale bedforms, recent investigations suggest that microtopographic bed features (such as cluster arrangements) also appear to influence flow resistance (Hassan and Reid, 1990; Robert, 1990a; 1991; Clifford *et al.*, 1992a; 1992b). These studies indicate that, as observed for any bedform type in sand-bed channels, the height and spatial concentration of obstacle clasts and associated microtopographic gravel bedforms determine the overall flow resistance and bed shear stress observed in gravel-bed rivers (Robert *et al.*, 1992). Since these small bedforms scale with bed material size, the use of a single large grain-size index in the flow resistance equation appears to be sufficient in many cases for a reasonably accurate prediction of mean flow velocity (Clifford *et al.*, 1992a). There is therefore a need for a comprehensive study of shear stress components in gravel-bed rivers at the reach scale. An ambiguity, for instance, remains as to what extent large-scale pools and riffles are significant roughness features since the empirical roughness length determined for riffle sections is the same as that determined over longer reaches characterized by many riffle-pool sequences (Hey, 1979; Bray, 1982; Robert, 1990a).

Further understanding of flow-resistance processes can possibly be best achieved from analyses conducted at a more local scale and from properties of vertical velocity profiles, especially in the near-bed region (e.g., Nowell and Church, 1979; Robert *et al.*, 1992a). The model for the flow field over a poorly sorted coarse gravel-bed elaborated by Wiberg and Smith (1987a; 1987b; 1991) exemplifies this approach. Although originally developed for steep streams with clasts comparable in size to stream depth, their approach remains valid for any poorly sorted gravel-bed river. This model illustrates the major effect of obstacles on the flow and the need for a partitioning of total shear stress into fluid and form drag components, the latter being associated with flow around large clasts. Their model shows that the spatially average flow field deviates considerably from a logarithmic velocity distribution.

Wiberg and Smith (1991) also suggest that the dominant sediment length scale to be used in vertical velocity profiles and mean flow resistance equations is C_{84}, where C is the small axis (the one that is generally vertical) and 84 represents the size for which 84% of particles are smaller. This distinction between the small axis (C_{84}) and the intermediate axis (D_{84}) is, however, generally overlooked by research workers since measurement of the intermediate axis is generally more convenient. Also, there appears to be a consensus on which sediment length scale should be used in both vertical velocity profiles and prediction of mean flow velocity. That is, the value of the roughness length, y_0, in

$$u/U_\star = 2.5 \ln (y/y_0) \tag{1}$$

(where u is the flow velocity at a given height above the bed, $U_\star$ is the shear velocity and y is the height above the bed surface) is best approximated by $0.1D_{84}$ (Whiting and Dietrich, 1990; 1992; Wiberg and Smith, 1991) while the value of k_s in

$$U/U_\star = 6.0 + 2.5 \ln (d/k_s) \tag{2}$$

is generally set equal to $3.5D_{84}$ (where U is the mean flow veocity at a cross-section and d is mean flow depth). This empirical constant results from numerous observations (Limerinos, 1970; Hey, 1979; Bray, 1980; 1982; Clifford *et al.*, 1992a; and many others). Although not strictly equivalent, those observations illustrate that the use of D_{84} integrates different bed roughness characteristics such as sorting and particle arrangements.

Interestingly, Wiberg and Smith (1991) also showed that even though vertical velocity profiles are not semi-logarithmic in streams with poorly-sorted gravel beds, estimation of mean flow velocity from equation (2) is still reasonably accurate, as long as the proper sediment length scale is used. However, the physical basis for choosing a particular sediment length scale is not clear. A recent study (Clifford *et al.*, 1992a) suggests that the dominant frequency of turbulent fluctuations in the near-bed region scales with grain size (D_{84}). This periodicity was attributed to vortex shedding from large particles (Levi, 1990) which is considered the dominant energy dissipation process over poorly-sorted gravel beds. This innovative approach, based on a modified Strouhal number, deserves further consideration.

III Flow turbulence

There has been a significant emphasis recently on the relations between flow turbulence phenomena, bed morphology and the transport of gravel in both marine and fluvial environments. These recent studies were based on either flow visualization techniques (e.g., Drake *et al.*, 1988) or instrumentation capable of measuring bedload (or suspended load) with a temporal resolution similar to that of flow measurements (e.g., Williams *et al.*, 1989a; 1989b; 1991). Similar considerations in sand-bed channels will be discussed separately (e.g., Lapointe, 1992; 1993).

