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Predicting channel patterns

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Abstract

The proposed distinction between meandering and braided river channel patterns, on the basis of bankfull specific stream power and bed material size, is analysed and rejected. Only by using regime-based estimates of channel widths (rather than actual widths) has discrimination been achieved, and it is argued that this procedure is unacceptable.

An alternative is to explore the patterning processes underlying the marked pattern scatter on bankfull stream power/bed material size plots. Of the five sets of patterning processes, large-scale bedform development and stability is seen as especially important for meandering and braiding. For *gravel-bed rivers*, bedforms developed at around or above bankfull stage appear important for pattern generation, with braiding relating to higher excess shear stress and Froude number. There seems to be an upper threshold to both meandering and braiding which is achieved at extreme discharges and steep gradients, as on steep alluvial fans, rather than for the rivers with available flow data here considered. For *sand-bed rivers* with greater excess shear stress, the equivalent upper plane bed threshold may occur below bankfull, with bed material mobility and bedform modification occurring over a wider range of sub-bankfull discharges. Sand-bed channel margin outlines appear to be less perturbed by bedform effects than gravel bed planforms, and they may have naturally straight or sinuous planforms. Bedform relief may nevertheless lead to some being designated as braided when viewed at low flows.

It is concluded that the use of a single-stage stream power measure and bed material size alone is unlikely to achieve meandering/braiding discrimination. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Channel pattern; Stream power; Meandering; Braiding; Bedforms; Grain size

1. Introduction

A major focus of recent research on channel patterns has been concerned with distinguishing a threshold between meandering and braided rivers, in terms of readily available data. These normally involve channel slope, a bankfull or some other representative discharge measure, and an index of bed

material size. The first two may be combined as a measure of specific stream power (ω), defined as:

$$\omega = \frac{\gamma g Q s}{w} = \gamma g D v s \quad (1)$$

where w is river width, γ is water density, g is the acceleration due to gravity, D is average depth ($\approx$ hydraulic radius), v is water velocity, s is channel slope and Q is a representative measure of discharge, usually bankfull discharge (Q_{bf}). An analysis by van den Berg (1995) presented a two-axis plot of “potential stream power” and median bed material size which appears to discriminate well between

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braided and meandering streams (Fig. 1b). His relationship has been widely cited; as Thorne (1997) has written, “a discriminate function of this type may well represent the logical endpoint of a line of investigation into the meander/braiding threshold begun by Lane and by Leopold and Wolman nearly 40 years ago”. The whole area of study has been usefully and comprehensively reviewed by Ferguson (1987).

However, we do have strong reservations about both van den Berg’s analysis and this approach in general. *Raw* specific stream power/grain size relationships using the van den Berg data are presented in Fig. 1a. To these he reasonably applies an adjustment factor converting the channel slope of sinuous rivers to valley slope. He then rejects the use of *observed* widths of both braided and meandering streams and derives them ‘independently’ of pattern

Fig. 1. Braided and meandering rivers in relation to bankfull specific stream power using the methods and data of van den Berg (1995); (a) for actual specific stream power, and (b) for “potential” specific stream power. There are fewer data points in (a) since channel width values, required for specific stream power calculation, are not available for all the original data sources.

using two separate regime equations (one for sand-bed and the other for gravel-bed rivers) of the form:

$$w = aQ_{bf}^b \quad (2)$$

It is by using these width estimates in plots of *potential* specific stream power that discrimination between the fields occupied by meandering and

braided channel patterns is achieved (Fig. 1b). It has not always been appreciated that adjusted ‘potential’ power is required to achieve this discrimination (see, for example, Knighton (1998), pp. 210–211).

