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Magnitude and frequency controlling fluvial sedimentary systems: issues, contributions and challenges

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Abstract This paper reviews the theme entitled "Variability: magnitude and frequency: controlling sedimentary systems. Understanding the effects of temporal and spatial variation on our river systems is key to their management." The paper considers the magnitude–frequency concept in the light of the theoretical problems with defining "important" flows. These are related to conventional wisdom where work is defined as long-term sediment transport and/or "irreparable" modifications to the landscape, and where hydrological seasonality of rivers means that rivers adjust to multi-scale discharges. It is argued that the magnitude–frequency debate is a useful tool around which the issue of "important" flows can move forward. These concepts are related to the 10 papers presented in this theme which are used to provide the context for demonstrating that it is only by adopting a scale-sensitive approach may we adequately assess the effects of spatial and temporal variations on our river systems that are key to their management.

Key words spatial; temporal; magnitude; frequency; variability; context; fluvial; framework; management

INTRODUCTION

The session on "Variability: magnitude and frequency; controlling sedimentary systems" at the International Symposium on the Structure, Function and Management Implications of Fluvial Sedimentary Systems considers the influence of high-magnitude low-frequency events and enhanced variability on fluvial systems. In the light of this statement, the aim of this paper is to identify the salient points of the papers presented in this theme, and to outline new challenges for this area. This, however, requires context.

CONTEXT

Fundamentally, this theme reflects the fact that there are theoretical problems with defining "important" discharges in rivers, and that this problem remains largely unresolved. In part, this is because fluvial systems reflect the imprint of past flows at a number of temporal scales, and that the relationship between process, form and flow is poorly understood. The complexity of this topic revolves around four major issues. First, the issue of the magnitude, frequency and variability of flow and sediment discharge controlling fluvial sedimentary systems is a spatial and temporal one that involves earth history, hydraulic understanding and vegetation–sediment–geomorphology interactions. Hence, form and process are difficult to distinguish and cause and effect is a function of time and scale. Second, variables in natural systems are difficult to quantify, so it is often necessary to rely on proxies rather than real quantities. Third, the issues are scale-dependent and require the identification of appropriate descriptors and drivers across a range of spatial and temporal scales. Fourth, the initial conditions necessary for an adequate understanding of fluvial system functioning are seldom known, so that the antecedent/inheritance factors and feedback are poorly accounted for. As a result, it is nigh impossible to reduce the fluvial system to simple-physics, except at very limited scales and domains. Consequently, researchers have attempted to "simplify" this issue by considering the magnitude, frequency and variability of sediment and discharge controlling fluvial sedimentary systems for a specified temporal dimension. This is not, however, without its complications, as will be discussed in the following section.

MAGNITUDE–FREQUENCY DEBATE

The magnitude–frequency debate has its origins in the late 1800s when British hydraulic engineers working in India attempted to develop stable irrigation canals. They noted that canals could adjust their boundaries until a stable configuration was attained and that the geometry of the canal was related to its discharge of sediment and water (Kennedy, 1895). This led to the development of regime equations, which were later applied to "natural channels" (Ackers, 1972). The rationale behind this was that, in principle, the morphology and dynamics of rivers should be explicable in terms of the laws of physics. The application of this suggested that for alluvial systems, channel form (and/or morphological features) could be related to a specific magnitude (discharge) and frequency (return period or duration) of flow. Early researchers sought a physical expression of this flow and the "bankfull" condition emerged as the dominant flow that shapes river channels—the stage at which flow onto the flood plain occurred.

Conventional wisdom has it that in temperate-humid environments where "work" is defined as sediment transport, moderate-magnitude, high-frequency events are considered the "effective" events in that they transport the "most" sediment over a long period of time (Wolman & Miller, 1960; Leopold, 1994). Although the largest flows have the greatest stream power and can do "work" at the greatest rate, they occur only rarely. Low flows on the other hand, have such low stream powers that they are incapable of altering channel boundaries, regardless of how often they occur. Moderate-magnitude, high-frequency events are often equated with the bankfull event. At this discharge, equilibrium is most closely approached and the tendency to change is least. A necessary pre-condition for this type of approach is that negative feedback and short relaxation times are required so that "system memory" is short, and consequently the preferred channel morphology is largely invariant.

