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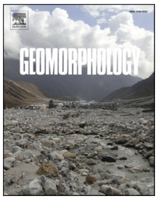

Invited Review

Morphodynamics of active meandering rivers reviewed in a hierarchy of spatial and temporal scales

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ABSTRACT

Meandering planforms are common on rivers but active, rapidly changing meandering channels are particularly instructive in indicating meander processes and dynamics and can extend our understanding of fluvial behaviour more generally. Questions arise in relation to the relative effects of flow events, phases and sequences of conditions, on the extent of autogenesis in changes, and the spatial propagation of change. In this review, the direct field and real-world evidence of the morphodynamics is examined through a hierarchy of spatial and temporal scales. Within bends, the channel interaction with bars is a major component of the morphodynamics. High variability in rates and patterns between events and years is evident, but a systematic sequence of mid-channel bar development emerges. Relations to discharge parameters are complex. At bend scale, clear autogenic sequences of bend evolution from simple loops to compound forms then cut-offs are apparent, in spite of short timescale episodicity and variability, and modulation by bank inhomogeneities. Two major morphodynamic issues are discussed, that of migration rate-curvature relations and of push-pull of bends. Cut-offs are important in active bend morphodynamics and an immediate phase of widening and multiple bars within the cut-off zone commonly occurs but then the channel stabilises. Conditions for clustering of cut-offs are discussed. Analysis at reach scale of multiple bends tends to produce much more systematic morphodynamics relations but may be obscuring the spatial and temporal variability. Evidence is equivocal on the extent and rates of spatial propagation of changes, some indicating change tends to be localised but other showing systematic interaction between bends. Much adjustment is by local feedbacks. The high rates and variability of the morphodynamics of active meandering rivers have implications and challenges for management. A strategy of allowing for the mobility is advocated. That requires understanding of the morphodynamics.

1. Introduction

Meandering channels are a common planform of rivers all over the world and in every type of environment. It is therefore very important to understand their dynamics, how their characteristics develop and the influences on their spatial and temporal variations. They are a basic component of landscape development, and rivers in a more natural state are very important as wildlife corridors and habitats, and as major contributors to biodiversity. Meandering rivers commonly shift in position and may change in characteristics over time, with the movement classically characterised as a tendency to migrate downstream, though the rates vary widely. Some meandering rivers can be very active, changing position and/or form by channel widths in periods of a few years to decades. These channels are particularly important for scientific investigation because they can inform us about the processes and dynamics of change on relatively short timescales and so increase our understanding more generally of river behaviour. Such rivers may also pose challenges in their interaction with human activities and land occupancy so understanding when, where and how they move is important for planning and management. This has long been the case, but it is vital now under the climate crisis to understand likely responses. It is increasingly realised that such natural forms of rivers are well adapted to conditions of discharge and sediment inputs and that such rivers, left alone, will have the flexibility to adjust. Such is the recognition of the need to 'work with nature' not against it, and that channelised river reaches are ecologically detrimental and not sustainable, that much restoration of meandering channels is now taking place.

In this paper, questions relating to timescales of drivers and responses are posed initially then issues of spatial interaction and propagation of changes are identified. Existing conceptual frameworks for interpreting morphodynamics are briefly outlined. The challenges of interpretation and synthesis associated with scales of evidence and

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analysis are introduced and scope of evidence briefly explained. The main part of the paper discusses the morphodynamics of active meandering rivers in a hierarchy of spatial and temporal scales, using mainly empirical, field evidence of real changes, as documented in the literature. These are complemented by the author's long experience of research on active meandering channels. The implications of the evidence for our understanding of river dynamics more widely, for management of active channels, and for prediction of future changes are brought together at the end.

1.1. *Questions*

This paper poses some key questions about the morphodynamics of active meandering rivers and reviews current evidence addressing those questions and the extent of our understanding. It discusses this through the lens of different scales, both spatially and temporally. Changes in position and characteristics of meandering channels take place by processes of erosion and deposition, usually under competent flow conditions that occur occasionally. Alluvial rivers, unconstrained, can adapt to the water delivered to the channel. Questions relate to the events that produce changes, the nature of those changes, how they propagate in space and the extent to which they produce a coherent response on the more extended spatial and temporal scales. Some of the key issues on the morphodynamics of meandering rivers relate to the timescales of effects and responses to varying discharge. This includes the length of period/number of events needed to cause adjustment and perceptible change in morphology, and the effect of sequences and phases of conditions, not just magnitude of events. Questions relate to how long conditions need to be persistent and what the effects are of high variability and legacy of previous change. Important issues to address are how the form changes to accommodate the discharge and sediment, particularly the extent of underlying trends in meander bend evolution, i.e., autogenic or inherent behaviour, on which adjustment is superimposed. In other words, to what extent are changes consistent and systematic, with a high degree of autogenesis, in spite of the periodic and pulsed or phased activity associated with flow events and conditions. In addition, other underlying changes in conditions, such as in vegetation cover may have an influence. Feedback effects are an important component of the morphodynamics. Finally, questions arise on the spatial interactions of these changes, the extent and mechanisms of transmission of effects, and over what distances and at what rates effects are propagated.

1.2. *Concepts*

Some of these questions have long been posed and various conceptual frameworks have been proposed and adopted as basic theory in fluvial geomorphology and in dynamic systems more generally. These include the magnitude-frequency question, the role of extreme events and the discharge to which channels are adapted (the bankfull issue) (Rhoads, 2020). Tendency to equilibrium or steady state has long been assumed, given a stability of conditions and inputs, with recovery from short-term disturbance occurring. Sudden and persistent changes in state have also been recognised, particularly in the idea of geomorphic thresholds and the key role of the state of the system (Schumm, 1979). Increasing attention has been paid to the idea of tipping points in systems and the need to identify these, especially in relation to climate change. These fit into wider frameworks of non-linear behaviour and chaos theory that have been applied to meandering channels (Stolum, 1996, 1998; Hooke, 2004; Hooke, 2007a). Transience and continuous change in geomorphic systems was recognised long ago (Brunsden and Thornes, 1979) but awareness that such behaviour may be inherent has grown. The complexity of natural systems, including river systems, is such that feedbacks are known to play an important role. Arguably, they are still neglected in many meandering models, particularly integration of biotic and physical elements. Distinguishing these different types of behaviour and trajectories and identifying the likely responses in particular situations and locations are challenging to address, especially in terms of prediction.

1.3. *Scale*

Scale is of fundamental importance in influencing what is detected or perceived in terms of spatiotemporal changes but analysis at a hierarchy of scales is also important to understand how small-scale processes feed into larger morphodynamics. Different aspects and degrees of variability are seen in evidence at different resolutions and over differing periods of time. Researchers have long warned of the danger of 'snapshots' such as those taken in historical maps or aerial photographs, and analysis between infrequent dates is known to smooth effects and hide variations. Donovan and Belmont (2019) consider that short- and long-term measurements are disproportionately affected by temporary rate variability, long-term hiatuses, and channel reversals. Here, a framework of spatial scales for examination of meander morphodynamics is taken in which changes at different timescales are examined. Various kinds of aspects and questions are addressed at the different scales. The spatial scales for analysis in this paper are within bend, individual bend, and reach scale (several bends), with different reaches and river systems addressed briefly at the end. The analysis is synthesised by a review of the extent to which the detailed components at higher resolution become resolved into apparent behaviour at wider and longer-timescales. It also highlights the dangers of ignoring the variability and mechanisms of change such analysis hides. Active meandering rivers are taken as those in which changes in position or characteristics are detectable on century timescales, with movement of at least a channel width. The focus is on those for which detailed evidence is available on timescales from a few events to multiple decades.

At these temporal and spatial scales, particular types of evidence have been used in river meander research. For longer periods and in earlier research, this was mainly historical maps, later complemented by aerial photography. Detailed methods of comparison and quantification have developed over time, particularly with advance in digitisation and GIS. Field surveys and detailed measurements of morphology and of changes have long been basic tools to provide evidence but these have rarely been continued over periods of more than a few years, especially at higher spatial resolution. The challenges of undertaking fieldwork and also of detecting complete cycles or responses of change to conditions have contributed to much research being undertaken via experimental and numerical modelling to understand dynamics, controls and fundamental processes. Such approaches have provided real insight, especially on the extent to which theory and assumptions are applicable, but they always require real-world data for validation. The focus in this paper is on the empirical evidence but complemented by brief discussion of what some modelling has revealed. The ability to collect real-world data is now advancing very rapidly and enabling not only high temporal resolution but high spatial resolution over large areas. The wide availability of satellite imagery of increasing resolution and frequency and with different detectors and signals, the routine surveys by LiDAR, and the ability to deploy drones (UAVs) for surveys, are now transforming our capabilities to detect and analyse change. Rapid developments in automated processing and use of AI to deal with the 'Big Data' now present enormous potential in relation to meandering rivers. This still needs to be complemented by adequate discharge data (preferably at greater spatial resolution than present gauging stations) and ideally by sediment flux data, which are sorely lacking in most areas. Technological advances in sensors will continue to enhance our field measurement capabilities (Kasvi et al., 2017a, 2017b).

1.4. *Information sources*

Some previous reviews of morphodynamics have been published that help provide a perspective for the present paper, including that by Guneralp and Marston (2012) on meandering rivers, and wider fluvial reviews by Church (2015), Church and Ferguson (2015) and Adams (2020). Background on meandering rivers is provided by Hooke (2013, 2nd edn 2020), and Rhoads (2020) provides an excellent detailed background on all aspects of fluvial systems. Research has mostly been rather restricted in type of fluvial environment studied, most being small and moderate-sized channels in humid -temperate areas. Some research has used remotely-sensed imagery from large tropical rivers but field and process measurements in that environment are more limited, with notable exceptions such as the work of Gautier et al. (2007, 2010). Very limited analysis of dryland ephemeral meandering rivers had taken place until recently (Ielpi, 2017, Li et al., 2017, Billi et al., 2018, Santos et al., 2019). In the last decade there has been increased research on cold climate/boreal rivers (e.g., Kasvi et al., 2013; Lotsari et al., 2014, 2020). Changes of meandering rivers induced by specific alterations of flow regime, such as dams, have provided some evidence about their responses, though most studies are of the wider fluvial changes. The focus here is on the underlying natural variability and trajectories of change that underlie responses. The present paper is provoked by questions posed or arising from the author's long-term study of active meandering rivers, mainly in the UK. In particular, evidence will be provided from two rivers in NW England, which have been studied in detail for >40 yr, the Rivers Dane and Bollin (Fig. 1), to complement other published literature. The 10 km study reach on the River Dane was designated as a Site of Special Scientific Interest (SSSI) in 1994 (Natural England SSSI detail (naturalengland.org.uk), n.d), under statutory legislation of nature conservation, and it has continued to justify such designation in the value of the site to subsequent research.

