River meander behaviour and instability: a framework for analysis

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Recent empirical and theoretical work on river meanders suggests that instability is inherent. Within this context, an occurrence of multiple cut-offs could be interpreted as a clustering associated with self-organized criticality. Types of meander behaviour ranging from stable to chaotic are examined as trajectories or attractors within the phase space of rate of meander movement and bend curvature and change to the system is explored as shift from one attractor to another. It is suggested that this new approach provides insights into meander dynamics and provides a basis to identify the conditions, limits and constraints under which different behaviour occurs. Basic controls of energy and resistance underlie planform behaviour, but need to be refined in relation to the morphology and stability of channel courses.

key words England river meanders chaos theory River Bollin sinuosity non-linearity equilibrium

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Introduction

River meanders have been subject to much analysis, of various kinds, in fluvial geomorphology because of their remarkable forms, their ubiquity, their dynamism and the practical consequences of their movement. Original work focusing on the regularity and stability of meander morphology and their interpretation as characteristic or steady-state forms (e.g. Langbein and Leopold 1966) shifted to increased attention on the instability of meander courses, the complexity of forms that frequently develop and the underlying theory of development (e.g. Hickin 1974; Carson and Lapointe 1983; Stolum 1996). Various types of qualitative conceptual and graphical models of bend evolution were developed, based on empirical observations, mostly showing asymmetric and compound development of loops (for review see Keller 1972; Brice 1974; Hickin and Nanson 1975; Carson and Lapointe 1983; Hooke 1984a 1995a). The recognition of non-linearity in rate of meander development came in the work of Hickin and Nanson (Hickin 1974; Hickin and Nanson 1975; Nanson and Hickin 1983), based on field evidence. Hooke (1991 1997) compiled evidence of the relationship between rate of movement and curvature from several rivers. Theoretical developments, particularly of Parker and Andrews (1986) and Howard and Knutson (1984), based on fluid mechanics theory (mathematical formulation of the perturbation of near-bank velocity due to upstream curvature) also demonstrated non-linearity in meander development.

Two main types of quantitative simulation models have been developed (Mosselman 1995): those based on fundamental theory and principles of physics (e.g. Johannessen and Parker 1989; Howard 1992) and those based on kinematic relations (e.g. Ferguson 1984). It is now widely accepted that mathematical theory demonstrates the inherent instability of meander bend forms (Furbish 1991). A concept that has been applied more recently to river meanders is that of self-organized criticality (Bak *et al.* 1987), which Stolum (1996) has used to interpret the occurrence of cut-offs and the variation in sinuosity over time, produced by a simulation model. Thus, a range of behaviour is now recognized, including development of compound loops and increased complexity as well as stable meander courses, but explanations still vary, from assumptions of equilibrium, with change as adjustment to external alterations (exhibited by

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stable relations of morphology to discharge), to attribution of meandering as inherent and autogenic and evolution being due to intrinsic factors (Hooke and Redmond 1992).

The aim of this paper is to examine evidence of complex behaviour and, in particular, possible operation of self-organized criticality in meandering systems, using primary evidence of a field study and also evidence from a kinematic model. The range of meander behaviour is then reconsidered as trajectories in the phase space of sinuosity (or curvature) and rate of movement (or erosion). The evidence from both modelling and empirical studies is synthesized to produce an integrating framework for analysis of the full range of meander and planform behaviour. The approach is suggested as providing a new way of examining river pattern development and an agenda for generating more specific hypotheses of the causes, controls and limits of channel pattern behaviour.

Theory and methods

The idea of self-organized criticality originates from Bak (Bak *et al*. 1987; Bak and Chen 1991; Bak 1996). It is suggested that many composite systems naturally evolve to a critical state in which a minor event starts a chain reaction that can affect any number of elements in the system. It is a holistic theory, which does not depend on microscopic mechanisms and the system cannot be understood by analysing the parts separately. Bak's most famous example is that of avalanches in sand piles. The theory has been applied to earthquakes, stock markets, ecosystems and other systems. Bak (1996) also asserts that self-organization is so far the only known general mechanism to generate complexity. Stolum (1996 1998) used a simulation model of meanders based on fluid mechanics theory to show that meanders will initially increase in sinuosity, then decrease due to cut-offs and then oscillate in sinuosity to maintain a self-organized state, which, in an unconstrained state, will be a critical sinuosity of 3.14 (pi). According to Stolum (1996), a straight course represents order and a highly sinuous course chaos. The system may at first undershoot or overshoot before average sinuosity stabilizes. In the phase approaching criticality, occasional cut-offs occur but in the supercritical state clusters of meanders or avalanches occur. He also recognized a power-law distribution of size of cut-offs, but this can be difficult to test in the real world because of insufficient lengths of homogenous reaches or insufficient time, though Stolum (1998) used an example of satellite imagery of some rivers in Brazil. Phillips (1999a) has identified 11 different definitions of self-organization in the literature, which is leading to some confusion. Phillips shows that autogenic differentiation is directly linked to dynamical instability and chaos. Self-organization is generally considered as manifest in the ability or tendency of a system to develop regular and organized forms, for example sand dunes. The behaviour of sinuosity in relation to the concept of self-organized criticality and evidence of clustering of cut-offs is examined below. The case-study examined also provides some evidence of the operation of clustering.

For the condition of self-organized criticality to be identified, suitable evidence of the evolution of a meandering course is necessary. Stolum (1998) and others have pointed out the difficulty of testing meander simulation models and theories of self-organization and chaotic behaviour. Where meanders have developed over a long time period and floodplain evidence indicates numerous cut-offs, the evidence is usually insufficiently detailed to trace the sequence of changes over time. Where evidence is more detailed, for example based on maps, air photos and/or satellite imagery, the evolution is usually insufficiently rapid to see development of sinuosity and cut-offs in the time-scale of evidence. In a few cases, activity is sufficiently rapid and evidence abundant enough to plot sequences and trajectories of behaviour. This has been done for a reach of the River Bollin in Cheshire in North West England. This has an almost entirely natural meandering course in erodible materials in which a high sinuosity has developed over the past 160 years or so. The historical evidence indicates a trajectory of increasing sinuosity, but in the past three years several cut-offs have taken place. This evidence can be examined to see if it fits with postulated ideas of self-organization and criticality and to see if it helps understand mechanisms and conditions for such behaviour.

The historical map courses are compiled from a range of sources (Hooke and Kain 1982; Hooke and Redmond 1989) at a scale of 1:2500. Independent checks have been made of the accuracy of the maps (Hooke and Perry 1976) and all the evidence has been corroborated in the field. Changes are consistent and the amounts of change are so great that they far exceed margins of error. More recent mapping is from aerial photographs of 1984 and 2001 and from topographic field surveying using total station and

GPS. The reach has been monitored annually for the past 20 years.