However, in arid, semiarid and tropical-humid regions where "work" is defined as "irreparable" modifications to the landscape, or in non-alluvial systems that are out of equilibrium or unable to adjust their form freely, high-magnitude, low-frequency events are considered "effective", simply because they are the only events capable of mobilizing the entire bed, altering channel morphology and affecting channel change (Kochel, 1988). Furthermore, the enhanced spatial and temporal variability of dryland rivers means that form and process are not always closely linked, while the propensity for major flood-induced channel change coupled with long recovery times and transient and unstable behaviour mean that non-equilibrium is generally the norm (Tooth, 2000). Hence, the emphasis on the temporal dimensions and variability in arid, semiarid and dryland systems.

Nested between these apparent "opposite" ends of the spectrum are those fluvial systems found in the seasonal tropics. These systems are characterized by highly variable hydrological regimes, which together with the physical template, generally result in nested channel architecture, often with an active channel inset into a wider macro-channel. The hydrological seasonality of these environments means that the equilibrium of river form requires adjustments to multi-scale discharges. Examples of these systems are found in India (cf. Gupta, 1995), central Australia (cf. Pickup, 1991), and South Africa (cf. van Niekerk *et al.*, 1995).

While it is clear that there is no singular relationship between event magnitude, frequency, duration and sediment flux or fluvial system change, the magnitude–frequency concept provides a useful tool around which the question of what flows are "important" for fluvial system functioning can move forward. This is not a trivial point, for our understanding of the structure and functioning of fluvial systems is the key to the way in which they are managed. Hence, we need to define our paradigm of understanding; the magnitude–frequency/variability concept helps us to do this. However, this needs to be defined for a specified temporal context.

TEMPORAL CONTEXT

The importance of the temporal context in fluvial system understanding was first made explicit by Schumm & Lichty (1965). They demonstrated that the variables that determine channel form and process can be viewed as either dependent or independent depending on the temporal scale within which they are considered. This highlights the importance of acknowledging that tectonic, climatic and environmental changes have left their imprint on modern fluvial systems, and that while there is a need to understand and manage fluvial systems in modern times, this always needs to be performed within a historical context. The following section will attempt to review the presentations of this theme in the light of the preceding discussion.

PAPERS IN THIS SESSION

Ten papers are presented in this theme (the full title of each may be found in the reference list at the end of this paper). These will be discussed in turn. **Erskine & Peacock** consider Late Holocene flood plain development following the 1949 1:1000 year flood at Payne's Crossing, Wollombi Brook, southeastern Australia. The peak discharge was estimated at 4400 $m^3 s^{-1}$, ~22 times greater than the mean annual flood. The flood deposited up to 500 mm of slackwater deposits (SWDs) on a low flood plain. Analysis of additional SWDs on the high flood plain indicated that at least three late Holocene floods with peak discharges ~32 greater than the mean annual flood had occurred. They point out that comparable events have been recorded in similar-sized drainage basins in New South Wales (NSW), and could be expected under the present-climatic regime.

Erskine & Peacock concluded that three sets of large floods were important for flood plain formation and destruction. First, large floods with peaks ~2 to 9 times greater than the mean annual flood which form a series of in-channel benches. Second, floods with peak discharges ~10 times greater than the mean annual flood which destroy in-channel benches and deposit SWDs on the flood plains, and third, cataclysmic floods ~40 to 50 times greater than the mean annual flood that extensively erode flood plains. **Erskine & Peacock** demonstrate that the fluvial architecture is a response to the entire range of antecedent flows, particularly large floods. Palaeoflood hydrology (PFH) methods are extremely useful for improving our understanding of the influence of high-magnitude, low-frequency events on fluvial sedimentary systems.

Golosov reports on the spatial and temporal variations in sediment "delivery ratios" (DR) for a number of small disturbed low land basins on the southern Russian Plain. Although **Golosov** does not describe the methods adequately, he reports on highly variable DR coefficients for drainage basins with areas of <100 km^2. Two groups of drainage basins were identified:

- "Transit-type" drainage basins with high DR coefficients which serve as pathways for the delivery of sediment to lower-order valleys that are typically found in the marginal areas bordering mountains, and
- "Trap-type" drainage basins, which detain and store sediment entering from cultivated slopes and are widespread in the central part of the Russian Plain.