2. Morphodynamics

2.1. Within-bend scale

2.1.1. Event scale

It is at within-bend scale that detailed measurements of variations of erosion and deposition over time tend to be taken, usually a few years, often by topographic surveys within bends or cross-section surveys at specific locations. **Within event** measurements of process dynamics are relatively rare but some detailed research has taken place on boreal meandering rivers, with their particular discharge regime of seasonal freezing. Kasvi et al.'s (2013) detailed field measurements of the effects of different discharge levels on processes showed how flow structure affects point-bar morphology and scroll bar formation with a feedback effect on the flow trajectory (Fig. 2). Further research revealed that flood duration and the rate of discharge increase and decrease are important influences on channel changes through flow velocities and depth (Kasvi et al., 2017b). Lotsari et al. (2020) and Karkkainen and Lotsari (2022) suggest that most bank erosion and deposition occurs during the low flow period after the spring flood and melting on these rivers, because of the long duration of the recession (Fig. 3). In the rather different environment of the Buyuk Menderes River in Turkey, areas eroded during high flow were redeposited as the water level decreased (Akay et al., 2020). The hydraulics and patterns of water and sediment circulation within bends have long been studied (Dietrich and Smith, 1984; Hooke, 2020; Rhoads, 2020) but recent research has demonstrated the differences in circulation between sharp and mild-shaped meander bends and between bends with differing width /depth ratio (e.g., Vermeulen et al., 2015; Ruben et al., 2021). Another factor influencing the detailed location of bank erosion and the flow configuration is that of vegetation. Modelling has helped to understand the influence of vegetation on

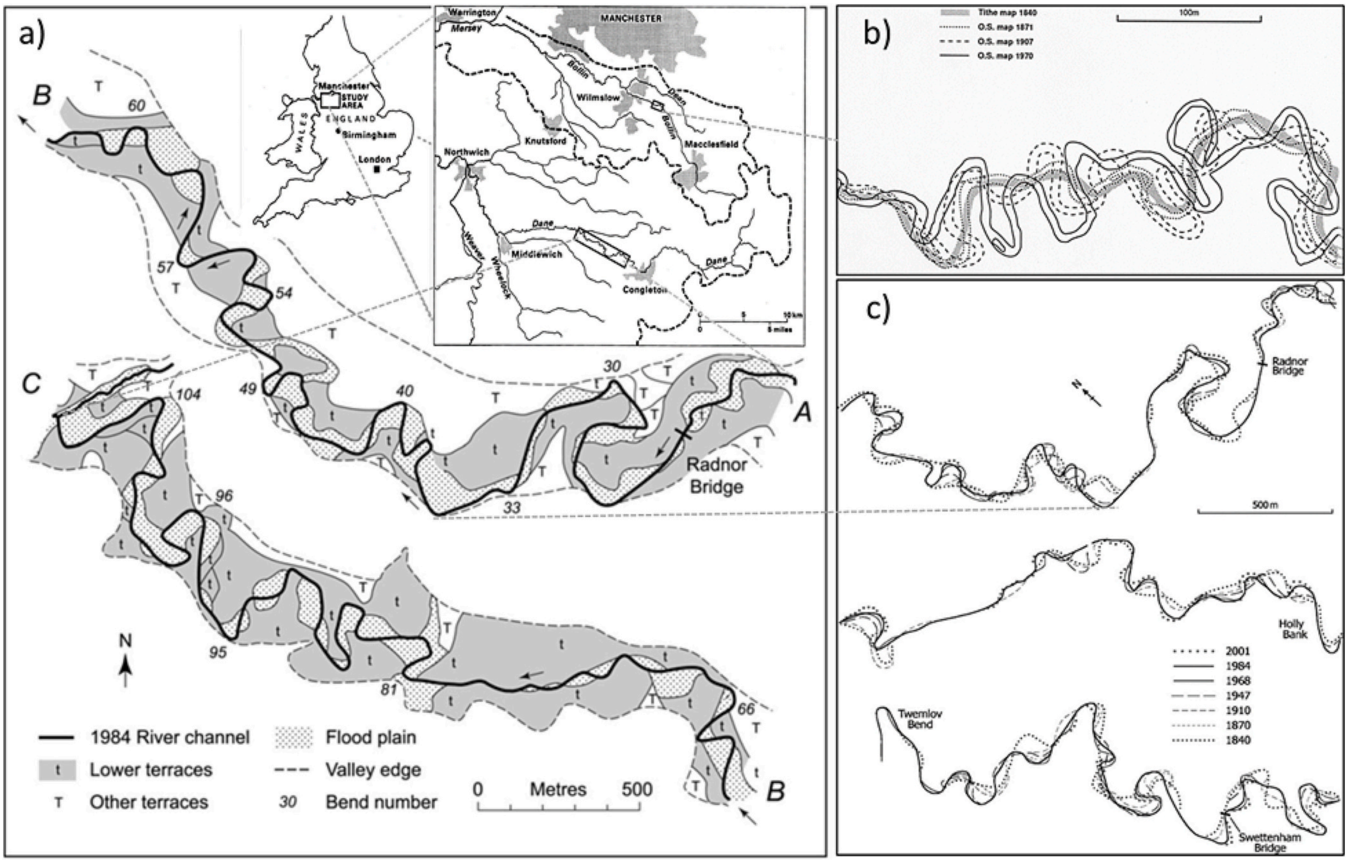


Fig. 1. a) Study reach of the River Dane, with insets of locations of River Bollin and River Dane in NW England, b) Historical changes on study reach of the River Bollin, c) Historical changes on study reach of the River Dane.

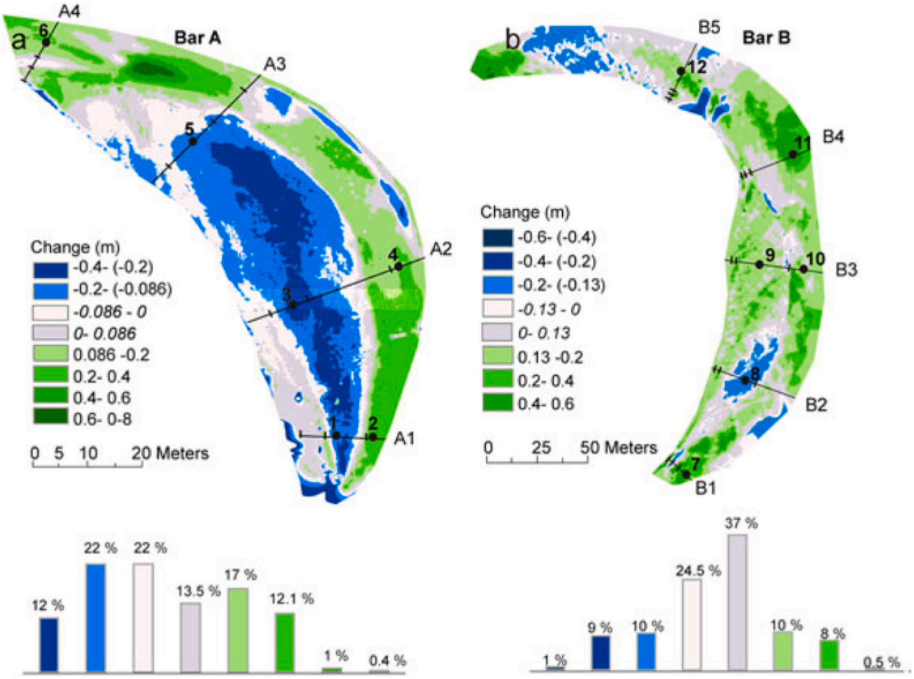


Fig. 2. Topographic changes on two point bars from measurements in 2008 and 2009 on the Pulmanki River, northern Finland, with the percentage amount of change of each class below, a) Bend A, b) Bend B. (From Kasvi et al. (2013) Fig. 8).

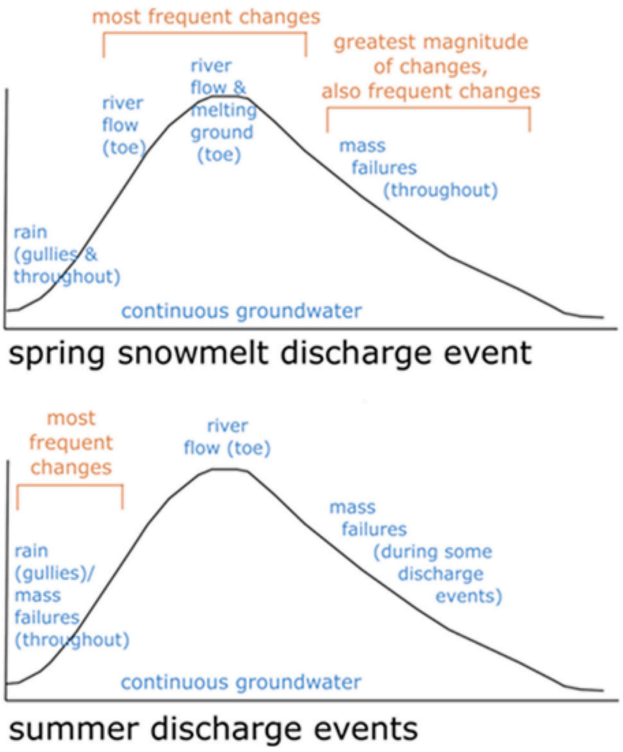


Fig. 3. a) Conceptual overview of the causes of bank erosion and their timing during spring snowmelt and summer rain-induced discharge events in a sub-arctic river. The "greatest magnitude" refers to the period with most occurrences of erosion/deposition. (From Lotsari et al. (2020), Fig. 11).

channel-bend hydraulics, point-bar vegetation steering flow towards the opposite bank, though also increasing point-bar accretion (e.g., Bywater-Reyes et al., 2018). Several researchers indicate that erosion can be found at differing locations over time and space. It may be very localised in a bend (e.g., Konsoer et al., 2017), often influenced by presence of trees and vegetation and/or more resistant materials, especially in early stages of evolution or in the short-term. However, the consistency of change in many bends demonstrates that it becomes more systematic (Hooke, 1995b) with maximum erosion at position of impingement of the fastest primary velocity current. This is a basic premise in some fundamental modelling (Parker et al., 1983; Hasegawa, 1989), though with feedbacks from the evolving bend morphology.

Most change in active meandering rivers takes place in association with high flow events. For example, Pizzuto (2009) calculated that hydraulic erosion is responsible for 87 % of all erosion on the Powder River, Montana. At the intra-annual scale, a key influence on the occurrence and rates of erosion and deposition is the number of events a year that produce change. Evidence from case studies indicate that, on active meandering rivers, effective events may occur several times a year and overbank flooding may be more frequent than the supposed bankfull frequency (Rhoads, 2020). Seasonality or timing in a year may be a factor (Hooke, 2015), not only in snow-melt regimes. Erosion tends to be much higher when banks are wet, though peak discharge is still the dominant control as Hooke (1979) demonstrated. Hence, frequent or clustered storms and wet periods may have more effect. Combinations of conditions have a crucial influence on variability of event effects. For example, Luppi et al. (2009) reported that the occurrence of mechanisms on the Cecina River, Italy, varied between the seven flow events in one year, slide failures being closely related to peak flow and cantilever failures occurring in hydrograph recession. Detailed changes in a mid-channel bar section during four events on the Drau River, Austria, were influenced by bed morphodynamics at intra-event scale, with bank failures taking place up to 20 days after the flood events (Klosch et al., 2015). The ratio of erosion and deposition may vary with discharge characteristics (Hooke, 2012, 2022). The effects of individual events have been examined, particularly in relation to extreme events, and how much erosion and deposition occur. On the Powder River in Montana, a single 50-yr recurrence interval event had much more effect on the bend morphology and movement than the subsequent 37 yr of smaller flow events (Ghinassi et al., 2019; Ghinassi and Moody, 2021) (Fig. 4). The deposits on point bars from the extreme event also differed in sediment