In addition, the evidence from some modelling is re-examined in the light of Stolum's (1996) work. Dynamical models based on fundamental theory are usually regarded as the more sophisticated and have simulated long-term development of meandering courses. However, most produce Kinoshita shape curves, which are not the same shape as many natural meanders, particularly those on gravel-bed rivers which tend towards double-heading and apex flattening, though they do resemble some large river meanders. The kinematic type of model is represented by that of Ferguson (1984), based on Hickin and Nanson's (1975) relationship between rate of movement and critical curvature, but with a spatial lag incorporated and a resistance factor influencing rate. Tests by Hooke (1991) and Moorman (1990) produced realistic-looking meanders, with lobing and double-heading (Figure 1a). Tests using an actual river course, the River Dane in Cheshire, for which historical evidence of course changes had been compiled and for which varying bank resistance was available from measured values in the field, produced simulations that replicate the major features of the course (Figure 1b). Similarly, Gilvear *et al.* (2000) tested a version of Ferguson's model and concluded that 'it appears to work well'. This model also produces varied actual patterns from similar initial conditions, as tested with a sine-generated course (Moorman 1990), a key characteristic of chaotic systems.

The difficulties of obtaining long enough time series of meander change from empirical sources to examine tendencies towards chaotic behaviour and self-organized criticality have meant that some researchers consider that these phenomena can only be found in models. The validity of the models can, however, only be assessed by testing with real data; tests and experiments with the Ferguson model point towards its verisimilitude. The following analysis is an attempt to examine whether some of the best data available are giving support to ideas of self-organized criticality and chaotic behaviour, in particular, the occurrence, in the early phase, of a cluster of cut-offs.

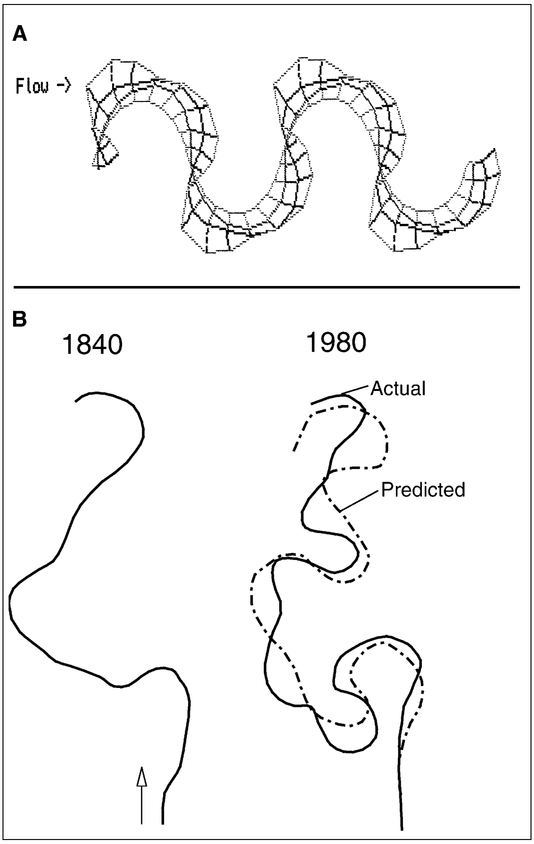

Figure 1 (a) Simulation of changes of a simple sine wave using Ferguson's (1984) model and producing asymmetry. (b) Results of simulation of change of the 1840 course of a reach of the River Dane

Results

Empirical evidence

The long-term sequence of channel change for a 600-metre length section (valley distance) of the River Bollin in Cheshire, UK, is plotted in Figure 2 and the courses are superimposed in Figure 3. When the sinuosity is plotted over time (Figure 4), it can be seen that sinuosity gradually increased from a value of 1.52 in 1840 to a maximum in ca. 1979 of 2.92. Three isolated cut-offs took place within the reach prior to that date, all between 1936 and 1970, of which, from the present state of the cut-offs and the subsequent bend development, two were probably in the 1940s, and one nearer the upstream end was actually in progress at the time of the OS mapping in 1970. Between then and 1998, three more bends were cut off (Hooke 1995b), of which one was artificial, which was the only interference with the whole reach as far as is known. In the period 1998–March 2001 at least five cut-offs occurred, another in winter 2001–2, with another pending in April 2002, of which four

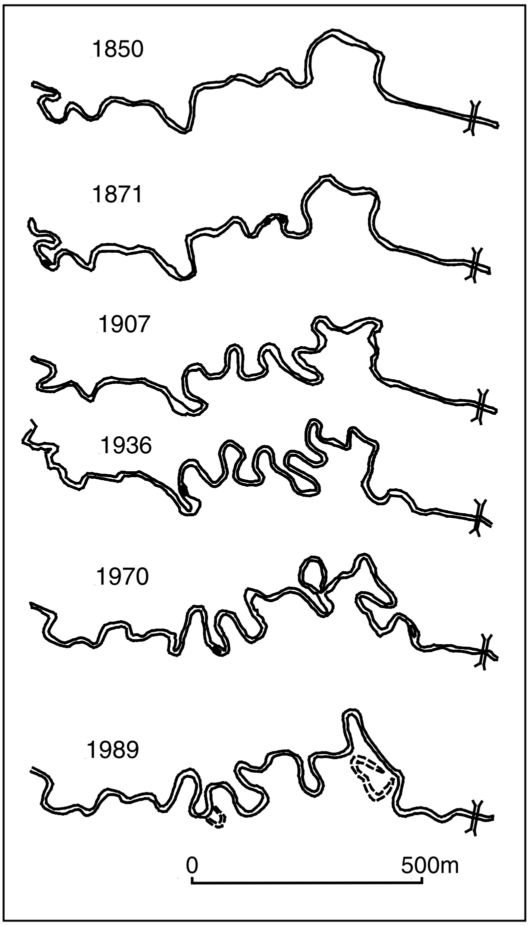

Figure 2 Historical sequence of changes on the River Bollin, Cheshire, UK

occurred in the winter of 2000–1. All of the cut-offs within this reach except one were neck cut-offs, which accords with the conditions for Stolum's modelling. This frequency of cut-offs within the recent two-year period, and particularly in one winter, is much greater than had occurred earlier (Figure 5) and can be seen to be taking place when sinuosity was relatively high (Figure 4). It could therefore possibly be interpreted that this is an example of self-organization, with a cluster of cut-offs occurring at a supercritical value. The concentrated cluster in the winter of 2000–1 has caused sinuosity to decrease markedly as in the initial phases of Stolum's simulations, and to move away from the critical value. Stolum states that systems can undershoot and overshoot, and it could be interpreted that the system reached such a state and that such an avalanche of cut-offs occurred that a severe undershoot has been caused. It would be anticipated that high sinuosity would redevelop. The supercritical sinuosity at which the cut-offs occurred happens to be close to the value of 3.14 (pi) which Stolum reckons develops in unconstrained meandering courses. According to his model, the critical self-organized sinuosity that later develops is lower and this might be expected in this case because terraces partially constrain the loop development. Thus course changes on the River Bollin could be interpreted as the early phases of Stolum's (1996) progression towards self-organized criticality and may give some insight into how this happens. Bak (1996) has identified that the effect of an event in a system in a subcritical state is isolated, but the effect in the supercritical state is for avalanches to migrate through a whole system. The distribution of cut-offs over time in this reach does indicate that cut-offs prior to 1999 had little, or only very long delayed knock-on effects, but that the changes in 1999–2001 had a domino effect that produced a clustering of cut-offs. It is suggested that this resembles the sandpile model of Bak (1996) and used by Stolum (1996 1998).