Detailed analysis of the data demonstrated that first-order valleys pass through a number of stages. Many valleys were filled with sediment shortly (10 to 20 years) after intense cultivation ("trap-type" stage). They then passed through the "transit-type" stage, where the sediment was delivered to lower-order valleys. The duration of the "trap-type" stage for the second-order valleys varied between 50 and 300 years, depending on local conditions. **Golosov** points out that it is common to have the upper and lower reaches of the same valleys functioning at different stages. At present, most of the second to fourth-order valleys are "trap-type" valleys; this has resulted in a regressive trend in sediment discharges for rivers draining the central part of the southern half of the Russian Plain. While **Golosov** makes little mention of the impact of extreme events or enhanced variability on DR coefficients, the paper makes a useful contribution through distinguishing zones of sediment flux and sediment entrapment, thereby providing rare information on long-term sediment movement.

Aalto *et al.* have presented an impressive piece of work on the fluvial transport of sediment across a pristine tropical flood plain drainage basin in the northern Bolivian Andes. Particular attention was paid to channel–flood plain interactions and episodic flood plain deposition along the Beni River. The research adopted a decadal-scale approach that highlighted the significance of spatial and temporal scales for fluvial system understanding. Utilizing an impressive array of methods, **Aalto *et al.*** developed a sediment flux model that estimated net foreland accumulation of ~100 × 10^6 t year^{-1} on the flood plain, an outcome confirmed by over 30 years of measured records—an impressive achievement considering the complexity of the task. Flood plain accumulation (decadal) was shown to occur as temporally isolated episodic pulses in relation to the cold phase of ENSO (La Niña).

Channel migration was shown to result in the erosion of ~220 × 10^6 t year^{-1} of cutbank sediment. ~212 × 10^6 t year^{-1} of this sediment was deposited back onto point bars (this exchange is larger than the total annual sediment discharge at Rurrenabaque gauged at ~200 × 10^6 t year^{-1}), resulting in a net transfer of ~8 × 10^6 t year^{-1} of sediment from the flood plain to the channel. Thus, while the annual transfer of sediment from the cutbanks to the point bars is enormous, the net change in storage due to channel migration is minimal.

McKee *et al*. provide results from a magnitude–frequency analysis of suspended sediment loads for the subtropical Richmond River drainage basin in northern NSW, Australia. The approach is a classic magnitude–frequency one in the Wolman & Miller tradition. Analysis of cumulative suspended loads *vs* cumulative time indicated that 50% and 90% of the suspended sediment load was transported by 0.47% and 2.3% of the flow respectively (1985–1999). They related this to the drought of 1991–1999 in which the suspended sediment loads were ~7 times lower than the wetter period of 1986–1990.

A limitation of the study was that bed load was not considered. From a management and/or process point of view, bed load is probably more significant than suspended load, despite the fact that in this instance it only accounts for 7% of the total load.

McKee *et al*. calculate the most effective discharge as having a return period of ~1 year on the annual maximum curve, or, on average occurring for ~5 days a year. It must be questioned whether the concept of effective discharge is an appropriate one, for while it represents the flow class that transports the most sediment over the 14-year period, it only accounts for 3.4% of the total suspended load. Perhaps it would be better to use a cumulative curve so that the entire distribution of the load (time series or flow duration curve) is considered. This is, to some extent, acknowledged by the authors who recognize multiple effective discharges associated with alternating climatic regimes such as prolonged floods or droughts (FDRs/DDRs). **McKee *et al.*** conclude that two sets of effective discharge are important, smaller flows that do the work, and larger flows that determine the channel capacity and are important for channel maintenance and channel changes. Similar results have been demonstrated for South African rivers (Dollar, 2000).

One point that is useful to emphasize here is the frequently quoted contrast between the highly episodic nature of Southern Hemisphere systems and the "steadier" nature of northern temperate systems. There is a slight sense of "bandwagon" in the oft-stated suggestion that Southern Hemisphere rivers differ from their much-studied northern equivalents. However, this is more a case of local conditions needing to be taken into account rather than attempting the blind application of principles (*sic*) established in the Northern Hemisphere to unexplored (Southern) Hemisphere systems.