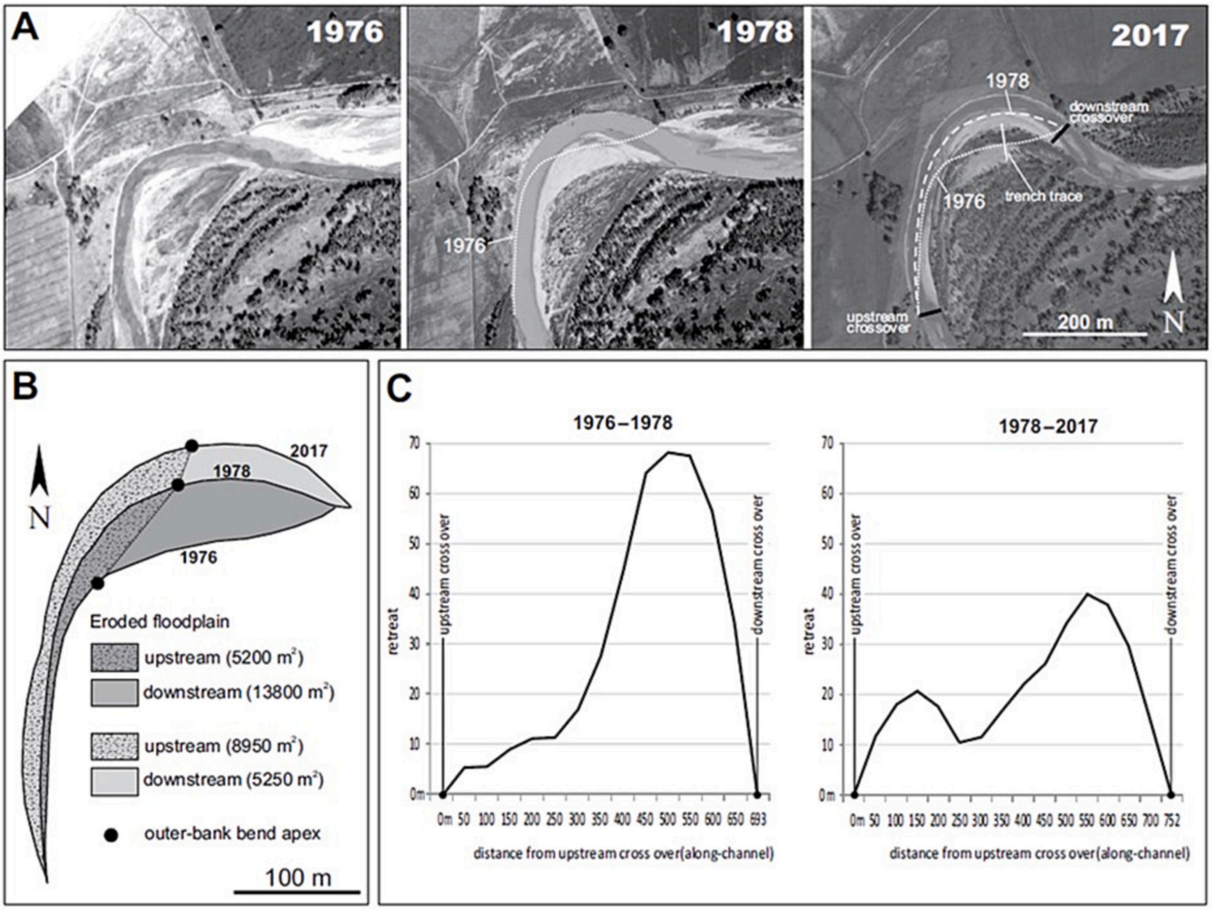


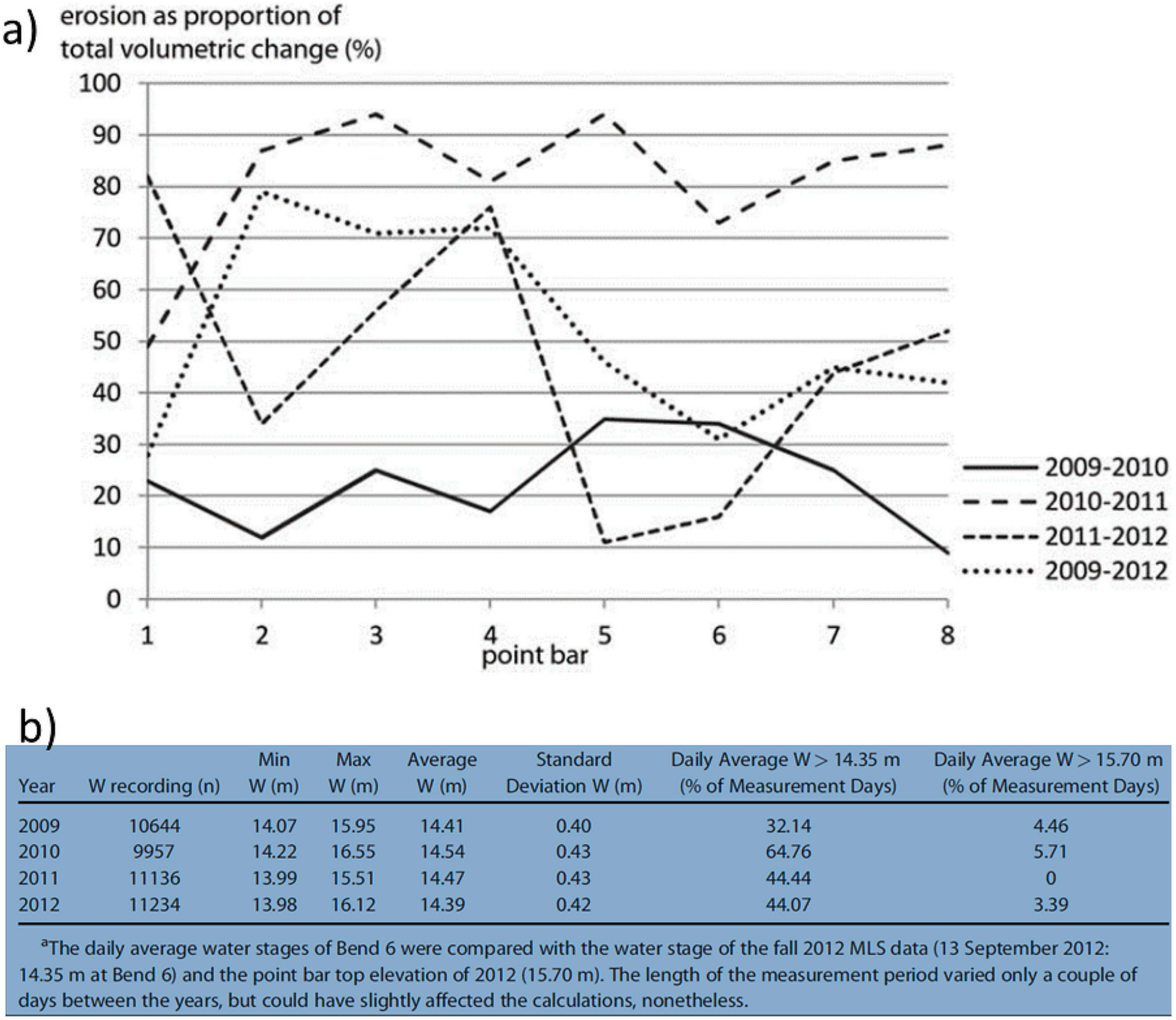
Fig. 4. Planform evolution of one bend on the Powder River, Montana, USA, since 1976. (A) Comparison between pre-extreme flood (1976), post-extreme flood (1978), and the planform configuration in 2017 of the bend, (B) Outer-bank retreat and terrace erosion during the 1978 extreme flood (light gray) and during the following 38 yr of annual floods (dark gray). (C) Quantification of the outer bank retreat during the single 1978 flood (left-hand diagram) and during the following 38 yr of annual floods (right-hand diagram) (Ghinassi et al. (2019), Fig. 4).

size, stratigraphy, and armouring from those of annual floods produced in the subsequent 37 yr because of differing circulation patterns and hydrograph phases in the two types of event. In analysis of a single extreme event, Storm Irene, in northern England, Buraas et al. (2014) suggested that, where unit stream power and bend stress parameter are high, widening was by bank retreat but elsewhere, it was caused by removal of the upstream end of mid-channel islands.

2.1.2. *Annual scale*

It is at the **annual scale** for which most evidence is available, revealing variations from year to year. Annual data over a period of several years allow analysis of the relation of erosion and deposition to discharge parameters. A major parameter of the dynamics and the balance of processes is variation in width. It emerges from several studies that high variability from year to year and lack of consistent relation to discharge, over a period of a few years (e.g., 3–7 yr) is very common. For example, in the boreal rivers, Lotsari et al. (2014) found the four years of study were all different from each other. The higher the flow and water stage peak, the more deposition occurred on point bars but the various point bars in a reach also differed spatially in their behaviour in any given year (Fig. 5). Similarly, Salmela et al. (2020) indicated that annual channel change was dissimilar year to year owing to different flow regimes and previous morphological changes, though seasonal differences between high and low discharge periods were similar each year. Kasvi et al. (2015) consider that analysis of discharge - morphological change relationships should be at a smaller scale than a point bar because of variations within a bend, but morphological changes of point bars also depend on the stage of bend development. Hooke (2022) recently examined evidence of change on a 1 km reach of the River Bollin in NW England, including annual surveys of sample cross sections from the limb and apex of a very active meander. It showed the variability in bank erosion and deposition amounts and in width over time, with differential rates in different vertical parts of the bank as well as within the bend over a period of 10 yr (Fig. 6). Amount of change in cross section morphology exhibited little relation to peak discharge but amount of shift in the banks was significantly related to number of peak discharges in a year. Unusually, it was a period of channel narrowing on the straight section of the meander bend. On the Amazonian River Beni, erosion and sedimentation were found to vary in the years 1996–2001 (Gautier et al., 2007) (Fig. 7) and sediment budgets of a meander bend measured over three inter-annual periods were very unequal. Erosion dominated in the first two intervals, and slight accumulation in the third, with point-bar accumulation amount not being related to the concave bank erosion (Gautier et al., 2010). In an environment lacking vegetation (Iceland), Ielpi (2017) found the major control on sinuosity is discharge, with fluvial planform changes directly correlated to discharge regime over monthly to yearly time scales. Accretion took place in stable discharge periods but point-bar reworking occurred in peak floods.

In research on the Carpathian Ondava River, Rusnak and Lehotsky (2014) showed that low-magnitude high-frequency floods stabilized the channel and produced concave-bank erosion of the and meander formation, whereas extreme floods resulted in greater erosion intensity and a change towards slight braiding. Much research has been undertaken on the Powder River, Montana, with exceptional annual measurements



Year	W recording (n)	Min W (m)	Max W (m)	Average W (m)	Standard Deviation W (m)	Daily Average W > 14.35 m (% of Measurement Days)	Daily Average W > 15.70 m (% of Measurement Days)
2009	10644	14.07	15.95	14.41	0.40	32.14	4.46
2010	9957	14.22	16.55	14.54	0.43	64.76	5.71
2011	11136	13.99	15.51	14.47	0.43	44.44	0
2012	11234	13.98	16.12	14.39	0.42	44.07	3.39

[a]The daily average water stages of Bend 6 were compared with the water stage of the fall 2012 MLS data (13 September 2012: 14.35 m at Bend 6) and the point bar top elevation of 2012 (15.70 m). The length of the measurement period varied only a couple of days between the years, but could have slightly affected the calculations, nonetheless.