Alternatively, it could be interpreted that the clustering of cut-offs is simply due to the occurrence of unusually high flows in 1998–2001. The highest flood for 30 years occurred in 1998 and the 2000 peak was lower than this but the second highest since 1972. However, on the neighbouring River Dane, similar in characteristics and behaviour to the Bollin, the 2000 peak was the highest for 50 years but did not produce cut-offs. It is proposed that this is because the sinuosity was not in the critical state for clustering. Phillips (1999b) has already cited the historical behaviour of the Bollin as not easily explained except by chaos theory (or as a non-linear dynamical system), based on Hooke and Redmond's (1992) evidence and proposals.

In terms of the mechanism of this possible manifestation of self-organization at the critical state, the sequence and processes of the avalanche of cut-offs can be inferred from the field evidence, though the actual cut-throughs were not observed. The sequence is shown in Figure 6. Cut-off at A took place in 1999. In winter 2000–1 the cut-off at B must have taken place first as judged by the extent of sedimentation and the freshness of the cut-off (though subsequent infill depends on location and orientation in relation to flows (Hooke 1995b)). For the

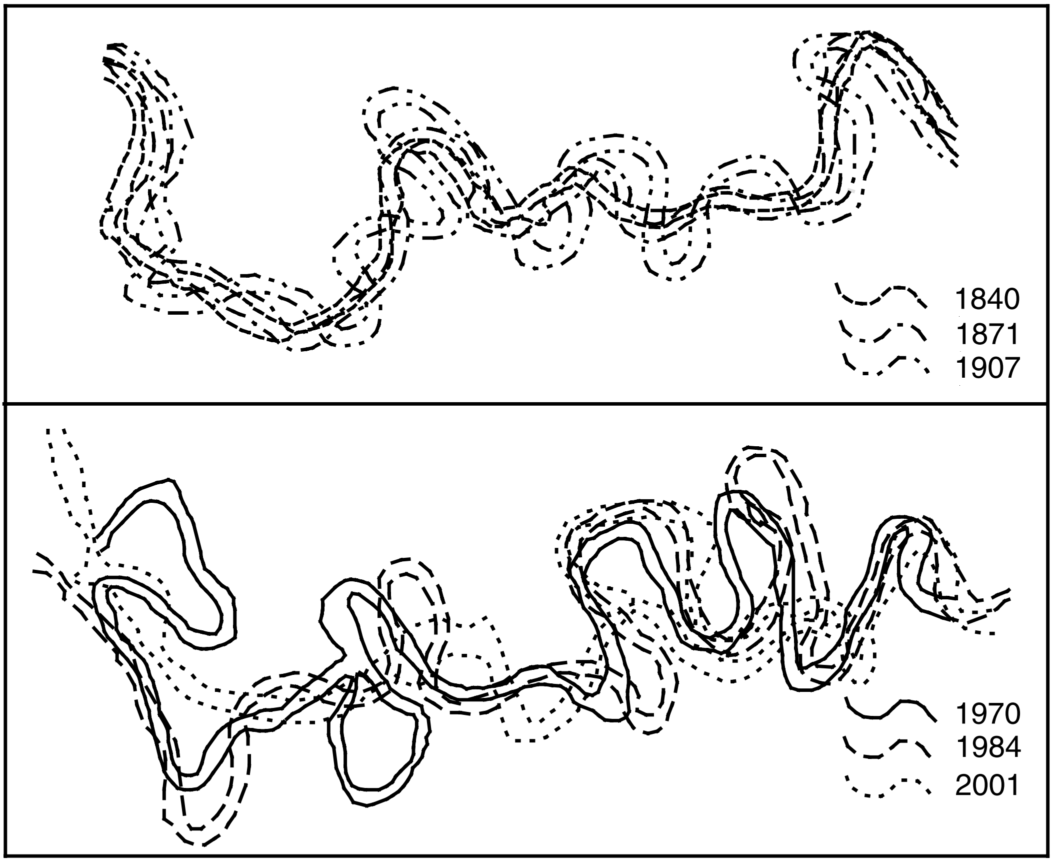

Figure 3 Superimposed courses of different date, River Bollin, Cheshire, UK

cut-off at D to have taken place, the cut-off at C must have occurred beforehand because of the relative heights, which have been surveyed. This would have created a very steep section between C and D and it is likely that a steep riffle originally at C would have acted like a headcut and processed rapidly upstream (to where a steep riffle is now visible). This would have created a steeply perched and sharply curved course at D with a very narrow neck. This would have rapidly cut through, creating the course as mapped in May 2001 from aerial photos, and in so doing must actually have led to the reversal of flow direction on the section from D to C. A subsequent cut-off at E in winter 2001–2, combined with these changes, left a much lower sinuosity course, with many bars, at April 2002.

Evidence of processes and behaviour subsequent to earlier cut-offs in the same reach and elsewhere that have been documented in detail (Hooke 1995b) indicate that a period of apparent disorganization within the channel is likely to ensue immediately after cut-off, with the form of bars and the number and position of riffles being particularly variable over a period of a few years, until a more regular distribution is produced and the reach becomes more stable in the short–medium term or activity is pushed elsewhere (cf. models of where bends are eliminated). It could also be interpreted that the behaviour at this scale within the channel, manifest in the earlier cut-offs and documented in detail, is an example of self-organization, with the riffles being at first irregularly spaced and variable in position but eventually stabilizing once the effects have been absorbed or transmitted and distributed along the course.

Evidence from meander modelling

Moorman (1990) carried out a series of tests using a program written to simulate meander development

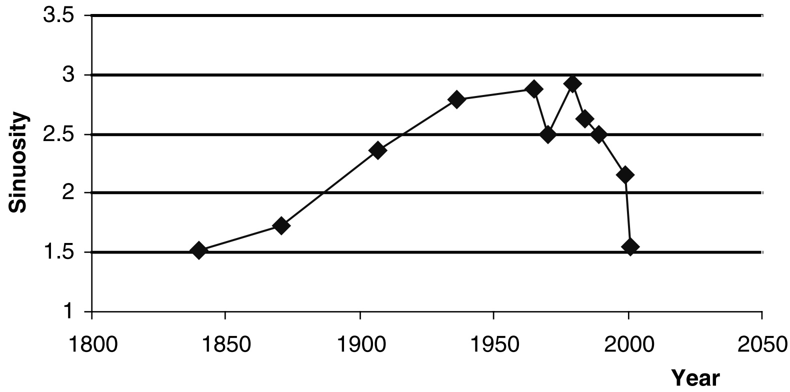

Figure 4 Change in sinuosity over time for reach of the River Bollin, Cheshire, UK