The effect of applying the two regime-based width estimates on meandering and braided rivers, rather than using actual widths, is illustrated in Fig. 2. The

Fig. 2. The adjustments effect produced in van den Berg's potential stream power method by applying his two regime-based estimating equations to sand and gravel bed rivers; (a) for meandering rivers, and (b) for braided channels. Triangles and solid circles represent the adjusted stream power using regime-based widths, and are compared to stream powers using actual widths (horizontal bars).

meandering data set is slightly modified (Fig. 2a), improving the correlation between stream power and grain size for this pattern type. But the effect on braided channels is to raise many specific stream powers considerably (Fig. 2b), and it is this above all which leads to the apparent discriminatory value of ‘potential’ (using adjusted widths) rather than the actual specific stream power (compare Fig. 1a and b).

Why should this be so? Van den Berg takes the constant a of Eq. (2) to be 3, citing Ferguson (1981). Ferguson’s analysis used data for British rivers, including those of Nixon (1959), Charlton et al. (1978), and others. But these data for (largely) gravel-bed rivers are for non-braided channels, in other words pattern-biased. If such relations are used for gravel-bed channels in general, they are likely to underestimate braided-channel bed widths, thus effectively enhancing their apparent specific stream power by decreasing the denominator in Eq. (1). Hydraulic geometry relationships for gravel-bed rivers usually exclude or give special consideration to braiding (e.g. Parker, 1979; Chang, 1980; Hey and Thorne, 1986). Flume studies of braided channels by Ashmore (1991) give a higher constant and lower exponent than is assumed by van den Berg (1995):

$$w = 12.76Q^{0.45} \quad (3)$$

Field data for braided stream hydraulic geometry have also been presented by Mosley (1983), again with higher constants and lower exponents than those used by van den Berg.

Width is of course only one of several hydraulic variables which may mutually adjust, and relationships with discharge are not likely to work well with complex channel patterns (see Ferguson and Ashworth, 1991). We therefore do not agree that this procedure for ‘potential’ specific stream power is a valid one: it achieves its pattern-discriminating results only by applying an unjustifiable regime-based width estimating relation, especially through a stream power adjustment to braided patterns, for which the regime relations used are inappropriate.

We also have a second objection. Quite understandably, many researchers’ objectives have been underlain, consciously or otherwise, by a desire to achieve a relatively simple discrimination for practi-

cal purposes so that engineers, palaeohydrologists and others may anticipate potential pattern transformation on a simple and comprehensive basis across the whole range of grain sizes using readily available data. However laudable the objective, we believe the approach does not involve hydraulic considerations in an appropriate manner, and it disguises rather than exposes the patterning processes which underpin the channel pattern continuum.

2. Patterning processes

There are five basic groups of channel patterning processes in alluvial channels:

1. Channelised flow leading to ‘streamlining’ and sinuosity development phenomena—as in meander development in single channels or on braided reaches, and the evolving, often multi-curved and faceted outlines of river islands.
2. Bedform development, which can initiate both meandering and braiding, or modify channel pattern especially where large-scale bedforms become stalled and stable relative to bank recession.
3. Channel junction and bifurcation effects.
4. Bank breaching, as in chute cutoffs, crevasses and avulsions.
5. Dissection phenomena, in which prior (generally high-flow) forms are subsequently dismembered or possibly infilled and obscured by activities which include headcut recession and local development of drainage networks within alluvial deposits.

These processes may occur in combination to be more or less important in any specific river environment. Thus, the initiation of braiding may involve an interrelationship between channels and large-scale bedforms, with braided patterns then being ‘maintained’ and modified by streamlining, junction/bifurcation effects, breaching and dissection. A distinction may be made for meandering rivers in which bends are ‘forced’ by bar development or ‘free’ with bends developing sinuous patterns by bank erosion

accompanied by point sedimentation which essentially follows channel sinuosity evolution (Ikeda, 1989).

Channels, and their dimensions, may reasonably be related to ‘formative’ bankfull discharges, though with some provisos. For example, bank strength may be independently significant including cohesive effects by non-bed sediments and vegetation (Hey and Thorne, 1986; Millar, 2000). The recurrence interval of bankfull discharges may vary (Williams, 1978), and extreme events may also require consideration since they can produce large channels that may revert to smaller ones over a period of years (for review and discussion, see Lewin 1989).