Fig. 5. a) The volume of erosion on a series of bends on the Pulmanki River, northern Finland, as a proportion of total volumetric change (%) for each analysed year and the entire study period; b) Water stage data for each analysed year. (From Lotsari et al. (2014), a) Fig. 10).

at many cross sections over a period of >38 yr. Three point bars were created in an extreme flood in 1978 and were subsequently built up over a period of a few years, but some of the initial deposits were also eroded in the longer-term (Moody and Meade, 2014). Analysis of annual bank erosion, using samples throughout the meandering channel in different positions of the meander planform, confirmed the high temporal and spatial variability of local annual bank erosion and that it was episodic and unsynchronized along the study reach (Moody, 2022). Analysis of relations between annual sediment deposition and peak-flood discharge in both floodplains and point-bar sections revealed that snowmelt floods dominate the processes annually but flash floods, ice breakup floods, and autumnal floods contributed episodically. Depositional thresholds were identified and the discharge - sedimentation relations were linear for both floodplains and point bars (Moody, 2019). In support of modelling of channel geometry in meandering rivers, Naito and Parker (2020) showed that short-term/ frequent flows had much more effect on cross-sectional than longitudinal morphology because of lateral movement. On the Minnesota sand-bed river, 5–25 % exceedance flows were more influential than 0.1 % or 90 % exceedance.

2.1.3. *Sequences of events and conditions*

Analysis of the relationship between process/ meander dynamics and flow variations also begs the question not only of the differing magnitudes and frequency but of the effects of **sequences of events and conditions**, a much neglected topic. Very little data are available that allows differing effects of sequences to be distinguished, at within bend or other scales. In some measurements of bank erosion alone the evidence of sediment exhaustion in multiple events in quick succession is apparent (e.g., Rovira and Batalla, 2006; Walling and Webb, 1987). On the other hand, one high flow can destabilise banks and lead to increased activity and sediment loads (e.g., Gintz et al., 1996). Feedback effects become very important as recognised, for example, in the effect of slumped blocks that remain at the base of banks (Thorne, 1982; Hackney et al., 2015), producing an armouring effect, though possibly also deflection. Depending on the sequence of events, these may be removed in the next high flow, but if there is a succeeding long period of low flows then the blocks may become stabilized by vegetation and the flow threshold for removal increased. On the sandy banks of the Bollin and Dane, it is very rare for slumped blocks to stabilise at the base; they tend to be removed by the next high flow. This question of effects of sequences relates to the concept of recovery time and assumption of the tendency to steady state equilibrium. Akay et al. (2020) found that effects of erosion were reversed after two years. Very rarely are sequences replicated sufficiently in nature for researchers to quantify effects. Hence, much research uses modelling and experimentation but few of these use more than two cyclically alternating discharges. Modelling,

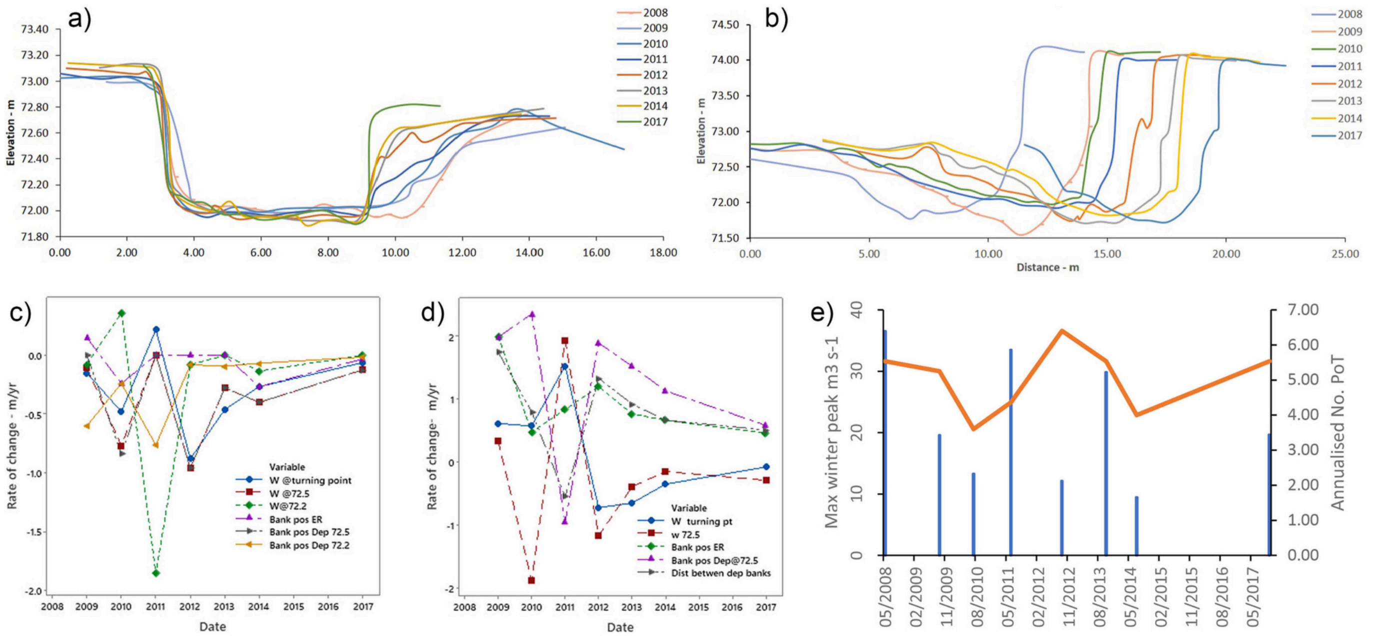


Fig. 6. Repeat cross section surveys on River Bollin, a) CS201 in straight upstream limb of a bend, b) CS211 in apex of bend, c) annualised rate of change in width and position of bank at various elevations in CS201, d) annualised rate of change in width and position of bank at various elevations in CS211, e) Maximum winter peak discharge and annualised number of peaks over threshold (POT) at dates of survey (based on Hooke (2022)).

not of meandering but of morphodynamics of ephemeral channels, showed that differing sequences of the same range of discharges, in a model that incorporated growth and processes of vegetation as well as erosion and deposition, produced different outcomes (Hooke et al., 2005).

2.1.4. *Dynamics of channel bars*

One of the causes or components of variations in portions of bends at timescales of a few to many years is the formation and evolution of channel bars. Much research has taken place focusing on point bars as an essential element of meandering morphology, as discussed above, but various other types of bars occur (Hooke, 1995b). These types vary in position, size, shape and composition (Hooke and Yorke, 2011). Free bars are those not attached to the floodplain (unlike point bars). In analysis of historical changes over a sequence of about 75 bends, Hooke and Yorke (2011) found none of the free bars migrated, they remained in position. One particular type of bar found to be common, and a key component of active meandering channels in influencing the locations of erosion and deposition and evolution of form, is the mid-channel bar (mcb) (Hooke, 1986). They are the locus of particularly high rates of processes. The rapidity of processes and longevity of the study period on the Rivers Bollin and Dane has allowed Hooke to identify the typical evolution and life-cycle of the mid-channel bars through numerous examples (Hooke and Yorke, 2010). Analysis of repeat photography and mapping showed the sequence of development from emergence of a small gravel bar through to full incorporation into the floodplain (Fig. 8a). The initial gravel bars tend to develop on riffles where widening has occurred; the total width increases further as two distinct channels develop. One channel then becomes dominant, and the other is sedimented-in until full floodplain attachment (Fig. 8b). It has been identified that the life-cycle timescale of these bars is typically 7–10 yr on the Dane and Bollin, (Fig. 8c). This sequence may be slowed or interrupted but overall exhibits strong autogenesis. Luchi et al. (2010), in measurements on the Bollin, demonstrate the correlation of width variation with curvature and the differences between bend apices and meander inflections, with the mid-channel bars initiated at the inflections, on the riffles. Luchi et al. (2011) and Zolezzi et al. (2012) went on to model the effects of local spatial variations in width on meander development, the latter stressing the autogenic element of the morphodynamics.

Other types of bars that occur and are distinctive to rapidly evolving, active meandering channels are concave bend bars and benches (Lewin, 1983, Page and Nanson, 1982, Andrle, 1994, Hodskinson and Ferguson, 1998) (also called counterpoint bars). These form in meander bends where separation occurs at the outer bend and/or rapid downstream migration takes place, leaving a large zone of low velocity and shear stress upstream in which relatively fine material is deposited. Hooke and Yorke (2011) identified that these concave bank bars can be quite common in active meandering channels, varying as a proportion of total bars (including point and mid-channel bars) from 2 % to 14 %. They are found in high curvature bends and tend to start initially as circular sandy deposits. They evolve slowly, with fine deposition, eventually to fill in the whole area vacated by the downstream progression of the meanders (Fig. 9). Recently, Sylvester et al. (2021) also recognised that these bars may be quite common, though they are not as neglected as they suggest. In experiments on the influence of sediment transport on bed erosion under variable discharge, Adams (2020) indicated that analysis at bar scale is important to provide insights into the complexities of morphodynamics and tendencies towards steady state, identifying that meandering rivers may undergo continuous non-linear changes under varying discharge.

2.1.5. *Decadal timescales*

In spite of this high variability of event to event and year to year, many studies have found that, over longer periods, erosion and deposition balance out to produce a more constant width. However, timescale of evidence/analysis and use of snapshots at a date have been shown to have a large effect on perceived changes (known as the Hurst phenomenon), with lower rates emerging at longer timescales than shorter measurement periods (e.g., Hooke, 1980). Donovan and Belmont (2019) attribute this to migration reversals, temporary rate variability, and long-term hiatuses of dormancy occurring within the longer 40–50-yr periods on the Root River, Minnesota. They warn that actual rates of channel movement may be underestimated. The river had not responded in the expected way to increased discharge, which might be a real stabilisation. Likewise, analysis by Dragicevic et al. (2017) produced a