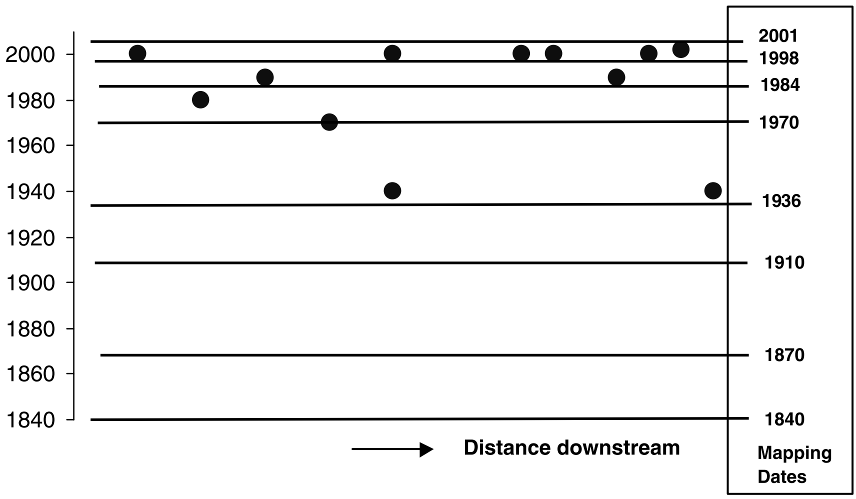

Figure 5 Occurrence of cut-offs in space and time for reach of the River Bollin, Cheshire, UK

based on Ferguson's (1984) relationship and incorporating a process of cut-off whereby the new course was created when two loops intersect. Moorman used a course of two simple sine-generated waves and simulated change over time through iterative applications of the curvature relationship. This produced the result shown in Figure 7a in which sinuosity increases to a maximum value then oscillates (SINE 1). The test was repeated with curves that only differed from the first in having 4 of the 60 digitized points omitted. This produced the second trace shown on Figure 7a (SINE 2). This confirms chaotic behaviour in that there is sensitivity to only slightly different initial conditions, but it also shows the similarity of behaviour in the development to a maximum sinuosity then oscillations. Even more convincing is the fact that application of the model to a real course, a section of the River Dane in 1840, produced the same kind of sequence (Figure 7b), which is similar to that of Stolum (1996). Interestingly, in these simulations some of the oscillations after the maximum value are large, similar to the Bollin temporal sequence of sinuosity. Thus it would seem that even in a very simple initial pattern of meanders, this complex and threshold behaviour is apparent, and it is so in both actual and simulated real river courses. This similarity of overall behaviour, but sensitivity in detail to initial conditions, conforms with Stolum's (1996 1998) statements that the global tendency towards a stationary state

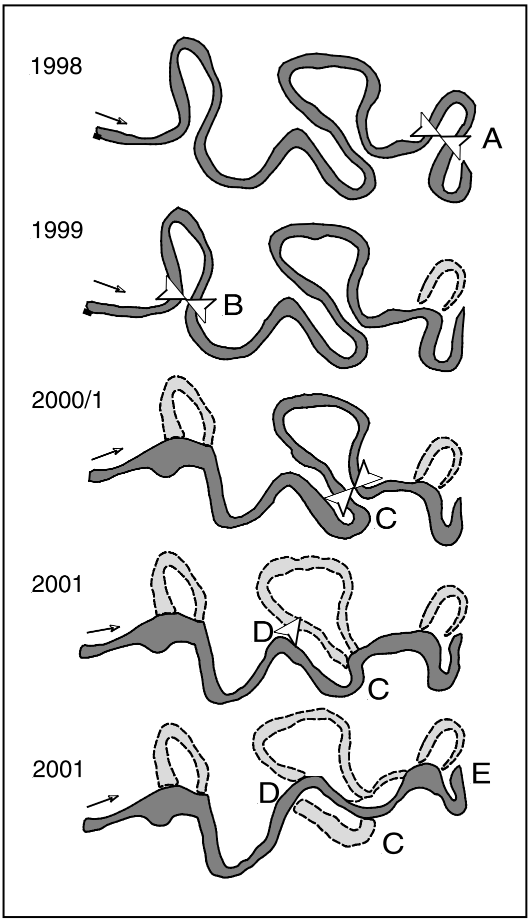

Figure 6 Sequence of changes associated with multiple cut-offs in reach of the River Bollin, Cheshire, UK

around some average sinuosity independently of initial conditions is evidence of the robustness of the self-organization process, suggesting a dynamic state of self-organized criticality, but that the outcomes are locally sensitive to initial conditions, in that these will cause divergence in local trajectory within the critical state, which is characteristic of chaotic systems. Moorman (1990), in longer simulations, also found that there was cyclicity and periodicity in the sinuosity fluctuations, again an example of possible emergent behaviour or properties. Those could be regarded as inherent, given that the curvature relationship seems to fit so many meanders, and the simulations of actual courses produced by the model were realistic.

Thus there would be seem to be considerable evidence, from both field examples and simulations, that there is an underlying tendency for meandering rivers to develop to a value of sinuosity at which clustering of cut-offs takes place. This is similar to the early phases of the progression towards self-organized criticality. If this interpretation and the longer-term simulations by the models are correct, sinuosity would then be expected to oscillate about a particular value in the longer term. This pattern of development of sinuosity to a maximum, then decrease and possible beginning of oscillation, is also illustrated by other examples in the UK, including the Teme (Hooke 1991; Hooke and Redmond 1992). Similarly, the values of sinuosity provided by Schumm *et al.* (1994) for the historical development of the Lower Mississippi prior to major artificial cut-offs were plotted over time and produced the same kind of pattern of downturn within the higher sinuosity values. However, Hooke (1991) had earlier identified that this development of sinuosity to a maximum then oscillation is inevitable from simple space filling and the shape of meanders following from the non-linear and double-heading behaviour apparent on many meanders (Hooke and Harvey 1983; Hooke 1987).