Large-scale *bedforms* are particularly important determinants of channel pattern: they may develop with excess shear stress above the threshold for sediment transport, but below the dune-plane bed transition. The situation is also complicated by the possible existence of upper regime bedforms and of large-scale rhomboidal bedform swarms in natural rivers which do not appear to distort the overall river bank outline (Collinson, 1970; Crowley, 1983). Ein-

stein and Shen (1964) noted the existence of lattice-like patterns and diagonal ‘bars’ developed at high Froude numbers (not necessarily the same as gravel-bed diagonal bars which develop at lower Froude numbers). Others are less inclined to recognise distinctive upper-stage dune regimes (Ashley, 1990).

In Shields dimensionless shear stress (θ) terms for coarser sediment, transport is achieved at values of around $\theta \approx 0.06$, whilst according to Carling (1999) the dune-plane bed transition is at $\theta \approx 0.25$. Parker (1976) and a number of other researchers have suggested that within the sediment transport and upper plane bed limits, dunes develop at higher Froude (Fr) numbers. Limits under field conditions are of course complicated by the existence of sediment size mixtures, armouring and bedforms, as field research has made clear (see Church, 1978; Komar, 1996). Though the applied force is usually expressed in terms of shear stress, it is possible to use stream power, in the manner of Bagnold (1980).

It has to be appreciated, however, that a given stream power can be achieved by different combinations of hydraulic variables. Fig. 3 plots a 100 W

Fig. 3. The specific stream power surface for $\omega = 100 \text{ W m}^{-2}$, in relation to slope, velocity and depth, showing also lines of equal Froude number.

m^{-2} specific stream power surface within the value limits for width, depth and velocity in the dataset used here. Also plotted are Froude number contours. In practice, real streams can only occupy certain locations on such constant stream power surfaces given the actual combinations of depth and gradient available in terrestrial environments and the flow resistance constraints on velocity as incorporated into the well-known Darcy–Weisbach or Manning resistance equations. But the point to note is that a single stream power value may reflect a variety of hydraulic conditions. Similarly, bankfull flows covering a range of incident stream powers (in our dataset $1 < \omega < 1000$) include a considerable range of mean Froude numbers, depths and velocities at bankfull as is shown in Fig. 4.

Finally, concerning bedforms, it should be stressed that there is a good body of laboratory data for small-scale bedforms in sandy sediment. This has most usefully been brought together by Southard and Boguchwal (1990), who show, incidentally, that plane beds develop well below a Froude number of 0.84, with bedform domain boundaries not exactly paralleling Froude number values. The laboratory data in general are derived from steep-gradient, shallow depth flumes, corrected for temperature effects on viscosity. Using these data for deeper-water gentler-gradient flows requires caution, and there are few

data on larger-scale field bedforms. For field bedforms in coarser materials this is equally the case, and it is much more difficult to obtain hydraulic parameters (though see Dinehart, 1989, 1992). Carling (1999) has, however, usefully collated and analysed the evidence for gravel dunes available to date.

Despite the scarcity of field hydraulic data relating to their formation, large-scale bedforms and their development and persistence are likely to be crucial patterning determinants in the distinction between dominantly braided and meandering rivers. This is unlikely to relate in a straightforward way to bankfull stream power alone. It may alternatively be possible to suggest some interpretations of what lies behind stream power/grain size/channel pattern relationships, given consideration of factors in bedform development as discussed above.

Fig. 5 provides a plot of 'raw' specific stream power at bankfull discharge, grain size and channel patterning data using a larger data set than that used by van den Berg (1995). We have included 113 additional data points from Chitale (1973; 33 sites), Ferguson and Ashworth (1991; 1 site), Hey and Thorne (1986; 44 sites) and Kellerhals et al. (1972; 35 sites); all studies which van den Berg used, but from which he selected only parts of the published dataset. The scatter in channel patterns is even more apparent, with many sandy meandering channels at

Fig. 4. Channel pattern, flow depth, velocity and Froude number (F) for the enlarged river data set (see text).