1 Bursting motions

Most of the observations on coherent turbulent flow structures and sediment transport processes in both sand- and gravel-bed streams explicitly refer to phenomena observed in laboratory channels (Kline *et al.*, 1967; Grass, 1971; Rao *et al.*, 1971; Offen and Kline, 1974; Jackson, 1976). A quadrant analysis of turbulent fluctuations is often utilized, where both horizontal and vertical turbulent flow fluctuations are considered in relation to upward or downward turbulent motions of varied intensities (Figure 1). Bursting motions have been shown to originate in the near-wall region from alternating zones of low and high velocity streaks and result in sweeps – movement of fluid parcels towards the boundary – and ejections – movement of water away from the bed.

Similar 'burst-like' features, with concomitant fluctuations of u′ and v′ (Figure 1), have been observed in marine and tidal environments (e.g., Heathershaw, 1979). Recent studies (Drake *et al.*, 1988; Williams *et al.*, 1989a; 1989b) have also shown that the transport of coarse bed material is relatively insensitive to vertical velocity fluctuations and

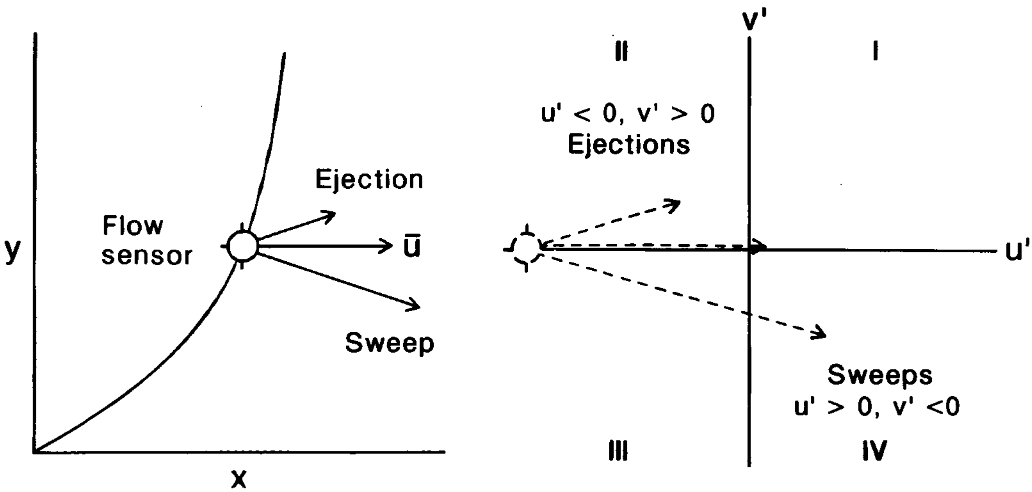

Figure 1 Definition diagram of turbulent flow fluctuations
Source: after Lapointe, 1992, Figure 1.

that most of the transport events occur during sweep and outward interactions periods (during which the horizontal flow component is greater than the mean). It remains, however, to investigate how the characteristics of the sweeps (e.g., magnitude, frequency) vary with the bed configuration (size, shape, and spatial density of roughness features), as well as variation of boundary shear stress during and between the sweep events.

Uncertainties also remain as to the exact nature of the links between the bursting process of the near-bed region and the large-scale flow structures associated with the boundary layer thickness (e.g., Grass, 1983). There remains a controversy surrounding the use of terms such as burst-like motions (Lapointe, 1992a) or quasi-bursts (Williams *et al.*, 1991) to differentiate between those phenomena which have been observed originating from the viscous sublayer (through flow visualization in laboratories), and similar features observed in large-scale geophysical turbulent flows where correspondence between vertical and streamwise velocity fluctuations (and associated movement of fluid parcels) is observed in the outer portion of the turbulent boundary layer. Clifford *et al.* (1991) argue that comparisons between bursting over smooth boundaries in laboratory flows and those phenomena observed over marine gravels may not be appropriate and that the true bursting process may not occur over hydraulically rough surfaces. There are however some indications (Williams *et al.*, 1991: 169) that low-speed streaks are present above rough surfaces and that such turbulent flow structures can be observed over coarse gravel beds and in large-scale geophysical flows. Evidence in this direction is also presented by Drake *et al.* (1988: 206–207), who showed that sweep-transport events result in the simultaneous entrainment of bed surface particles from areas typically 3 to 5 cm in diameter. These sweeps transport events were apparently randomly distributed, both spatially and temporally. These events have been shown to account for as much as 70% of total transport rate even though they occurred only 9% of the time. The instantaneous shear stress associated with sweeps was of the order of three times the critical shear stress for initial motion. Drake *et al.* (1988) also suggest that sweeps are associated with large-scale turbulent fluctuations.