Bourke reports on suspended sediment concentrations (SSC) and the geomorphic effects of sub-bankfull flows for the Todd River in central Australia. Data for 1995 are related to previously unpublished SSC data for the region. The patterns presented are not uncommon to many studies related to SSCs, i.e. SSCs are poorly correlated to discharge (peak concentrations may precede, coincide or lag behind peak discharge), peak concentrations reflect bed load entrainment at individual hydrograph peaks following low stage troughs in multi-peaked flows, peak SSC's can be higher for low-magnitude events, but that total loads are greater for the high-magnitude events, and that concentrations are related to supply, source, and sediment/vegetation/hydraulic interactions.

While **Bourke** recognizes the importance of sub-bankfull flows as agents of minor channel change, and points out that some flood plain processes dominate during lower magnitude events (the formation and accretion of flood plain insets for example), these explanations do not adequately explain the processes involved and therefore remain unconvincing. The significance of the results are, however, that **Bourke** highlights the importance of the entire flow regime, and that antecedent flows provide the context for the moderate and larger flow events—a limitation of the effective discharge concept. Similarly, **Bourke's** paper sheds light on the overemphasis placed on large infrequent events (particularly in arid and semiarid areas) to the exclusion of all other events.

Rushmer *et al.* report on two recent Icelandic jokulhlaups. The Sólheimajökull jokulhlaup (July 1999) was characterized by an even rise to peak discharge (4500 $m^3 s^{-1}$) in less than an hour, with an average rate of increase of 75 $m^3 s^{-1}$ per minute. The hydrograph displayed a broadly asymmetrical shape with a gradual 8-h falling limb. In contrast, the Skeiðarárjökull jokulhlaup (November 1996) produced a hydrograph shape that was broadly symmetrical, but had a 20-h exponential rise to peak. Both the rising and falling limb discharge changed at a rate of 25 $m^3 s^{-1}$ per minute. While utilizing discharge as a descriptor was useful, it may have been more appropriate to express this in hydraulic terms—changes in unit stream power or shear stress for example. The contrasting hydrograph shapes affected different sedimentological effects for the two events. The Sólheimajökull jokulhlaup had a significant erosional and depositional effect; the short duration of the rising stage inhibited the development of well-structured bed forms. The high sediment flux and prolonged flow conditions which were maintained during the rising and falling limb of the hydrograph allowed sufficient time for well organized sedimentary successions to be deposited.

Symader & Roth report on changes in the chemical characteristics of riverbed samples from 1993 following large floods in the Kartelbornsbach near Trier, in Germany. Variations in the concentrations of major ions and heavy metals were explained by the varying contributions from different sources, and by in-channel contributions such as the growth of periphylon and bioprecipitation. They were able to show that the effects of high floods in diluting concentrations depended on the input of fresh sediment from the drainage basin.

Dragovich & Morris present information on sediment and organic matter transfer following bushfires in the Blue Mountains, NSW, Australia using 10 runoff plots. Data were collected over a 6-month period following fires of high, moderate and low intensity. As expected, the data demonstrated that sediment and organic matter transfer was substantially higher on the intensely and moderately burnt areas than on the unburnt (low fire intensity) areas. The most interesting aspect of this paper was the fact that there was much between-plot variability in sediment and organic transfer for similar burn intensities. Disappointingly, this aspect of the data was least explored. An aspect of the paper, which was limiting was the lack of a rigorous definition of the difference between low, moderate and high intensity burns. The definitions presented are unsatisfactory (e.g. high intensity burns leave no canopy leaves or pre-fire ground intact etc.). A similar critique could be levelled at the terms "sediment transfer" and "sediment transport". It would have been instructive to quantify these terms, or to provide more rigorous definitions, or both.

At a finer scale of temporal resolution, **Moliere *et al.*** report on the methods used to estimate the baseline hydrological characteristics of the Ngarradj drainage basin in the Northern Territory of Australia from 1998 to 2001. The data are of a sufficient resolution to demonstrate that peak rainfall and runoff occur late in the afternoon and early in the morning. This has implications for the design of an effective sediment-monitoring programme, amongst other things. It would have been useful for the authors to place the results into a longer-term context, in relation to ENSO or FDR/DDR regimes for example.