Fig. 5. Unadjusted specific stream power and bed median grain size for the enlarged data set (see text) and showing rivers reported as braided, meandering and straight.

relatively high specific stream powers, and considerable overlap between meandering and braided gravel-bed river occurrence fields.

Fig. 6 plots channel pattern in relation to mean bed shear stress at bankfull and grain size. Such plots have commonly been used in considering sediment transport and dune development, but not channel pattern. Here it may be helpful to consider sand and gravel-bed rivers separately. In dimensionless shear

stress terms, most of the non-straight *gravel-bed river* data plot within $0.06 < \omega < 0.25$ limits, with a tendency for braids to develop at higher Froude numbers (Table 1) as might be anticipated following Parker (1976) and others. Some patterns appear to have been achieved below the assumed limit for sediment transport. It has to be borne in mind that the data used are mean reach data, and this does not preclude particular channel locations within a reach

Fig. 6. Channel pattern, mean bed shear stress and median grain size. Shields dimensionless shear stress values (θ) of 0.25 and 0.06 are also shown.

Table 1

Bankfull Froude numbers from the van den Berg data for rivers where surveyed channel dimensions are available

	Bankfull Froude number				Total
	< 0.40	0.40–0.59	0.60–0.79	0.80–0.99	
Sand-bed braiding	4	2	0	0	6
Gravel-bed braiding	4	10	12	2	28
Gravel-bed meandering	14	0	0	0	14
Sand-bed meandering	20	26	15	0	61
Total	42	38	27	2	109

from having higher shear stresses and thus erosional/depositional activity. Alternatively, patterning may relate to shear stress achieved at higher than bankfull stage.

Straight gravel-bed channels, which have been rather neglected in the literature, can relate to high and low shear stresses and stream powers. It may be that high stream power ones naturally develop under plane bed conditions when they are undiverted by near-stationary bedforms. Alluvial fan rivers, which may branch but remain relatively straight, could provide helpful information in this regard though they are not usually incorporated into channel pat-

tern analyses. Although not all researchers have done so, it is interesting that Blair and McPherson (1994) in effect restrict their definition of fans to high-gradient features (greater than about 1°). They note a common absence of either braiding or meandering in the construction of fan sedimentary bodies and the prevalence of sheetflood or debris flow deposits.

Sand-bed rivers exhibit considerable scatter at bankfull conditions on the shear stress/grain size plot. When data are alternatively plotted in a depth/velocity field in the manner of Southard and Boguchwal (1990), but extending (at some risk) their laboratory bedform-type boundaries to greater depths and velocities, it seems *likely* that these rivers could be in the upper plane bed domain (Fig. 7). Physical modelling of highly sinuous meandering has proved notoriously difficult, though it is perhaps not surprising that Froude-scale modelling at higher Froude numbers, or unscaled but steep-gradient sand tray experiments, produce ‘gravel like’ channels rather than field forms at the lower Froude numbers suggested for larger sand-bed meanders (Fig. 4). For bedforms, the laboratory data and boundaries relate to shallow (less than 1 m) flows under accurately determined conditions, as previously discussed, and these strictly relate to small-scale bedforms. Nevertheless, it does not seem to have been previously

Fig. 7. Bankfull depth, velocity and channel pattern for sand-bed rivers. Also shown are Froude numbers of 1.0 and 0.84, and the upper regime plane bed limit lines (upper regime to the right) for grain sizes of 0.10–0.14 mm and 0.64 mm for laboratory experimental data from Southard and Boguchwal (1990), but extended to greater depths than those reported in their experiments.