An appropriate design remains to be established in order to obtain relevant and detailed information on the scales of turbulent flow structures in relation to the bed configuration (e.g., properties of velocity signatures and dominant frequencies in relation to height above bed and position along profile for a given reach) and how that relates to sediment transport rates locally occurring on the bed. A step in this direction is provided by the velocity correlation analysis of Robert *et al.* (1993) wherein it is shown that in depth-limited flows and over coarse-grained bed material, turbulent fluctuations appear to be dominated by periods of the order of 1–2 seconds, and there is a tendency for a decrease of the dominant frequency with an increasing height above the bed surface.

2 Sand bedforms

Similar questions have been addressed in sand-bed channels. In a detailed analysis of vertical mixing of momentum and suspended sediment at 1 m above a dune field in the Fraser River (British Columbia), Lapointe (1992) showed that intermittent and intense ejections (parcels of upward-moving fluid) of a few seconds duration dominate fluctuating suspended sediment concentration and turbulent momentum exchange. Active for 10% of the time, these burst-like motions apparently account for as much as 90% of the vertical sediment mixing.

There is again a debate as to what mechanism is responsible for these intermittent mixing events (Lapointe, 1992). Complex interactions between burst-like motions and eddies shed from dune separation zones may be associated with upwelling events observed over sand bedforms. Similarly, the links between surface boils (Kostaschuk *et al.*, 1991; Rood and Hickin, 1989) and turbulent eddy motions is far from being resolved. These boils have been related to 'kolks' (Kostaschuk *et al.*, 1991), turbulent bursting, or eddy shedding (Rood and Hickin, 1989). It has been shown clearly, however, that surface boils are associated with vertically-oriented rich zones of suspended sediment and only simultaneous visualization of near-bed flow phenomena, vertical mixing of momentum and suspended sediment, and surface activity would resolve the question. In large-scale geophysical flows, there appears to be no dominant period of recurrence of burst-like motions. The absence of a dominant time scale of the turbulent eddy motions responsible for the bulk of the transport of the bed material (both suspended and bedload, albeit from different burst-like motions) is reminiscent of a self-similar process for flow turbulence in alluvial channels.

Best (1992) has conducted investigations on the initiation of current ripples and its interaction with turbulent structures in the lower part of the boundary layer. Current ripples present a high degree of uniformity in terms of amplitude and spacing (Yalin, 1977; 1985; Robert and Richards, 1988). Best's visualization experiments show the formation of multiple hairpin vortices which in turn appear to generate 'multiple sweeps'. The latter then define patches of entrainment from which bed defects are created, flow separation is initiated, and a sequence of ripples is generated. Valuable laboratory research on sand bedform development and its links with features of turbulent boundary layers remains to be conducted on numerous questions (Leeder, 1983).

Finally, and using a totally different approach, the investigation of Kostaschuk *et al.* (1989) on bedload transport and large dune bedforms in a salt-wedge estuary (Fraser River, British Columbia) needs to be mentioned here. Very little work has been conducted on large dunes in natural fluvial environments (Kostaschuk and MacDonald, 1988), i.e., on the links between their morphology, the transport of bed material and turbulent flow structures (Kostaschuk *et al.*, 1991).

3 Channel junctions

Another key area of research, both in Canada and internationally, has been the relation between bed morphology, sediment transport and turbulent flow at channel confluences (e.g., Best, 1986; 1987; Roy *et al.*, 1988; Roy and Bergeron, 1990). It has been shown that the interactions between the scour zone generally present at confluences (Ashmore and Parker, 1983; Mosley, 1976; 1982; Best, 1986; 1987), flow separation zones, location of shear layers, and sediment transport pathways are complex and difficult to characterize.

Three significant research questions associated with channel junctions can perhaps be mentioned. The first deals with the origin and significance of helicoidal flow cells generally observed at confluences (Ashmore *et al.*, 1992). Two mechanisms have been suggested as dominant processes responsible for their formation: curvature of streamlines (and imbalance between centrifugal and pressure gradient forces; Ashmore *et al.*, 1992) and processes associated with unequal channel depths (shear layer distortion; Best and Roy, 1991; Biron *et al.*, 1993).