The papers presented consider the importance of the magnitude, frequency, duration and variability of the factors controlling fluvial sedimentary at a variety of scales from thousands of years (**Erskine & Peacock**), to hundreds of years (**Golosov**), to decades (**Aalto *et al.***; **McKee *et al.***), to years (**Bourke**; **Rushmer *et al***; **Symader & Roth**), to months (**Dragovitch & Morris)** and even to days and hours (**Moliere *et al***.). Although not explicitly stated, the authors defined the descriptors and drivers appropriate to the spatial and temporal context of their respective studies. The question is how do we integrate our understanding of fluvial system functioning (in terms of the magnitude, frequency and variability of sediment and discharge regimes) across various spatial and temporal scales, and by so doing, satisfy the need for fundamental fluvial science, while still fulfilling the management agenda? The following section presents some suggestions in this regard.

INTEGRATING FRAMEWORK AND CONCLUSIONS

At present, conventional paradigms are inadequate for describing, explaining, predicting and managing river systems. This is, in part, a consequence of the dominant research paradigm (reductionist falsification approach) which has limited explanatory or predictive power as system processes are seldom due to single causal events except when considered at very small scales and within limited domains.

These limitations have manifested themselves in the failure of conventional methodological paradigms to provide an adequate conceptual framework for understanding and managing fluvial systems. For example, the conventional approach to riverine science and management practice in South Africa has been one that has adopted a short-term (10^1 years) understanding based on equilibrium-type thinking. Managers have attempted to manipulate processes based on the view that systems should remain in equilibrium, rather than acknowledging that river systems are dynamic, and that at any one point, a section of the river is on some trajectory of change which is a function of antecedent patterns and processes.

Identifying the appropriate spatial and temporal scale, as well as the historical context is therefore critical. There is an urgent need, therefore, to develop a conceptual framework that considers rivers as ecosystems, and that recognizes the interconnections between the physical, biological and chemical components of riverine ecosystems; the different scales of operation of each; linkages between upstream–downstream and the river channel–flood plain and, that different parts of the river system may operate over different spatial and temporal scales. This demands a scale-sensitive hierarchical framework that recognizes complex response to system drivers, so that pattern and form can be matched to process at appropriate spatial and temporal scales.

Dollar *et al*. (2002) have developed a framework that attempts to match the description of the problem, and the river section, to the matching river processes so that the appropriate causal explanations can be identified at the appropriate spatial and temporal scales, and therefore appropriate management action taken. This will satisfy the need for appropriate science (description, explanation, prediction) and allow for prediction, in that the pattern response to process can be appropriately identified, and that the impact of pattern on process can be accounted for. Explanation and prediction are pre-eminent, so that river science and management can solve real world problems and breakdown the barriers between the different scientific disciplines, so that pattern and form can be matched to causal processes, and appropriate variables and descriptors can be identified at a range of spatial and temporal scales. It is argued, that it is only by adopting a scale-sensitive approach that we may adequately assess the effects of spatial and temporal variations on our river systems that is key to their management.

REFERENCES

Aalto, R., Dunne, T., Nittrouer, C. A., Maurice-Bourgoin, L. & Montgomery, D. R. (2002) Fluvial transport of sediment across a pristine tropical foreland basin: channel–flood plain interaction and episodic flood plain deposition. In: *The Structure, Function and Management Implications of Fluvial Sedimentary Systems* (ed. by F. J. Dyer, M. C. Thoms & J. M. Olley) (Proc. Alice Springs Symp., September 2002). IAHS Publ. no. 276 (this volume).

Ackers, P. (1972) River regime: research and application. *J. Instn Wat. Engrs* **26**, 257–281.

Bourke, M. C. (2002) Suspended sediment concentrations and the geomorphic effect of sub-bankfull flow in a central Australian stream. In: *The Structure, Function and Management Implications of Fluvial Sedimentary Systems* (ed. by F. J. Dyer, M. C. Thoms & J. M. Olley) (Proc. Alice Springs Symp., September 2002). IAHS Publ. no. 276 (this volume).

Dollar, E. S. J. (2000) The determination of geomorphologically effective flows for selected eastern sea-board rivers in South Africa. PhD Thesis, Rhodes University, Grahamstown, South Africa.

Dollar, E. S. J., Rogers, K. H., James, C. S., Thoms, M. & Rountree, M. R. (2002) A scaled hierarchical framework for understanding pattern and process in river systems. In preparation.

Dragovich, D. & Morris, R. (2002) Sediment and organic matter transfer following bushfires in the Blue Mountains, Australia. In: *The Structure, Function and Management Implications of Fluvial Sedimentary Systems* (ed. by F. J. Dyer, M. C. Thoms & J. M. Olley) (Proc. Alice Springs Symp., September 2002). IAHS Publ. no. 276 (this volume).