appreciated that there may be an *upper threshold* for larger sub-critical-flow bedforms and thus braiding in relation to dune development for sandy rivers, in addition to those in coarser sediments as just discussed. For sand, this could be achieved at less than bankfull stage. Sand-bed rivers are also often well above the threshold for sediment motion at bankfull stage, and this confirms the point that sandy bedforms can be generated at *intermediate* flow stages, possibly being eliminated as stages rise to bankfull, and reworked as they fall to lower ones still above the threshold level for sediment transport. At bankfull, the sand-bed dataset used here is dominated by rivers described as meandering, with no real distinction in Froude number between meandering and braided types (Table 1). But overall, the point to note is that the channel outline and channel bedforms may relate to different river stages. Channel-forming and dune-forming conditions may be differentially achieved for gravel and sand-bed rivers over the field range of incident stream powers. For dune formation, Fig. 6 implies that terrestrial conditions allow dune formation in fine sediments at well below bankfull, but possibly above bankfull flows are required for the coarsest materials which can only move in extreme events when channel forms are also determined.

There are also implications for meander development. In the field, larger-scale bedform generation in gravels at high flow may initiate the development of channel sinuosity (eventually at greater wavelengths than the bedforms) around stalled bars (Lewin, 1976). This has been explained in terms of two-stage bar-bend models, for example by Seminara and Tubino (1989). But field investigations of sand-bed channels have proved somewhat disappointing in this regard. Welford (1994) observed bar development in six floods, forming on the descending limb of the flood hydrograph, but eradicated at lower flows in all but one bar. Field sand-bed meander initiation may not in practice be related to persistent bend forcing high-flow bedforms, and it is possible to model meander generation physically (Schumm et al., 1987; Fig. 5.2b) or numerically (Howard, 1996) without them in a manner which appears realistically to replicate the high-sinuosity forms achieved in some finer-sediment environments in the field. Sandy bedforms may have neither the appropriate size nor the

persistent stability to influence channel outlines. Field comparison of gravel- and sand-bed meander forms shows that the former have multi-arc bends which quite commonly are diversified with bedforms achieved at high flows (and extreme floods) and stalled thereafter; the latter are more normally characterised by smoother bends and develop 'platform' point bars which follow the evolution of planforms and which are a result rather than an initiating cause of meandering (see also Ikeda, 1989). In fact such 'unforced-bend' sedimentation and erosion is important in many channel patterns in single and multi-thread courses, which have lunate growth increments (on the inside of meander bends) or streamlined islands (with pointed ends and convex, concave and convexo-concave sides) which are quite unlike larger linguoid depositional bedforms which may, in some cases, have played an earlier core role in 'forced' planform pattern initiation.

3. Conclusions

We believe that van den Berg's (1995) analysis of 'potential' bankfull stream power and grain size is invalid, and that it obscures the complexity of processes which underlie the patterning of river planforms. When the vital factor of bedform development is taken into account, the following suggestions may be made with reference to the apparent scatter of channel patterns within the *raw* stream power/grain size data plot.

(1) Large-scale dune development ($\approx$ transverse bar) takes place alongside channel development at around bankfull stage in gravel bed rivers, below the dune-plane bed transition and broadly but not precisely in relation to Froude number. Available channel width may affect the number of braids (Parker 1976). There are *upper thresholds* to braiding and meandering as may be observed in extreme flows and the steepest gradients (as in alluvial fans), but not generally in the dataset used here.

(2) Sand-bed braiding may take place at intermediate stages, not necessarily at bankfull when beds can already be in an upper plane bed regime, and so also possibly above an upper threshold for dune development and braiding. Dunes may also be formed, reworked and reduced over a wide range of

flows. Whilst such dunes may diversify exposed channel beds, their scale or persistence makes them less significant in their effect on the outline of bankfull channels than in the case of gravel-bed rivers.