Associated with the debate on helical flow cells is that on the origin and maintenance of the scour zone observed at confluences in relation to the position of the mixing shear layer and secondary circulation. That is, the shear layer is closely associated with the zone of maximum flow depth and probably with bed scour, although this has not been quantified yet (Roy and De Serres, 1989). Moreover, the complex interactions between the upwelling of fluid from a deeper to a shallower channel, the distortion of the mixing layer and the presence of separated flow in the lee of the step in the shallow section of the bed may have several implications (see Best and Roy, 1991). Preliminary turbulence measurements in the shear layer show a 4–5 fold increase in turbulence intensity (in comparison with the freestream outside the shear layer; Biron *et al.*, 1993). The significance of these intense vertical and streamwise velocity fluctuations for sediment transport and bed evolution is currently under investigation.

Finally, the role played by a zone of flow separation and recirculation downstream of the junction corner has been investigated. Even though the existence of a separation zone has been clearly established in the laboratory (e.g., Best and Reid, 1984), its significance in natural conditions may be relatively minor perhaps due to the nonconcordance of the channels (Roy *et al.*, 1988; Biron *et al.*, 1993).

IV Entrainment and transport of coarse bed material

Following the elaboration of the equal mobility hypothesis of Parker and associates (Parker and Klingeman, 1982; Parker *et al.*, 1982a; 1982b), significant emphasis has been put on the characterization of critical shear stress at which particles start moving (or flow competence evaluations) and how the relation between critical shear stress and grain size departs from that expected for uniform beds (and standard Shields curve; see Richards, 1990). The empirical results reported by Andrews (1983) and Carling (1983) (among others) illustrate the range of critical dimensionless shear stresses that can be observed in coarse-grained channels. Three main reasons are generally invoked to explain the decrease in dimensionless shear stress with an increase in grain size: (i) relative protrusion or grain exposure effects; (ii) imbrication or clustering of particles; (iii) pivoting or friction angle effects in poorly sorted coarse-bed streams (e.g., Komar, 1987a; 1987b). Many empirical results are summarized in Richards (1990) and will not be repeated here. Only a schematic illustration of the empirical results is presented (Figure 2).

Despite different methods used to estimate initial motion of particles (see Wilcock, 1988), and limitations associated with estimates of critical bed shear stress from the largest particle(s) moved (Wilcock, 1992), a consensus from these empirical investigations is that selective transport does take place in coarse-grained alluvial channels and that the range of critical shear stress estimates is somewhat intermediate between that expected for uniform grains (the Shields curve), and the hypothesis originally proposed by Parker and others. Moreover, entrainment of large particles at comparatively small dimensionless shear stresses has been ascribed to a larger exposure to the flow and a smaller pivoting angle (and vice versa).

Church *et al.* (1991) analysed the question of equal mobility from a unique perspective. Using traps distributed along a bar in a cobble/gravel channel, they sampled a range of particle sizes (< 10 mm) over long periods (from several hours to several days). They showed that, at various times, the size distribution of the trapped material varies significantly and that equal mobility may represent a 'period-average' condition of the sediment transport (Church *et al.*, 1991: 2951).

An increasing emphasis on frequency distributions and statistical analysis of bedload transport is also apparent from recent studies on movement of individual clasts of coarse-