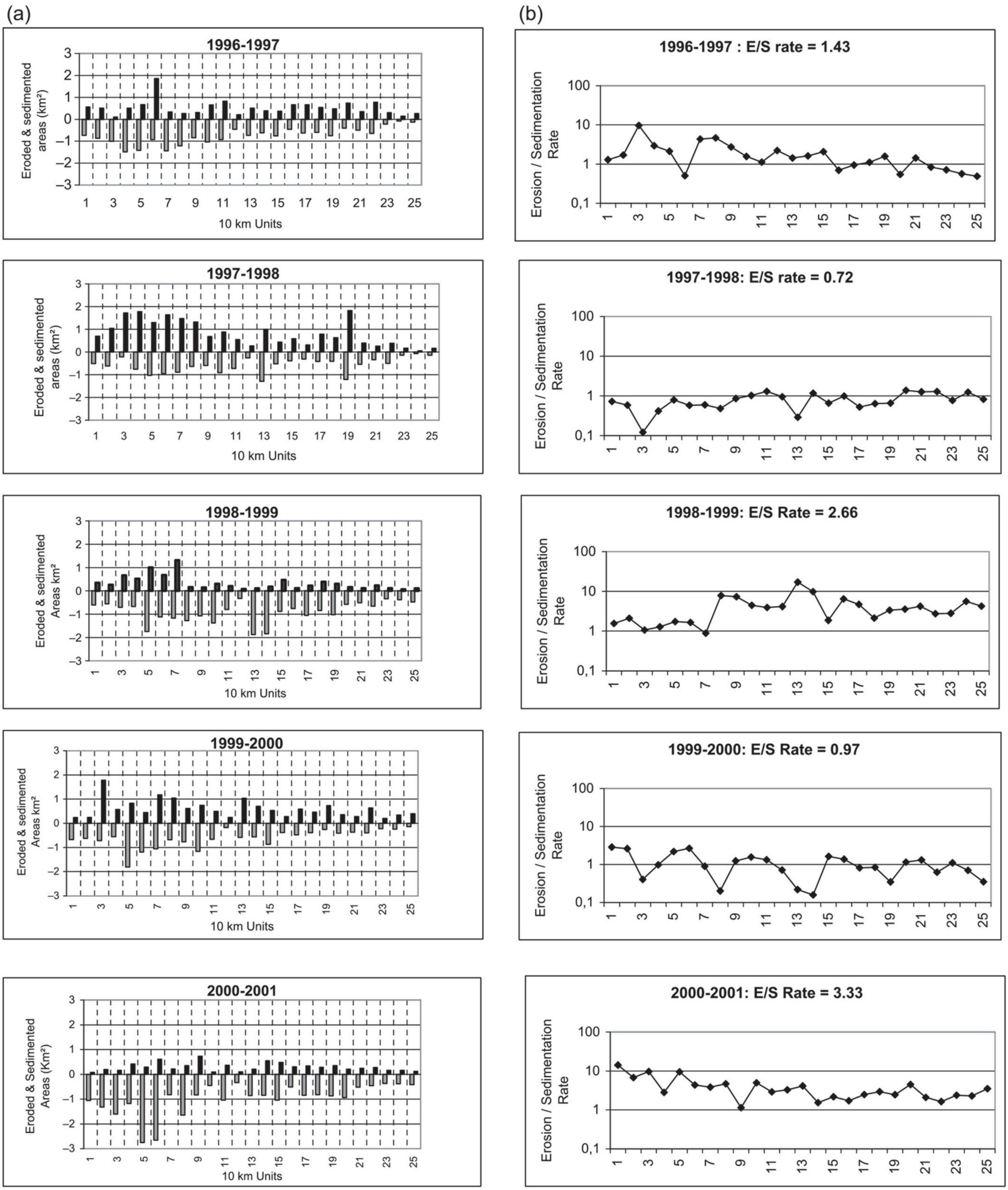


Fig. 7. Interannual variability of erosion and sedimentation in a meandering bend of the Rio Beni, Amazonia, 1996–2001, a) longitudinal distribution of erosion (gray) and sedimentation area (black), b) erosion/sedimentation ratio. (From Gautier et al. (2007), Fig. 5).

higher rate of bank erosion in a short-term period, 2010–2016, characterised by frequent discharge variations and rapid change in extreme values, than the long-term rates over the 1930–2016 period on the Kolubara River Basin (Serbia). In research on scroll bars in 30 consecutive bends of the Trinity River, it was found that 20 bends narrowed then widened in the period 2011–2015 or the opposite but, over time, inner and outer bank movements balanced out to produce a constant width, over a timescale of only 2–3 yrs. (Mason and Mohrig, 2019).

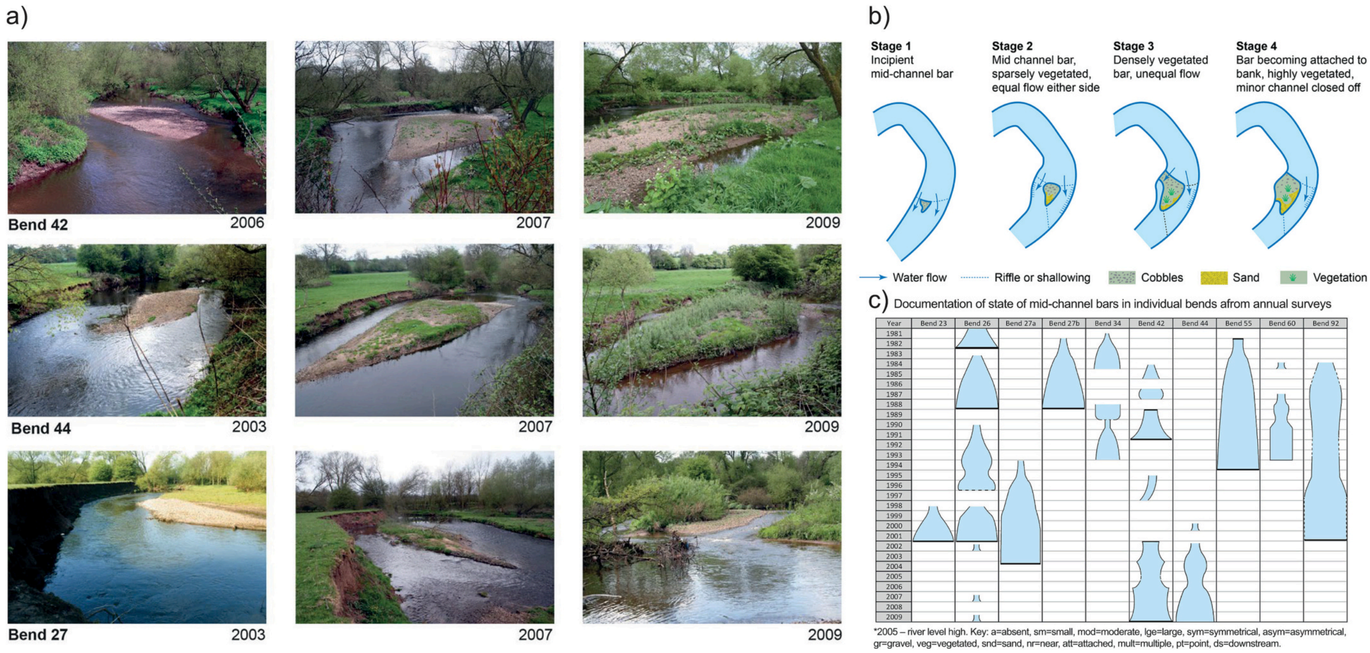


Fig. 8. a) Examples of evolution of mid-channel bars, b) Conceptual model of evolution of mid-channel bars, c) Life-cycle of mid-channel bars on the River Dane (based on Hooke (1986), Hooke and Yorke (2010)).

Fig. 9. Example of a concave bank bar and bench development on the River Bollin, a) Initial circular, sandy bar, April 2010 (from left bank), b) enlarged bar, March 2010 (from right bank, c) attached bar developing into a bench (April 2013). Flow direction and meander movement is from right to left in a) and c) and left to right in b). (Photos by Hooke).

High temporal and spatial variability was evident, with spatial differences related to curvature of bends. In contrast, in an analysis that combined evidence at decreasing timescales, involving tree rings, aerial photos and cross-sectional surveys, Schook et al. (2017) found, that migration rates declined in the two decades after an extreme flood in 1923 on the Powder River. Short-term cross section channel migration was slower than that indicated by the medium-term air photo record and both rates were lower than for the lengthy tree-ring record (Fig. 10). This is the opposite direction of the effect of timescale from that identified by Donovan and Belmont (2019) but peak annual flows decreased by 48 % after the largest flood of the gauged record in 1978 (post-1930), leading to a 53 % reduction in channel width and a 29 % increase in sinuosity over the 1939–2013 period. Schook et al. (2017) consider that the last four decades do not represent the past two centuries. The influence of big floods on the morphology and bend evolution are illustrated in a conceptual model, based on the evidence (Fig. 11d).

Net changes in width over periods of a few years may show large differences but clear relations to various discharge parameters may not emerge, implying a complexity of conditions or challenges of identification of the key discharge characteristics. For example, Hooke (2022) examined width variations in mostly 6-yr periods and found only the relation to number of winter peaks was significant, implying lack of a distinctive controlling effective discharge. The high variability found from event to event and year to year raises the issue of whether the relations are entirely stochastic. Davidson and Eaton (2018) advocate not to use just single discharges for modelling but a stochastic approach, especially for rivers with highly variable flow, pointing out that recurrence interval of formative flow varies with different flow regimes. Moody (2022) is of the opinion, from the Powder River analysis of annual erosion over 40 yr at 23 bank sites, that the processes are not just random but because of complex combinations that produce more predictable results by averaging over time and space. The results from the Rivers Dane and Bollin and other UK rivers concur with this (Hooke, various dates).

2.2. Bend scale

2.2.1. Bend evolution

It is at the individual bend scale that the patterns and rates of evolution emerge, though generally, a period of many years is needed for this to be evident. Thus, much analysis has been based on historical maps, aerial photographs (e.g., Fig. 1) and then, more recently, satellite images. The problem with much of this evidence is that it only gives a snapshot in time and thus the variability in between evidence dates and the processes of the overall bend development are obscured. Greater frequency of satellite imagery is now helping to overcome this and the

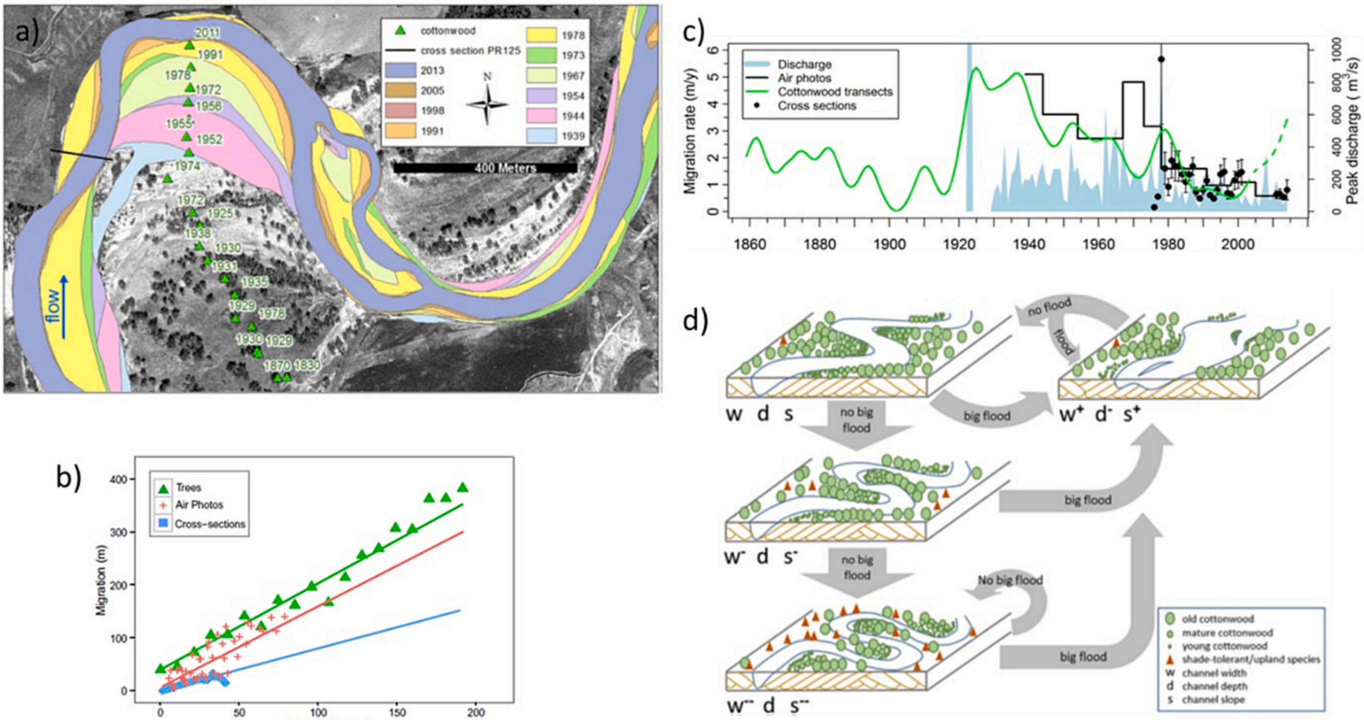


Fig. 10. Analysis of meander evolution over differing timescales on the Powder River, a) An example of the meander development sequence, b) Channel migration rates over the measurement periods for cottonwood transects (1830–2014), air photos (1939–2013) and cross sections (1975–2014), c) Channel migration rates through time derived from the different types of evidence and timescales, d) Conceptual model of the evolution of the Powder River. Changes in channel width (w), depth (d), and slope (s) are relative increases (+) or decreases (−) from that of the baseline sinuous river (Schumm, 1969). (From Schook et al. (2017)).

problem of spatial resolution of data is diminishing, allowing extension to smaller rivers.