(3) Processes of meander initiation may differ as between sand-bed and gravel-bed meanders in field conditions. The latter may be initiated and their planforms recurrently diversified by large and extreme-event stalled duneforms; the simpler planforms of sand-bed meanders in the field may be initiated by down-channel wave propagation without bedform triggering, as some models have suggested.

(4) Given the very limited amount of direct observational data on bedform development in natural rivers (including the fact that there is little information concerning even river stage and bedform generation), it is for the present inevitable that these suggestions require further field validation.

Predicting the incidence of the other overlapping patterning processes listed earlier on a reliable basis is also far from straightforward. For example, the bank-breaching process is important in maintaining both anastomosed and braided channel patterns. The process (including the variants of chute cut-off, crevassing and avulsion) appears to depend on successful combinations of: local or general channel sediment build-up, momentum effects involving channel curvature and gradient, greater than channel full discharges, bank resistance and profile irregularity, and finally out-of channel topography and resistance which determine the short or long course subsequently followed by the new breaching channel. These factors are not resolvable in terms of in-channel grain size and bed shear stress or bankfull stream power. Overall, we believe that it is better to consider thresholds and process domains within each group of patterning process rather than to seek a simple across-the-board discrimination of pattern types on the basis of bankfull specific stream power and bed material size alone.

References

- Ashley, G.M., 1990. Classification of large-scale subaqueous bedforms: a new look at an old problem. *Journal of Sedimentary Petrology* 60, 160–172.
- Ashmore, P., 1991. Channel morphology and bed load pulses in braided, gravel bed streams. *Geografiska Annaler* 73A, 37–52.
- Bagnold, R.A., 1980. An empirical correlation of bedload transport rates in flumes and natural rivers. *Proceedings of the Royal Society of London* 372A, 453–473.
- Blair, T.C., McPherson, T.G., 1994. Alluvial fans and their natural distinction from rivers based on morphology, hydraulic processes, sedimentary processes and facies assemblages. *Journal of Sedimentary Research, Section A: Sedimentary Petrology and Processes* 64, 450–489.
- Carling, P.A., 1999. Subaqueous gravel dunes. *Journal of Sedimentary Research* 69, 534–545.
- Chang, H.H., 1980. Geometry of gravel streams. *Journal of the Hydraulics Division, ASCE* 106 (HY9), 1443–1456.
- Charlton, F.G., Brown, P.M., Benson, R.W., 1978. The hydraulic geometry of some gravel bed rivers in Britain. Report IT180, Hydraulics Research station, Wallingford, England.
- Chitale, S.V., 1973. Theories and relationships of river channel patterns. *Journal of Hydrology* 19, 285–308.
- Church, M., 1978. Palaeohydrological reconstructions from a Holocene valley fill. In: Miall, A.D. (Ed.), *Fluvial Sedimentology*. Canadian Society of Petroleum Geologists, Calgary, pp. 743–772.
- Collinson, J.D., 1970. Bedforms of the Tana River, Norway. *Geografiska Annaler* 52A, 31–56.
- Crowley, K.D., 1983. Large-scale bed configurations (macroforms), Platte River Basin, Colorado and Nebraska: primary structures and formative processes. *Geological Society of America Bulletin* 94, 117–133.
- Dinehart, R.L., 1989. Dune migration in a steep, coarse bedded stream. *Water Resources Research* 25, 911–923.
- Dinehart, R.L., 1992. Evolution of coarse gravel bed forms: field measurement at flood stage. *Water Resources Research* 28, 2667–2689.
- Einstein, H.A., Shen, H.W., 1964. A study of meandering in straight alluvial channels. *Journal of Geophysical Research* 69, 5239–5247.
- Ferguson, R.I., 1981. Channel form and channel changes. In: Lewin, J. (Ed.), *British Rivers*. Allen and Unwin, London, pp. 90–125.
- Ferguson, R.I., 1987. Hydraulic and sedimentary controls of channel pattern. In: Richards, K.S. (Ed.), *River Channels: Environment and Process*. Blackwell, Oxford, pp. 129–158.
- Ferguson, R.I., Ashworth, P., 1991. Slope induced changes in channel character along a gravel-bed stream: the Allt Dubhaig, Scotland. *Earth Surface Processes and Landforms* 16, 65–82.
- Hey, R.D., Thorne, C.R., 1986. Stable channels with mobile gravel beds. *Journal of Hydraulic Engineering* 112, 671–689.
- Howard, A.D., 1996. Modelling channel evolution and floodplain morphology. In: Anderson, M.G., Walling, D.E., Bates, P.D. (Eds.), *Floodplain Processes*. Wiley, Chichester, pp. 15–62.
- Ikeda, H., 1989. Sedimentary controls on channel migration and origin of point bars in sand-bedded meandering rivers. In: Ikeda, S., Parker, G. (Eds.), *River Meandering*. American Geophysical Union, Water Research Monograph, vol. 12, pp. 51–68.
- Kellerhals, R., Neill, C.R., Bray, D.I., 1972. Hydraulic and geo-