Meander trajectories: synthesis of behaviour

Notwithstanding the considerable evidence for unstable and accelerating behaviour in the most active meanders, some meanders do exhibit stability or low rates of activity and some can also be transformed into braided patterns. Thus a range of behaviour is apparent. Hickin and Nanson (1975) originally suggested that rate of meander migration or lateral erosion rate is non-linearly related to curvature of bends and plotted Figure 8a (Hickin 1978), in which phases of behaviour were recognized. They, and Hooke and Harvey (1983), Hooke (1987) and others, subsequently showed that individual meander loops tend to progress from migration at low curvature, to growth and extension (increase in amplitude), to increased complexity and double-heading to the limit of curvature, which may be of various modes, including neck cut-offs, a process of meander dismemberment (Lewin 1972), or a pulling out of bends (Hooke 1987 1995a; Gilvear *et al.* 2000). Hooke (1991 1997) combined evidence from several rivers to show the similarities of behaviour but the varying intensities on different

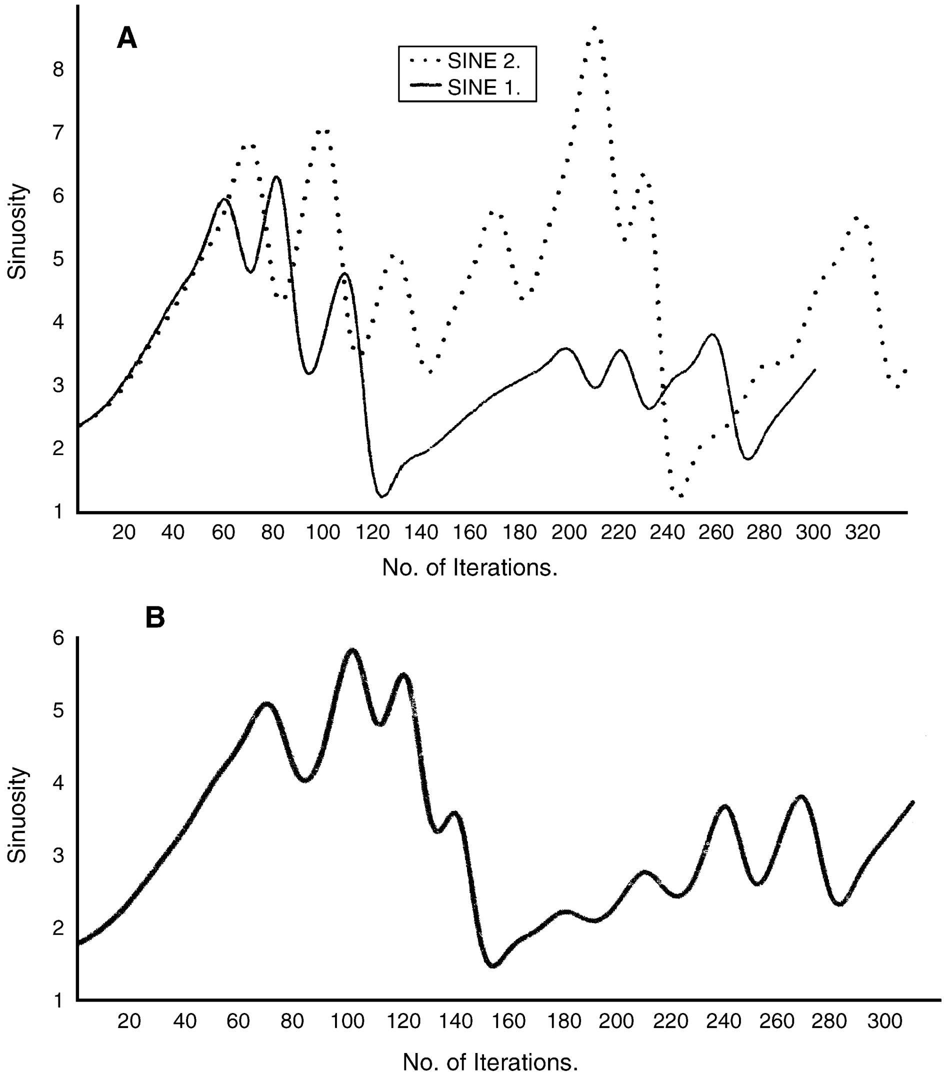

Figure 7 Variations in sinuosity over time from simulations of meander change using Ferguson's kinematic model (Moorman 1990), (a) sine waves, (b) a reach of the River Dane

rivers (Figure 8b) (rates are in channel widths and plot is dimensionless). These are envelope curves derived from values over time of individual meanders. The behaviour of individual bends can be plotted continuously as trajectories, as shown in Figure 9a. Individual bends are rarely as smooth and consistent in detail as the generalized pattern, but emergent behaviour can be discerned by phase plots of trajectories of bends over time.

The phase diagram can be further interpreted if various general types of behaviour of meanders are considered and plotted as trajectories (Figure 9b). A meander which develops according to the above sequence, increasing in curvature and rate through to cut-off, would plot as A on the trajectory in Figure 9b, with the neck cut-off having the effect of reducing the curvature markedly. If this was repeated over time, then a loop as shown by the dashed line trace A would be produced. This is the attractor of such a system. If, on the other hand, a meander loop follows a similar sequence but tended to develop chute cut-offs (these tend to occur at lower curvatures than