The analyses of historical sequences over multi-decadal timescales have revealed the sequences and types of bend evolution on active meanders. Various types of meander movement have been identified in the literature (Hooke, 1984b, Hooke, 2020) such as translation, extension, and rotation. Specific qualitative models of bend evolution have been produced, notably in the work of Brice (1974) and Hickin and Nanson (1975), and the sequence continuing through to cut-off (Hooke and Harvey, 1983; Hooke, 1995b; Hooke and Redmond, 1992) (Fig. 11). The applicability has been evaluated and demonstrated by Hooke (1997) and others on various rivers; examples of the evolution can be seen in Fig. 1. On an Ozark river, four active bend-form movements were identified with proportion of length as follows: extension (8 %), megabar (6 %), cut-off (5 %), and translation (2 %) (Martin and Pavlowsky, 2011.) In the Tibetan Plateau, movement was dominated by extension and translation and their combination, with higher rates in translating bends, but many bends exhibited compound development (Guo et al., 2021). Guo et al. (2019) found that bends in a pristine environment evolve from downstream-skewed low-sinuosity bends to upstream-skewed high-sinuosity bends before cut-off. Analysis of changes on the Dane, in >50 bends from four dates of aerial photos and annual mapping in the period 1984–2007, showed that most bends exhibit morphological change that largely follows the autogenic sequence from low sinuosity curves through growth and migration to simple symmetric and asymmetric bends and then lobe development in the apex region to compound forms (Hooke and Yorke, 2010). The changes were exemplified for one bend on the Dane in which compound development was predicted (Hooke and Harvey, 1983), and that is exactly what happened a few years later (Hooke, 1995b; Hooke and Yorke, 2010) (Fig. 12). Compound development is associated with development of an additional riffle in the apex region and upstream lobing (Hooke and Harvey, 1983; Frothingham and Rhoads, 2003). Engel and Rhoads (2012) made detailed measurements of 3D turbulent flow structures in a compound bend on two dates, 10 yr apart, and examined their relations to morphology, bank erosion and bend evolution. They demonstrate very clearly the development of an upstream and downstream lobe, the patterns of flow and the changes in bed topography as well as bank positions. Slumped blocks have some influence by deflecting flow. Rates of erosion and deposition have been found to be related to both bend form and type of movement (Hooke and Yorke, 2010) (Fig. 13). In another example, Hasanuzzaman et al. (2022) assessed the changing nature of meander movements and meander geometry of Raidak-I River in the Himalayan foothills, West Bengal, using Landsat Imagery 1972–2021 in eight-year periods and field evidence on 12 active river bends. Lateral movements predominated initially, but later, rotational movement became more prominent, considered to indicate increased dynamics (Fig. 14). The changes involved reversal of bank directions but were influenced by human intervention, especially the construction of embankments.

2.2.2. Temporal variation

Analyses of the changes in bend morphology over more detailed timescales also allow insights into the extent to which the changes are continuous or jerky and again the effects of individual events and periods as well as any interference. The extent of trend and consistency in individual bends and the extent to which they are synchronous has been examined on the River Dane using the annual erosion index (Hooke, 2007b, 2008). This shows the high temporal variation and differing patterns over time, with a lack of consistency between bends, even adjacent ones, under the same hydrological conditions (Fig. 15). In many of the bends, activity is not persistent but the phases of activity are not synchronous in relation to discharge events. The degree and phasing of activity partly relates to the morphology and stage of the development of the bend; for example, in Fig. 15, bend 27 is newly developing, Bend 26 stabilises, and bends 58 and 60 were symmetrical, consistently highly

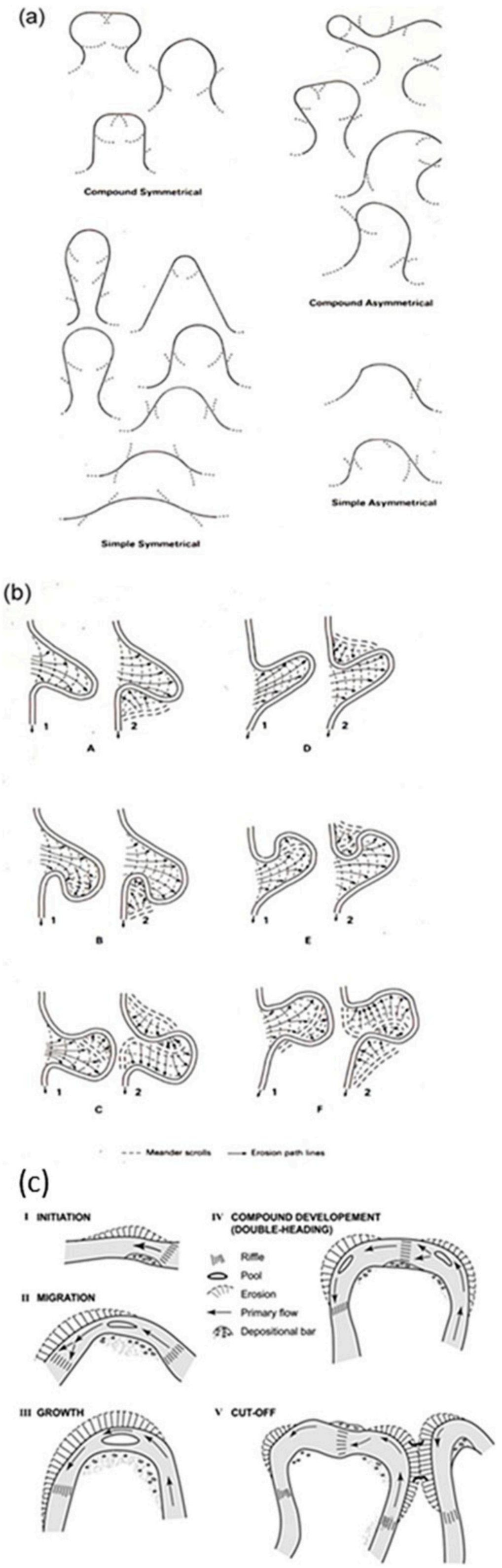


Fig. 11. Models of sequences of meander development. (a) Sequence through from simple symmetric bends to asymmetric and compound (Brice, 1974), (b) Elongation, skewing and compound development, based on meander scroll bar evidence on Canadian rivers (Hickin, 1974), (c) Sequence of migration, growth and compound development through to cut-off, involving development of an additional riffle in apex (Hooke, 1995b).

eroding bends at the time. The mechanisms of morphological change, including formation of bars, are also illustrated for the different types and phases of bend development (Fig. 16). Examination of Bend 40 (Figs. 15 and 16) (Hooke, 2007b) exhibited a phase of multiple and varying bars but then a much less active phase. This may indicate a self-stabilisation, where downstream movement is restricted by bedrock, which may be akin to a process identified by Candel et al. (2020). Thus, the changes take place episodically, in phases that are not simply related to discharge but to inherent, autogenic sequences and feedbacks in development of bars and bend morphology. Overall, systematic planform change emerges but is moderated by spatial variations in channel confinement and boundary features of the valley floor, and by temporal variations associated with discharge events and sequences of conditions. Results of modelling and experiments complement empirical results and have been used to develop understanding of the behaviour of different morphology bends (Frascati and Lanzoni, 2009; Abad and Garcia, 2009; Zolezzi et al., 2009) and effects of width variation (Luchi et al., 2011; Monegaglia et al., 2019), several of these identifying autogenic behaviour within their models.

2.2.3. *Relation to curvature*

Two major questions on meander behaviour and evolution apply at this spatial scale: 1) the relation or rates of meander movement/migration to curvature, and 2) whether the mechanism of bend development is push or pull. Associated with their identification of the sequence of bend evolution, Hickin and Nanson (1975, 1984) and Hickin (1978) produced a curve indicating a non-linear relationship of rate of migration to r/w (radius of curvature/width), with rate increasing as bends tighten through the sequence (Fig. 17a). They applied it to other rivers and Hooke (2003b) then tested it on various streams in the UK and subsequently on other published evidence (Hooke, 2007a), the envelope curve largely exhibiting the hypothesised relation (Fig. 17b). The relationship was also tested in a simple simulation model of Hickin and Nanson's relation of rate vs. curvature (from Ferguson, 1984) but incorporating a lag to curvature and varying resistance, which was found to give a reasonable fit for the River Dane study reach (Hooke, 2003b). Differing types of meander behaviours in relation to curvature and trajectories over time were suggested by Hooke (2003b). The model of increasing complexity and rate increase fit the most active bends, but other types of meander behaviour are recognised, conforming with Brice's (1982) suggestions and typologies Hooke (2007a). Whether the relationship of rate of meander erosion and migration to curvature is non-linear and shows a decrease at low r/w values (high curvature) (Hickin and Nanson, 1975, 1984; Nanson and Hickin, 1983; Nanson and Hickin, 1986) or whether monotonic increase occurs, with rate increasing with curvature as argued by Furbish (1988) and more recently by Sylvester et al. (2019a, 2019b) using evidence from >1600 bends, is an ongoing debate. Hooke and Yorke (2010) and Seminara et al. (2001) maintain there is evidence of acceleration of rate though the growth phase but a slowing during the compound phase of meander development may occur. Hooke and Yorke (2010) also analysed changes in curvature within different types of bend and Fig. 18 shows clearly the increase in length of several bends and the progression of maximum curvature. A range of curvature parameters have been tested (Hooke, 1977, 1987; Hooke and Yorke, 2010). Average rates of erosion in a bend have also been calculated from both areas of erosion in whole bends and linear distances of maximum shift of banklines, showing that rates differ for type of morphology and type of change (Fig. 13) (Hooke and Yorke, 2010). Donovan and Sylvester et al. (2021) suggest that sub-meander bend measurement scales are needed for the analysis and find a near-linear relation rather than the peaked relationship, though this breaks down for low sediment supply conditions. In two meandering rivers in the Qinghai-Tibet Plateau, China, Guo et al. (2021) found the highest migration rate in medium curvature bends but calculation of the average migration rates of bends using bend curvature class intervals indicated a 'quasi-monotonic' relation. Much of the argument about the relationship