- morphic characteristics of rivers in Alberta. Alberta Cooperative Research programme in Highway and River Engineering, Report 72-1, 52 pp.
- Knighton, A.D., 1998. Fluvial forms and processes. A New Perspective. Arnold, London, 383 pp.
- Komar, P.D., 1996. Entrainment of sediments from deposits of mixed grain sizes and densities. In: Carling, P.A., Dawson, M.R. (Eds.), *Advances in Fluvial Dynamics and Stratigraphy*. Wiley, Chichester, pp. 127–181.
- Lewin, J., 1976. Initiation of bedforms and meanders in coarse-grained sediment. *Geological Society of America Bulletin* 87, 281–285.
- Lewin, J., 1989. Floods in fluvial geomorphology. In: Carling, P.A. (Ed.), *Floods: Hydrological, Sedimentological and Geomorphological Implications*. Wiley, Chichester, pp. 265–284.
- Millar, R.G., 2000. Influence of bank vegetation on alluvial channel patterns. *Water Resources Research* 36, 1109–1118.
- Mosley, M.P., 1983. Response of braided rivers to changing discharge. *Journal of Hydrology* 22, 18–67.
- Nixon, M., 1959. A study of bankfull discharge of the rivers in England and Wales. *Proceedings of the Institute of Civil Engineers* 12, 157–174.
- Parker, G., 1976. On the cause and characteristic scales of meandering and braided rivers. *Journal of Fluid Mechanics* 76, 457–480.
- Parker, G., 1979. Hydraulic geometry of active gravel rivers. *Journal of the Hydraulics Division, ASCE* 105 (HY9), 1185–1201.
- Seminara, G., Tubino, M., 1989. Alternate bars and meandering: free, forced and mixed interactions. In: Ikeda, S., Parker, G. (Eds.), *River Meandering*. American Geophysical Union, Water Research Monograph, vol. 12, pp. 267–320.
- Schumm, S.A., Mosley, M.P., Weaver, W.E., 1987. *Experimental Fluvial Geomorphology*. Wiley, New York.
- Southard, J.B., Boguchwal, L.A., 1990. Bed configurations in steady unidirectional water flows: Part 2. Synthesis of flume data. *Journal of Sedimentary Petrology* 60, 658–679.
- Thorne, C.R., 1997. Channel types and morphological classification. In: Thorne, C.R., Hey, R.D., Newson, M.D. (Eds.), *Applied Fluvial Geomorphology for River Engineering and Management*. Wiley, Chichester, pp. 175–222.
- Van den Berg, J.H., 1995. Prediction of alluvial channel patterns of perennial rivers. *Geomorphology* 12, 259–279.
- Welford, M.R., 1994. A field test of Tubino's (1991) model of alternate bar formation. *Earth Surface Processes and Landforms* 19, 287–297.
- Williams, G.P., 1978. Bankfull discharge of rivers. *Water Resources Research* 14, 1141–1158.