Erskine, W. D. & Peacock, C. T. (2002) Late Holocene flood plain development following a cataclysmic flood. In: *The Structure, Function and Management Implications of Fluvial Sedimentary Systems* (ed. by F. J. Dyer, M. C. Thoms & J. M. Olley) (Proc. Alice Springs Symp., September 2002). IAHS Publ. no. 276 (this volume).

Golosov, V. (2002) Temporal–spatial variations in the sediment delivery ratio of small drainage basins: the Russian Plain example. In: *The Structure, Function and Management Implications of Fluvial Sedimentary Systems* (ed. by F. J. Dyer, M. C. Thoms & J. M. Olley) (Proc. Alice Springs Symp., September 2002). IAHS Publ. no. 276 (this volume).

Gupta, A. (1995) Magnitude, frequency and special factors affecting channel form and process in the seasonal tropics. In: *Natural and Anthropogenic Influences in Fluvial Geomorphology* (ed. by J. E. Costa, A. J. Miller, K. W. Potter & P. R. Wilcock), 45–56. American Geophysical Union, Washington DC.

Kennedy, R. C. (1895) Prevention of silting in irrigation canals. *Instn Civ. Engrs Proc.* **119**, 281–290.

Kochel, R. C. (1988) Geomorphic impact of large floods: review and new perspectives on magnitude and frequency. In: *Flood Geomorphology* (ed. by V. R. Baker, R. C. Kochel & P. C. Patton), 169–187. John Wiley, New York.

Leopold, L. B. (1994) *A View of a River*. Harvard University Press, Cambridge.

McKee, L. J., Hossain, S. & Eyre, B. D. (2002) Magnitude–frequency analysis of suspended sediment loads in the subtropical Richmond River basin, northern New South Wales, Australia. In: *The Structure, Function and Management Implications of Fluvial Sedimentary Systems* (ed. by F. J. Dyer, M. C. Thoms & J. M. Olley) (Proc. Alice Springs Symp., September 2002). IAHS Publ. no. 276 (this volume).

Moliere, D. R., Boggs, G. S., Evans, K. G. & Saynor, M. J. (2002) Hydrological response of Ngarradj—a seasonal stream in the wet–dry tropics, Northern Territory, Australia. In: *The Structure, Function and Management Implications of Fluvial Sedimentary Systems* (ed. by F. J. Dyer, M. C. Thoms & J. M. Olley) (Proc. Alice Springs Symp., September 2002). IAHS Publ. no. 276 (this volume).

Pickup, G. (1991) Event frequency and landscape stability on the floodplains of arid Central Australia. *Quatern. Sci. Rev.* **10**, 463–473.

Rushmer, E. L., Russell, A. J., Tweed, F. S., Knudsen, Ó. & Marren, P. M. (2002) The role of hydrograph shape in controlling glacier outburst flood (jökulhlaup) sedimentation. In: *The Structure, Function and Management Implications of Fluvial Sedimentary Systems* (ed. by F. J. Dyer, M. C. Thoms & J. M. Olley) (Proc. Alice Springs Symp., September 2002). IAHS Publ. no. 276 (this volume).

Schumm, S. A. & Lichty, R. W. (1965) Time, space and causality in geomorphology. *Am. J. Sci.*. **263**, 110–119.

Symader, W. & Roth, M. (2002) Changes in chemical characteristics of river bed samples caused by exceptional high floods in the Kartelbornsbach basin near Trier. In: *The Structure, Function and Management Implications of Fluvial Sedimentary Systems* (ed. by F. J. Dyer, M. C. Thoms & J. M. Olley) (Proc. Alice Springs Symp., September 2002). IAHS Publ. no. 276 (this volume).

Tooth, S. (2000) Process, form and change in dryland rivers: a review of recent research. *Earth Sci. Rev.* **51**, 67–107.

van Niekerk, A. W., Heritage, G. L. & Moon, B. P. (1995) River classification for management: the geomorphology of the Sabie River in the Eastern Transvaal. *S. Afr. Geogr. J.* **77**(2), 68–76.

Wolman, M. G. & Miller, J. P. (1960) Magnitude and frequency of forces in geomorphic processes. *J. Geol.* **68**(1), 54–74.