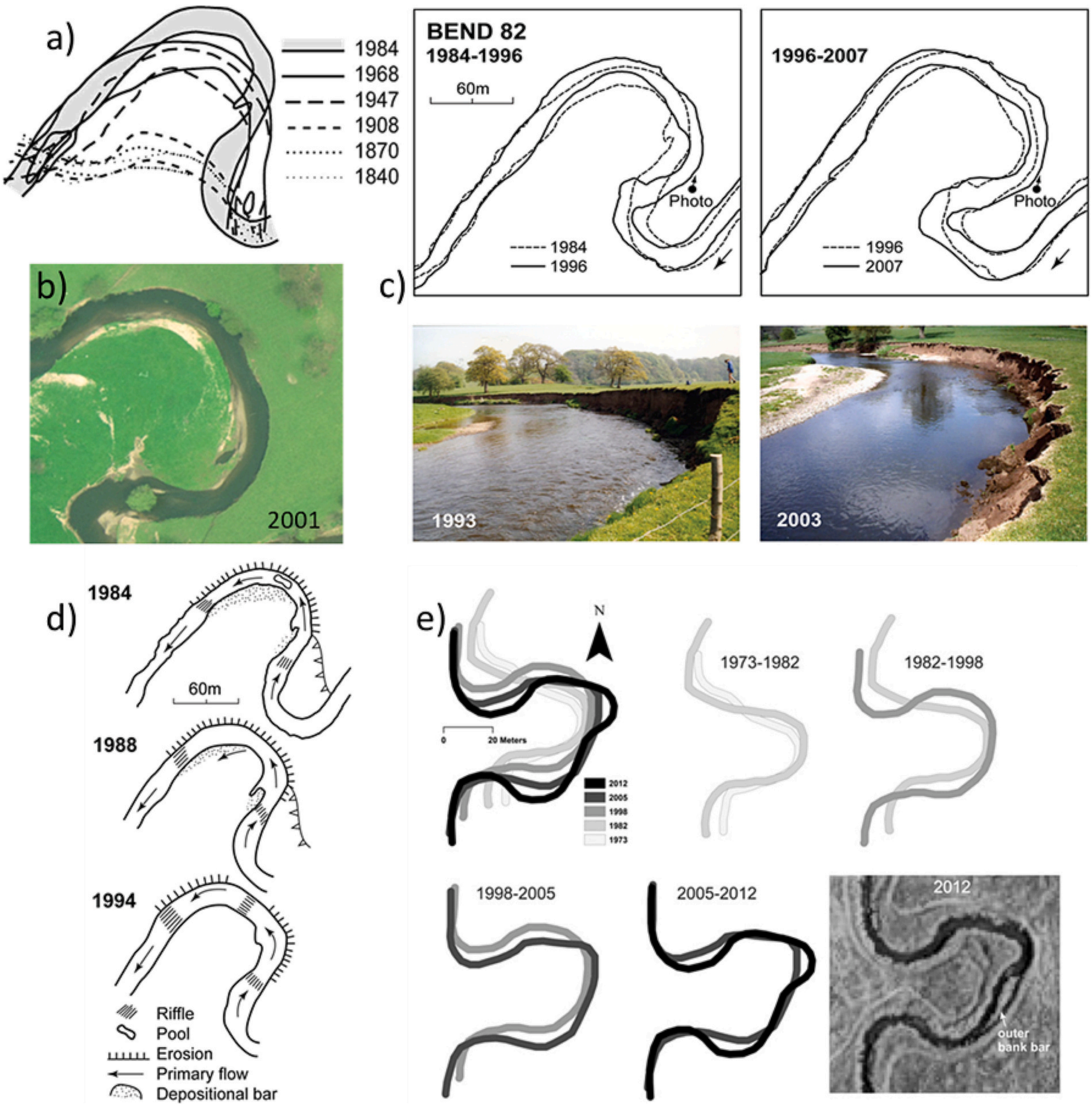


Fig. 12. Development of compound bends, one bend (Bend 82) of the River Dane (Hooke) (a–d) and a bend on the Embarras River, Illinois (e) (Rhoads): a) Historical sequence 1840–1984, b) aerial photo 2001, c) photogrammetric plots from air photos 1984, 1996, 2007, with ground photos of 1983 and 2003, d) Sequence of morphological development, with extra riffle and lobes; e) Evolution of a simple bend into a compound loop with lobes along the Embarras River, Illinois (Rhoads, 2020, Fig. 9. 38).

(summarized in Hooke (2020)) is dependent on the methods used, these varying between use of circles/whole bends and use of link curvature, how many links and whether averaging, and whether lag between curvature and movement is incorporated. The influence of the latter was discussed in a series of papers by Guneralp and Rhoads (2008, 2009, 2010). Finotello et al. (2019) questioned Sylvester et al.'s (2019a) results and analysed them using yet another method. Differences also arise from use of envelope curves compared with statistical relations. There could also be differences in measurements of the rate and whether down-valley or cross-valley. In addition, there may be differing interpretation of the breakdown stages, ultimately leading to cut-off of very tight bends. The important characteristic is the strong evidence of acceleration of rate as the bend develops.

2.2.4. *Push-pull mechanisms*

The push-pull question is whether, in meander movement, erosion tends to take place first (widening) and pulls the bend out or deposition takes place on the concave bank (narrowing) and pushes the meander out. Hooke (1987, 1995a, 1995b) had long ago raised the question of the extent to which each occurred in active meanders. On the active meandering channels studied in the UK, the evidence over extended time periods is that the erosion and widening of bends tends to take place first and deposition then follows, eventually catching up. This is also why maximum rate of erosion in a bend is a useful parameter because it is pulling the bend and having most influence on the morphology. Occurrence of bars has been found to be closely related to gradient (and therefore stream power) and amount of erosion in individual bends (Hooke and Yorke, 2011). The lack of bars in stable sections tends to corroborate the hypothesis that the main source of sediment is the channel itself, with erosion greater in the steeper bends (Hooke, 2003a). Free bars (mcbs) tend to form where widening takes place but then produce feedback, as discussed above. However, Mason

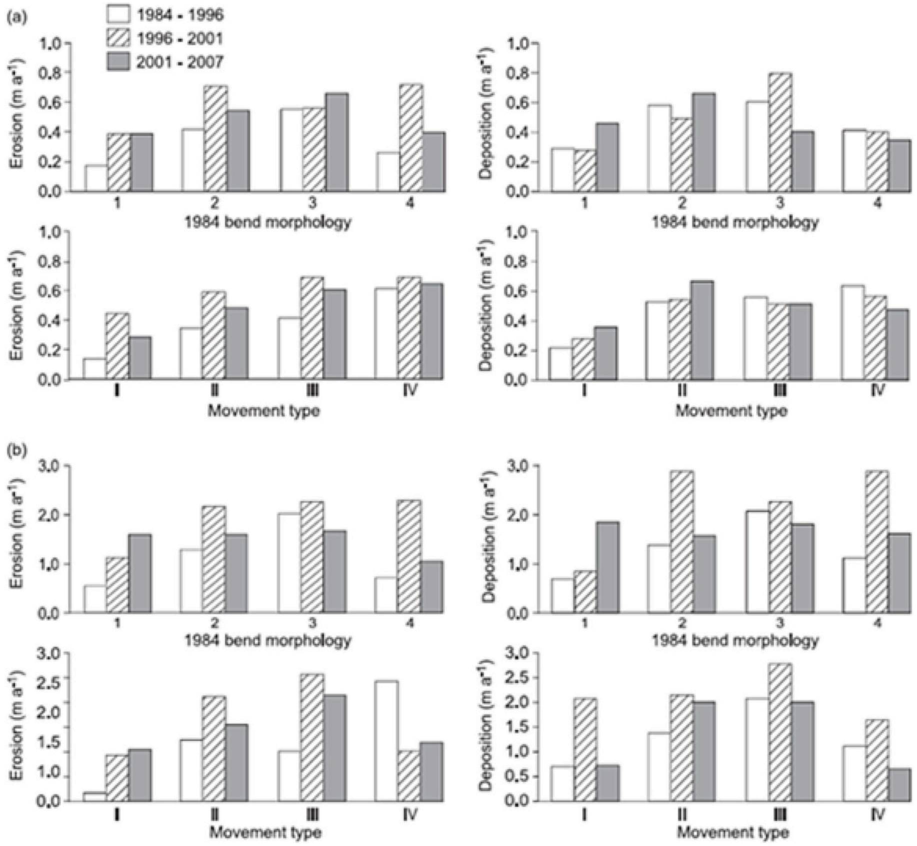


Fig. 13. Mean rates of erosion and deposition of each mapped epoch for all bend sections on the River Dane, classified by 1984 bend morphology (1 = straight/low sinuosity, 2 = simple symmetrical, 3 = simple asymmetrical, 4 = compound) and by type of movement (I = straight/low sinuosity, II = migrating, III = growth, IV = compound lobe development. (a) Rates derived from areal calculations of course changes in GIS; (b) Rates derived from direct linear measurements of maximum bank line shift. (From Hooke and Yorke (2010), Fig. 6).

and Mohrig (2018) revealed spatial variations between zones where bank pull, instigated by large floods, dominated and zones of bar push, produced by deposition. Parker et al. (2011) addressed the push-pull issue in a model of migration incorporating separate relations for eroding and depositing banks, and also effects of slump blocks. Eke et al. (2014a) further developed the modelling of the push-pull morphodynamics and found that the river width reduces slowly over time, but in different phases of opposite banks, eventually producing an asymptotic state. A correlation between local curvature, width and bed elevation in the bend evolution emerged (Eke et al., 2014b). Zhao et al. (2021) modelled the effects of bank collapse (slump block) events on meander evolution, showing the distribution becomes more coherent over time.

2.2.5. *Meander cut-offs*

One particular type of change that has been the focus of much research, because of its major impact on the dynamics of meandering rivers, is that of cut-offs. Most studies have focused on sequences and timescales of processes within the cut-off section, usually over short timescales of a few years. In neck cut-offs, the neck between two bends narrows over time, often at an accelerating rate, and then the river cuts through to create a new straighter channel and an abandoned loop (Fig. 19a) (Gautier et al., 2007). It has been found that the cut-through does not necessarily take place in high flow events but may occur during moderate flow events if the bend neck has narrowed sufficiently (Gautier et al., 2007; Hooke, 1995a). Neck cut-offs may result in a much straighter channel but in other cases a high-curvature bend may be created. Processes immediately following a cut-off tend to be varied in space and time, but a phase of high sedimentation, channel erosion and morphological changes within the main channel has been identified by Hooke (1995a) and Fuller et al. (2003), involving rapid channel widening and formation of bars within the cut zone (Fig. 19b,c). Hooke (1995a) has shown that the sedimentation can be very rapid during or immediately after the cut-off event and continue in succeeding weeks and months. In many of the cases on the Bollin and Dane, the cut-through section later narrows after the first ‘chaotic’ phase of 2–4 yr and gradually stabilises over a longer period (Hooke, 2007a, 2007b).