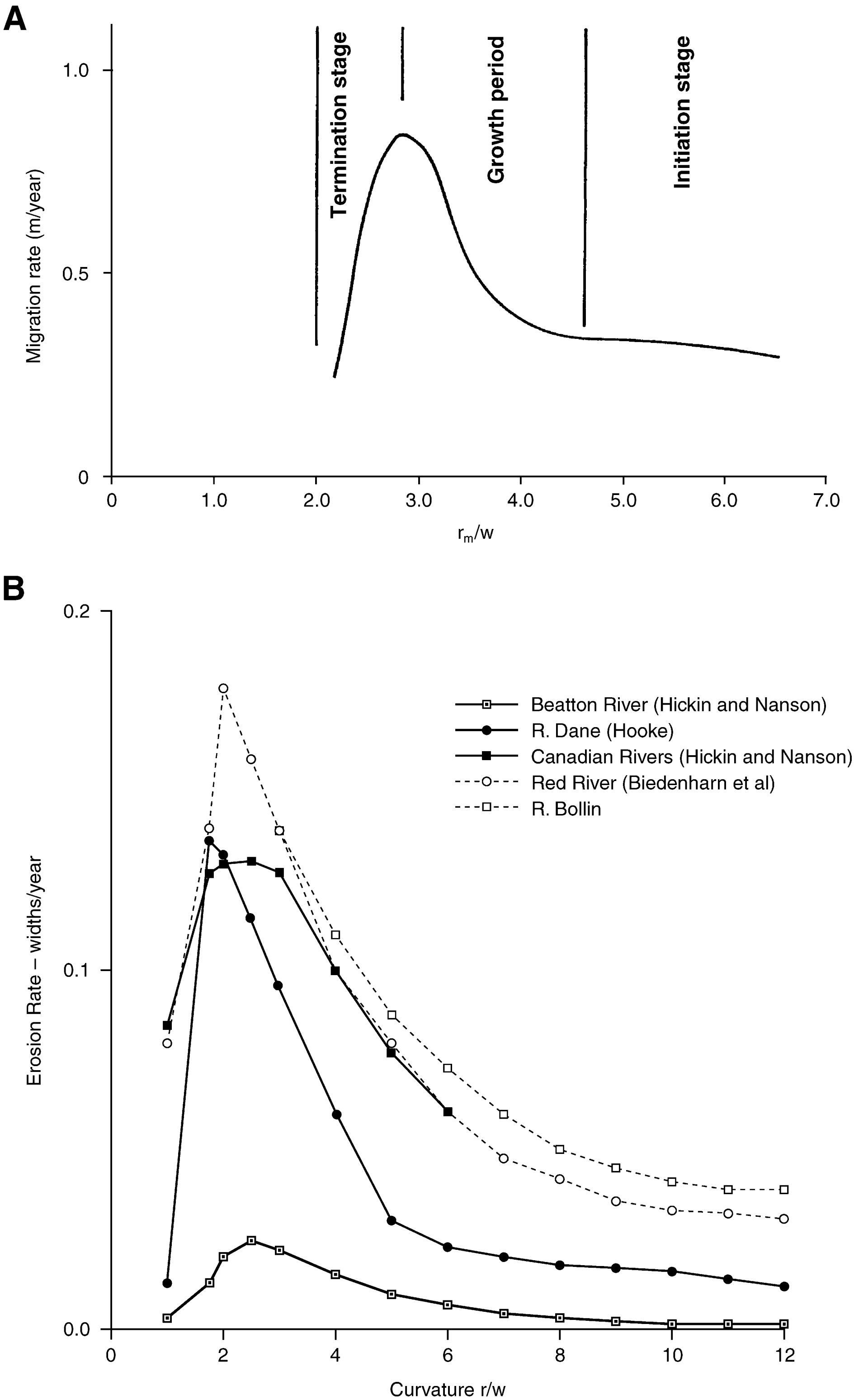

Figure 8 (a) Model of non-linear relationship and stages of change in meander evolution (Hickin 1978). (b) Compilation of plots of relationships between rate of meander movement and curvature (Hooke 1997)

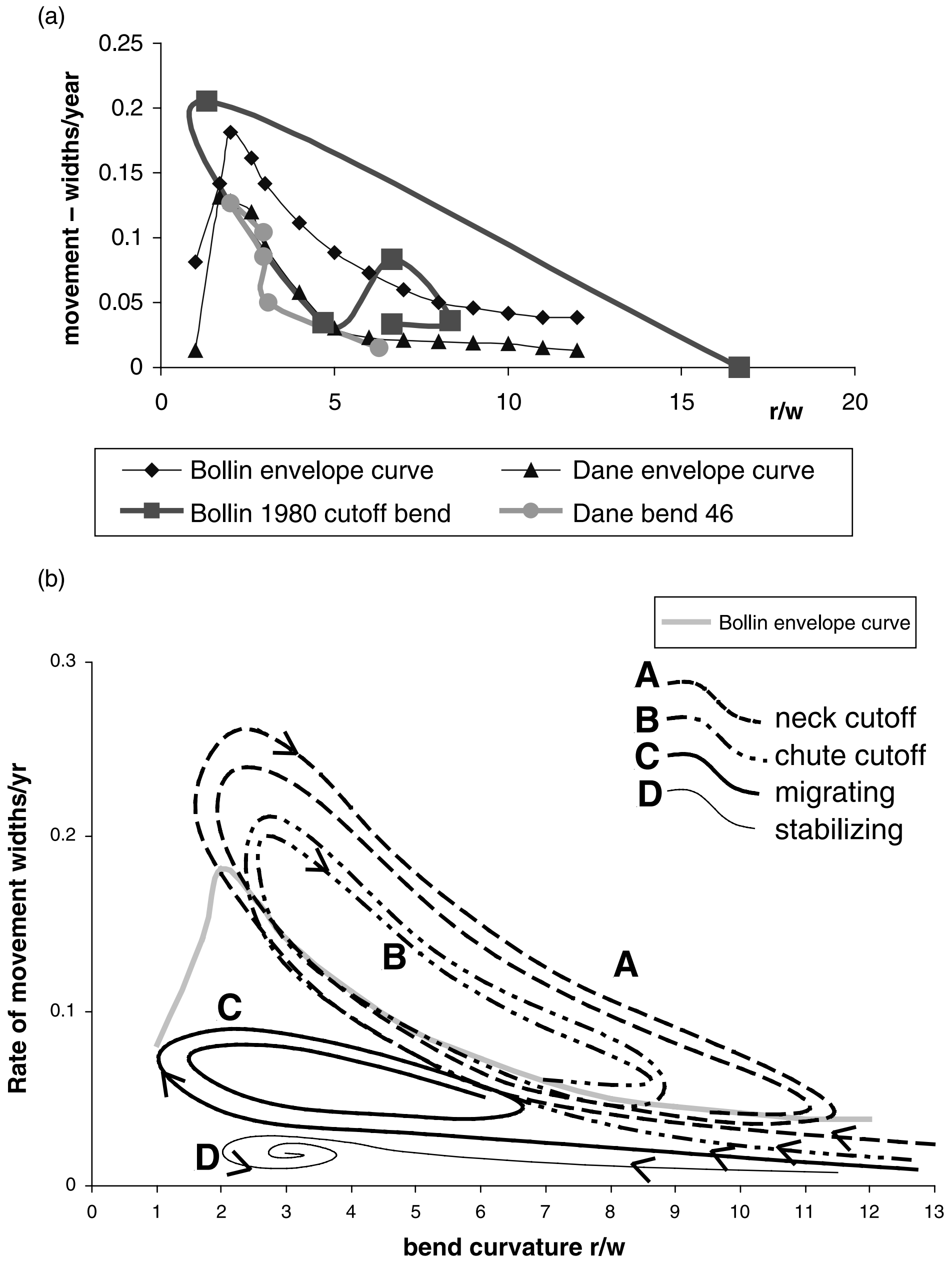

Figure 9 (a) Example of plots of individual bend behaviour in relation to rate and curvature. (b) Plot of hypothetical trajectories of types of meander behaviour in relation to rate and curvature

neck cut-offs and may leave a more curved course (Hooke 1995b)), plotting a theoretical sequence over time of a meander continuously developing in this mode gives the trajectory of B. However, other meanders develop sinuous courses with quite high curvatures, but do not seem to cut off. Some seem to continue to be active and simply migrate, varying slightly in their sinuosity and rate of migrations. These would plot as loop C. Still other meanders develop but eventually stabilize, and would therefore plot with the trajectory of D, i.e. to a point attractor, representing equilibrium. Many of those systems seem to develop slowly, presumably over a long time, and certainly have very low rates of activity now. Thus various types of behaviour can be seen as attractors of meandering systems. Rarely can multiple circuits round the attractor actually be followed or documented in real meander development because of the difficulties of evidence and because of the lack of sustained conditions. Hypothetically, however, these meanders could redevelop, but would not do so with exactly the same form because of variations in materials, vegetation etc., hence producing the kinds of loops plotted. This kind of analysis accommodates both a holistic deterministic relation and variations in behaviour.

In the short-term at least, progress over time will be jerky because change is episodic and related to occurrence of competent events. All changes are mediated through discharge events. Many authors have recognized that in periods of lower flows or moderate floods, lateral migration may prevail but that cut-offs will occur in large floods, leading to alternation of behaviour (e.g. Leys and Werritty 1999). This produces an attractor for such a system. An example of an alternating behaviour is that of Bartholdy and Billi (2002) in which there was a tendency to form regular meanders interrupted by larger floods, which generate chute cut-offs.