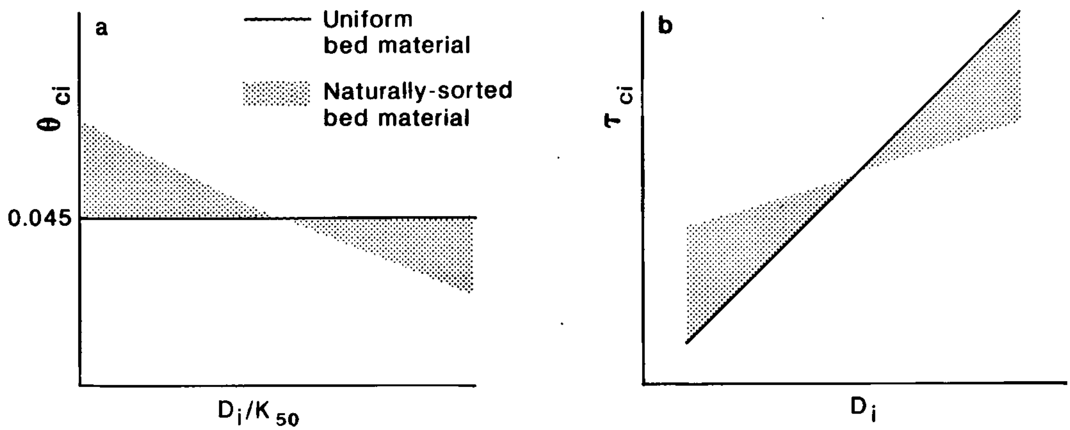

Figure 2 Summary schematic diagrams of empirical results on critical shear stress as a function of grain size in naturally-sorted coarse-grained channels (the dimensionless form of the relation being illustrated on the left-hand side of the diagram wherein θ_c is the critical Shields number). Each diagram illustrates the differences between critical shear stress for uniform bed material and the range of empirical results observed in naturally-sorted alluvial channels. The transition from above to below the expected shear stress for uniform grains occurs at a ratio of D_i to K_{50} of the order of 1.

bed material. These studies refer to the original theoretical work of Einstein (1937) and further similar flume and field investigations conducted a few decades ago (e.g., Hubbell and Sayre, 1964). Using tracer techniques, Schmidt and Ergenzinger (1992) showed a tendency for size-selective transport of coarse bedload in a high gradient stream (step-pool system). The scatter, however, is considerable, and is mainly due to different particle shapes and positions in the river bed. The step length and the duration of the rest periods both appear to be stochastic in nature and both distributions can be approximated by an exponential or a Gamma function. Very similar conclusions are reported by Hassan *et al.* (1991) and Hassan and Church (1992).

Using data from a range of fluvial environments, they also showed that the distance of movement for large particles declines rapidly with increasing size, that bars interrupt particle progress, and that a weak correlation exists between mean distance of movement and excess stream power (Hassan and Church, 1992; Hassan *et al.*, 1992). Although the movement of unconstrained clasts appears to be size preferred, additional analysis of constrained and buried particles indicates clearly that the effect of the bed surface structure is to reduce the differential movement (Church and Hassan, 1992). Burial depth and probability of re-exposure are significant factors to consider when analysing links between distance of movement, particle size, flow intensity, and rest periods (Hassan, 1990).

V Conclusion

In each of the aforementioned areas of research, Canadian geomorphologists have contributed significantly. The research questions discussed in this article are central to the understanding of fluvial processes in both sand- and gravel-bedded rivers.

A number of prominent research themes which appear to be particularly relevant for future work can be identified. The first is the use of fractal concepts in the study of fluvial processes. Although geomorphologists have taken more than a decade to react to the concept of fractals (Mandelbrot, 1982 and related papers), recent research on fractals and chaos in earth sciences indicate that this is likely to become a significant area of research in the near future (e.g., Middleton, 1990; 1991; Robert and Roy, 1990; 1992; Klinkenberg and Goodchild, 1992), as it is in other natural sciences. The use of fractals as a descriptive tool (e.g., Robert, 1991) but also as a way to analyse fluvial processes and flow turbulence phenomena is particularly promising.

The study of turbulent flow structures represents a second major research direction. Combined with visualization methods, the widespread use of electromagnetic current meters and simultaneous indications of sediment transport at a similar temporal scale (e.g., acoustic and turbidity sensors) will yield significant improvements of our understanding of the links between sediment transport processes and coherent motions in turbulent boundary layers. Flow visualization studies are perhaps best exemplified by the papers of Drake *et al.* (1988), Kostaschuk *et al.* (1991), Best and Roy (1991) and Best (1992), but work similar to that conducted in marine environments on bedload transport processes (e.g., Williams *et al.*, 1989a; 1989b) is lacking. Both fractal and turbulent flow analyses appear to be well integrated into the recent trend of small-scale (temporal and spatial) investigations emphasized in this article, together with a combination of probabilistic and mechanistic approaches.

Finally, this review clearly focused on bed microtopography and related flow turbulence and sediment transport processes. Larger scale aspects of fluvial forms and processes have not been explicitly discussed. Extensive work has been conducted in Canada on meandering and braided channel patterns (among other themes). Recently, the studies of Carson (1984), Carson and Lapointe (1983), Carson and Griffiths (1987), and Ashmore (1982; 1988; 1991a; 1991b), for instance, have greatly contributed to our understanding of river channel morphology and classification, sediment transport processes, bar formation, and bed evolution. Clearly, considerations such as turbulent flow structures, bed microtopography, local velocity distributions, friction angles and sediment step lengths (and rest periods) as emphasized in this review have some direct links with larger-scale study of fluvial forms and processes through construction of bar forms and creation of channel morphology. Both approaches are clearly complementary and further understanding of fluvial processes will be best achieved from both laboratory and field investigations, at a range of spatial and temporal scales.

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