It can thus be seen that all types of meander behaviour, from the low activity, highly stable to the highly unstable and chaotic types, are projected here (Figure 10). Both the asymptotically stable behaviour of conventional meander theory, in which meanders develop to an equilibrium wavelength, and the highly chaotic behaviour are accommodated. To be valid, the full range of planform behaviour and changes that a meandering river can undergo ought to be considered and thus braided channels need to be included. They would tend to plot in the zone shown in Figure 10a as low sinuosity, but high rates of lateral movement. Thus an attractor or trajectory of alternation between braiding and meandering and the occurrence of channel metamorphosis can also be accommodated (Figure 10a).

An advantage of this kind of analysis is that it can incorporate contingencies that alter trajectories. For example, this could be the effects of a change in discharge due to climate or land use, which has the effect of shifting the attractor (e.g. A–B, Figure 10b). Or it could be the effect of a high magnitude flood which causes metamorphosis, so a flip from a meandering trajectory to braided, but in time an adjustment back (e.g. the Gila River documented by Burkham 1972 and Hooke 1996), or a stabilization deliberately created by bank protection, which restricts activity. Cyclicity between meandering and braiding can also be plotted (e.g. Brewer and Lewin 1998). Analysis of the position of any channel on this phase diagram at any time will allow some assessment of its sensitivity to different types of change, particularly whether it is likely to take off in terms of meander activity and sinuosity development. Ability of a system to switch from one trajectory to another or flip from one attractor to another means this is not necessarily a predictor of behaviour, but general tendencies may become apparent. Historical information will allow trajectories to be plotted and therefore the general tendencies under prevailing conditions of that section of channel to emerge. The apparent high instability of many meandering patterns may be because there is not a long enough sequence of evidence to see the later phases of self-organization before the system is kicked into a different trajectory by, for example, river incision.

An issue arising from this which requires further evidence and analysis is the time base of development of certain types of meanders or systems. Numerous meandering reaches exist in which there are highly developed loops, but these now have very low rates of activity and are more or less stable. The question is whether most of these developed very slowly over a very long time period, as plotted in Figure 10b, or whether they exhibited some of the non-linear characteristics of development, with an accelerated phase of loop extension, but then stabilized, in other words trajectory C or D in Figure 10b. Many of these rivers appear to be developed in relatively resistant materials such as clay. However, it is possible that, in the long term, a course would become more stable after an initial unstable phase of development, then cut-offs as it fluctuates about the self-organized critical state. Thus, a second requirement of the future research agenda is to investigate the trajectories of a greater range of meanders over longer time-scales than allowed by historical data. This also entails establishing the prevailing conditions at the time to understand the controls.

The pattern of trajectory of meander behaviour can be plotted as rate and sinuosity rather than curvature (all still dimensionless) and produces the hypothetical patterns shown in Figure 11. This conforms with ideas of increasing activity with energy in potentially chaotic systems and, for example, the progression of

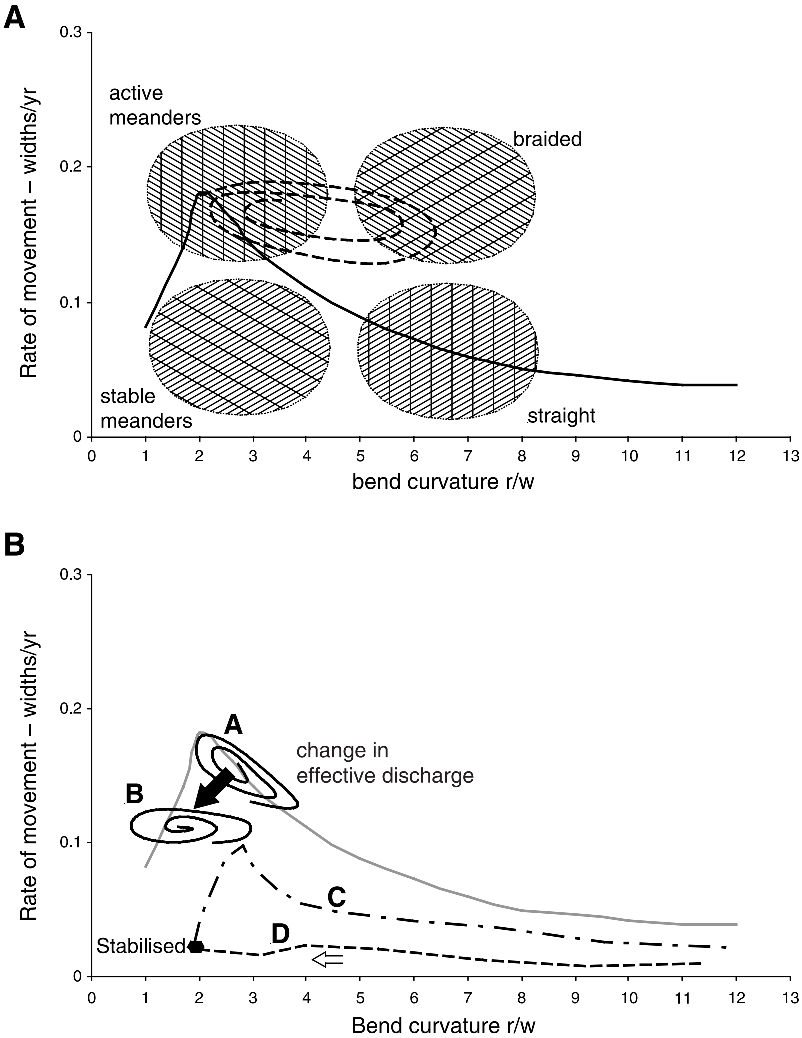

Figure 10 (a) Zones of different types of pattern behaviour and trajectory of meandering/braiding oscillation. (b) Examples of change in meander behaviour, A–B change in effective discharge; C, D alternative pathways of development of sinuous but now stable meanders

pattern with valley gradient for a given discharge (Schumm and Khan 1972) and includes braided patterns. Braided patterns have also been interpreted as self-organized systems (Sapozhnikov and Foufoula-Georgiou 1997 1999), showing self-similarity at different scales. Many researchers recognize a threshold or sharp transition between meandering and braiding and, though transitional forms arise, the meandering and braiding can be thought of as particular forms of self-organization which each take place under particular conditions, but that transitions between the states are systems lacking self-organization. Sapozhnikov and Foufoula-Georgiou (1999) also recognize this and say that the behaviour of a natural braided river can be driven out of the critical state by external conditions, resulting in deviation from dynamic scaling.

Discussion and research agenda

This recognition that characteristics of meanders are not static or stable but tend to occupy a domain or phase space provides the basis for identifying the conditions for that domain. Underlying controls are

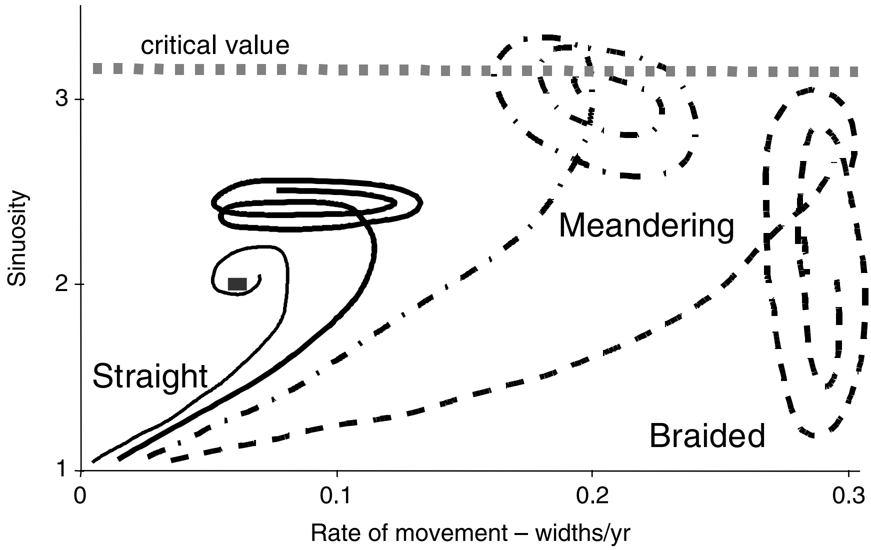

Figure 11 Plot of hypothetical trajectories of pattern behaviour in relation to sinuosity and rate of movement, with Stolum's (1996) theoretical critical value of sinuosity

known to be force and resistance, in particular the excess energy of stream power over resistance of materials of the channel boundary. The challenge now is to identify under what conditions each type of behaviour or attractor occur and what might tip a system from one trajectory to another. Phillips (1999b) has said that the same Earth Surface System can have both stable and unstable modes and that there are inherent limits on modes. According to him, we are now in a fourth phase of analysis of non-linear dynamical systems in which the task is to determine when, if and under what circumstances self-organization or various types of behaviour occur.

Sinuosity has been shown to be related to valley gradient (e.g. Schumm 1979; Hooke 1984b). Relations of pattern stability to boundary sediment size are also well known (e.g. Schumm 1960; Hickin and Nanson 1984). However, resistance may incorporate not only channel sediment but vegetation, and this may be a critical control as shown by, for example, Mack and Leeder (1998) working on the Rio Grande, USA and Stanistreet *et al.* (1993) studying channels confined by vegetation on the Okavanga Fan. Differing materials in floodplains have also been shown to make a difference in plot position (phase space) on the rate-curvature diagram (Hooke 1997; Hudson and Kesel 2000), suggesting a difference in trajectories between homogenous and heterogeneous floodplains. The presence of sediment is also not necessary for the development of bends, as has long been cited for example for meanders on ice, and compound and double-headed forms are found in sediment-free situations and in bedrock meanders. Bedrock meanders exhibiting the whole range of meander behaviour through to double heading and cut-off are illustrated, for example, by the channel course at Natural Arches National Monument in Utah, USA.

Limit on sinuosity and actual value of criticality is dependent on degree of spatial constraint, in other words the valley width. According to Stolum (1996), the critical value for a reach will depend on the valley width and will only be 3.14 in unconstrained meanders, rather less in confined meanders. Much work on meander changes has shown that type of change is influenced by degree of confinement (e.g. Lewin and Brindle 1977), and, for example, Rutherfurd (1994) identified that chute cut-offs took place on confined sections of the River Murray in Australia and neck cut-offs on unconfined reaches. Obviously other factors act to influence meander development in particular locations, for example the influence of tectonics or of geological structure (e.g. Schumm *et al.* 1994; Goswami *et al.* 1999), but the conceptual model outlined above provides a means by which the historical contingency can be allowed for and recognized because this will provide the limits or constraints on the phase space.

There are minor practical difficulties in consistency of definitions of rate of movement for a series of meanders, though arguably it is maximum rate that is the control and driver of behaviour (Hooke 1987). There are some methodological problems associated with definitions and scale of resolution of patterns; for example, degree of sinuosity may vary with length of channel selected and therefore limits will be dependent on this (Lancaster and Bras 2002). Similarly, Moorman (1990) has shown that the maximum sinuosity and curvature values attained are very sensitive to the resolution of digitizing. Similar arguments apply to the definition of curvature and whether it is maximum or average curvature and for what unit lengths. Hooke (1997) suggests that it is the maximum curvature and shape of the apex that is a key characteristic.

The idea of self-organized criticality and effects of a small event being large and propagated through or transforming the system (Bak 1996) is very similar in some ways to the idea of an intrinsic geomorphic threshold suggested by Schumm (1979) and both have been said to account for apparent catastrophism. Both incorporate the principle that the response of a system is dependent on its state. Thus this type of analysis and the application of the concepts presented here demonstrate that many of our present or even past theoretical frameworks are not mutually exclusive. Further exploration of emergent behaviour can take place by experimenting with plots of other phase space, including three-dimensional plots, for example involving meander wavelength or bend spacing or bend length. Controlling variables should also be plotted as ranges, e.g. of discharge.

The strength of the empirical relation between rate of movement and curvature of a bend and the verisimilitude of models based on the relation suggest that such a relationship adequately simulates this type of meander behaviour. It is an illustration of a holistic or top-down approach in which the component physics and detailed movements and effects of minor variations in form and roughness are not modelled but the whole is integrated. It implies that we do not need to know or understand those components in order to understand the behaviour of the reach, which accords with Bak's (1996) assertions about systems exhibiting self-organized criticality. This has implications for predictability of change, i.e. that we can predict overall behaviour, but, if the phenomena are chaotic, that we cannot predict the detail.

Conclusions

A range of behaviour is apparent in meandering systems, varying from the highly stable and ordered to the unstable and chaotic. Considerable empirical evidence has now been amassed to indicate that there is close association of high rates of activity with high sinuosity or curvature in many systems, and the non-linear relationship of rate and form indicates a positive feedback. Stolum (1996) previously used a simulation model to show that meanders develop to a high value of sinuosity at which multiple cut-offs occur, reducing sinuosity and resulting over the longer-term in oscillation about a critical condition. A case study has provided possible evidence of this early phase of sinuosity increase, then a sudden and large decrease when the system is in a particular state. Much evidence has also accumulated to substantiate the idea that a holistic model integrates the process and effects within a curve to reproduce behaviour realistically. However, not all sinuous systems exhibit high activity. A conceptual model has been developed here that accommodates both highly non-linear unstable and chaotic behaviour and orderly systems in equilibrium. The challenge now is to identify in more detail the conditions under which each type of behaviour occurs and the circumstances in which a system may change from one trajectory to another. Manifestly, the regularity of many meander patterns indicates a degree of self-organization, but the phase within the time series of sinuosity now needs to be recognized. Research is now needed to identify the limits of conditions for the various types of behaviour through further empirical work and also in order to calibrate these values for input to holistic models such as Ferguson's (1984), which appear to simulate meander behaviour well. In addition, further data on the trajectory or history of development and behaviour over various time-scales are needed.

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