In the period after cut-off, sedimentation usually takes place within the former channel; the patterns and dynamics of these have been studied in field examples (e.g., Hooke, 1995a; Piégay et al., 2002; Gautier et al., 2007; Constantine et al., 2010a). These sediment plugs form in the upstream entrance to the old channel very quickly, but more slowly downstream, with finer sedimentation in the exit than entrance (Fig. 19b). This sequence has been observed and measured on many more cut-offs on the Bollin and Dane since the conceptual model of fill and development and of exponentially decreasing rate of adjustment proposed by Hooke (1995a). Similar patterns of sedimentation and differences between upstream and downstream have been found by Constantine et al. (2010a) and Piégay et al. (2002). If a high plug forms rapidly at the upstream entrance, then the old channel becomes disconnected from the new main channel section and an oxbow lake is formed. However, in some cases a hydrological connection persists for a much longer time and so sedimentation is carried farther into the former channel; thus, any potential lake becomes infilled more quickly. Angle of bifurcation is a major control on pattern and rate of plug formation (Constantine et al., 2010a; Piégay et al., 2002; Citterio and Piégay, 2009). In low angle bifurcations, less aggradation occurs so more sediment is carried into the old channel, infilling it. In high angle cut-offs, faster aggradation occurs, quickly isolating the former channel, thus producing the oxbow lake. Piégay et al. (2002) demonstrated the high variation in plug characteristics and in rate and pattern of cut-off infill even within one reach of a river; sedimentation characteristics were mainly related to channel geometry and age of cut-off. They are also affected by ecological succession and effects of vegetation on roughness and hydraulics. The sedimentation rate and patterns are influenced by and have feedback effects on overbank flow frequency (Citterio and Piégay, 2009). Li and Gao (2019) found that the cut-off channel widened

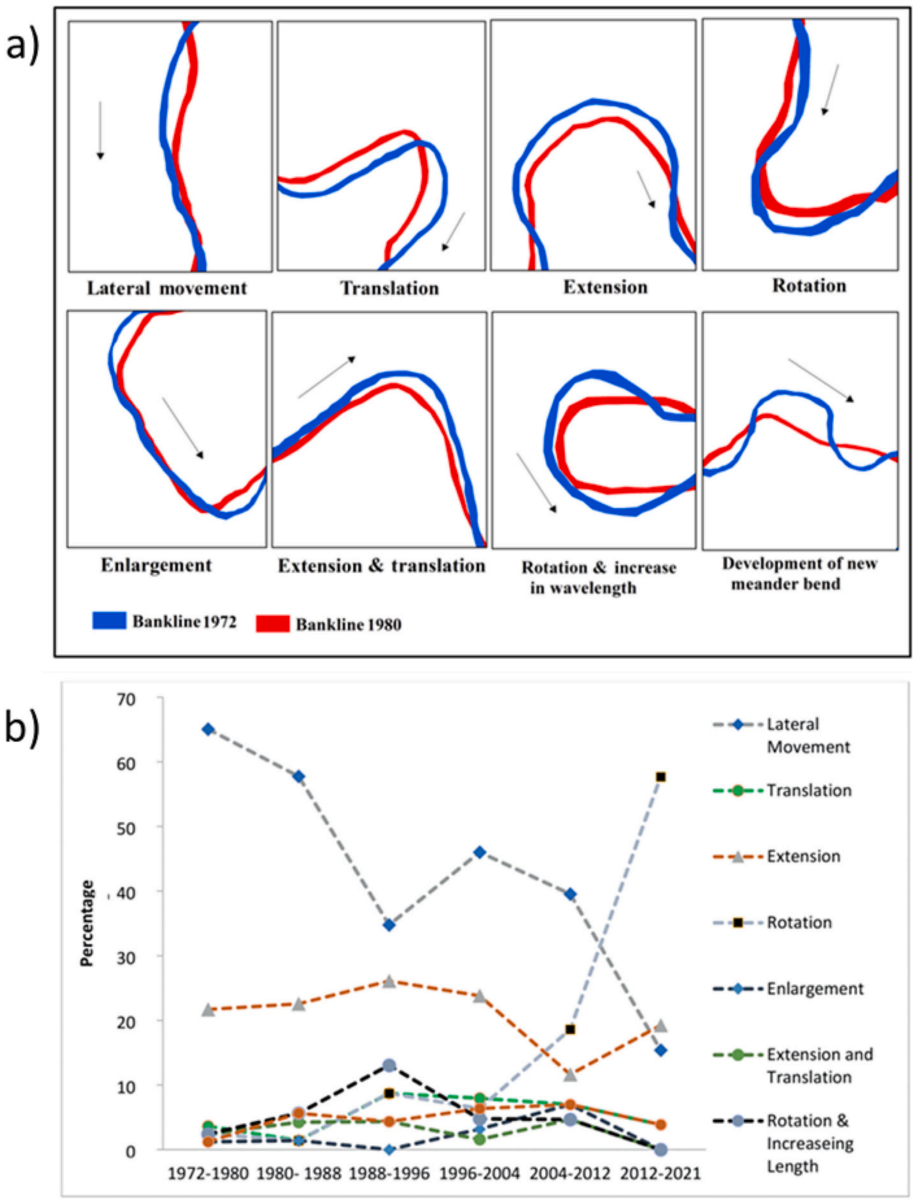


Fig. 14. Meander changes on the Raidak-I River in the Himalayan foothills, West Bengal, a) Different types of meander change, b) The changing nature of meander movements in the period 1972–2021. (From Hasanuzzaman et al. (2022) Fig. 2(a), Fig. 5(b)).

rapidly and the abandoned channel and oxbow lake were quickly disconnected, but the temporal trends and some characteristics differed between two cut-offs studied. The rate of formation of the plug at the entrance is largely attributed to the flow patterns and creation of a separation zone at the entrance. In contrast, some recent research has shown the opposite pattern, with low sedimentation taking place in a high angle diversion (Richards and Konsoer, 2020; Richards et al., 2022). A conceptual model of this sequence (Fig. 19c), based on detailed changes within three high curvature bend cut-offs over three years of measurement was produced (Richards and Konsoer, 2020), (Fig. 19d). They attribute this different pattern, at least partly, to development of a downstream scour hole and movement of flow away from the cut-off entrance (Richards et al., 2022). On the Beni, the functioning of abandoned branches is strongly associated with the mobility of the main channel rather than with flood intensity (Gautier et al., 2007). On the Bollin and Dane some infills have been reworked within a few years, altering the dynamics of flow into the abandoned channel. Overall, the dynamics and rates and patterns of subsequent infill of the abandoned channel vary with angle, bend morphology, main channel mobility, and connectivity to the main channel and its dynamics (Citterio and Piégay, 2009; Konsoer et al., 2016; Li and Gao, 2019).

Chute cut-offs occur across wide meander necks, usually by overflow and erosion of a channel, rather than by bank erosion and channel intersection. Height of floodplain, sediment supply and discharge regime may influence locations of formation. Cut-offs were found to be more frequent in rivers with high sediment load in Amazonia (Constantine et al., 2014). One mechanism of formation is the occurrence of a gully on the downstream side and extension of this headwards to connect the upstream side of a bend, creating a cut-through (Gay et al., 1998). Constantine et al. (2010b) identified that chute cut-offs can take place where an embayment forms on the upstream side of a bend. Similarly, in modelling, van Dijk et al. (2014) found that the morphology just upstream of the channel bifurcation was highly influential on chute cut-off development through the effect on channel curvature and gradient advantage. One control on creation of chute cut-offs is that of vegetation, generally only occurring where the floodplain is light, grassland vegetation. Denser vegetation appears to prevent chute formation (Constantine et al., 2010b).

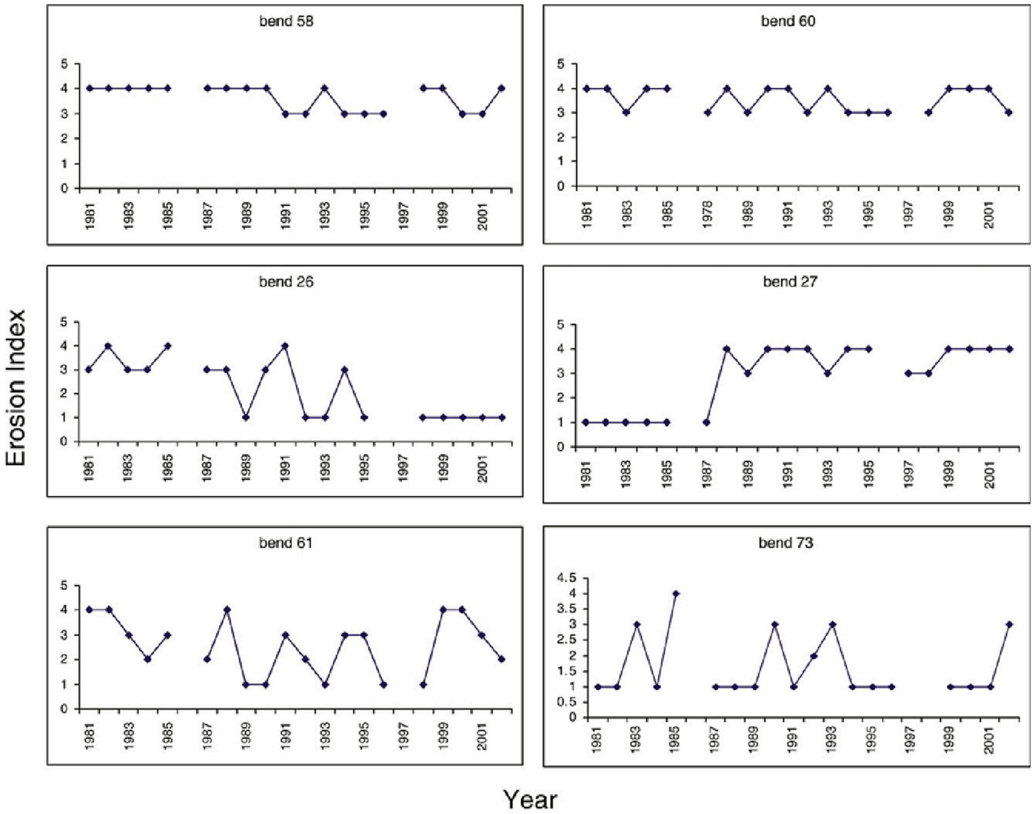


Fig. 15. Variation in erosion intensity over time for different bends, River Dane. (From Hooke (2008), Fig. 5).

In examples of chute cut-offs, Zinger et al. (2011, 2013) showed that sediment eroded within the cut-off was deposited immediately downstream. On three large, sand-bed tropical meandering rivers, the Strickland, Lower Paraguay and Beni, the probability of chute formation in a meander bend was found to be a function of the bend extension rate (Grenfell et al., 2012). In a very different environment, that of an ephemeral channel in Bolivia, Li et al. (2020a) suggest that chute cut-offs are driven by flood events occurring more than once per year and spatial occurrence is again related to increase in bend amplitude. Deposition at the upstream end in overbank flow plays an important role in the chute cut-off development. In the Bolivian channel, more rapid bend migration and clusters of chute cut-offs may be associated with episodic La Nina-driven flood events. Modelling has also been used to address the dynamics of cut-offs, demonstrating the effects of particular conditions (van Dijk et al., 2014, Schwenk et al., 2015, Weisscher et al., 2019, Li et al., 2022, Pannone and De Vincenzo, 2022). Floodplain elevation, sediment composition, and the presence of vegetation emerge as important controls.

2.3. Reach scale

2.3.1. Spatial and temporal variation

Examination of the kind of evidence analysed at bend scale can be applied to spatial sequences of several bends, enabling identification of the extent to which bends under the same hydrological conditions may exhibit synchronous trends or behave differently over time, as well as the extent of spatially variability within a reach. Such analyses are often at decadal timescales. Analysis is being extended to an increasing range of rivers; for example, Debnath et al. (2022) showed decrease in width and sinuosity over the period 1932–2017 on the River Manu in north-eastern India. On the Lower Deduru Oya (River) in Sri Lanka, bend curvatures and migration rates have increased over the past three decades (Basnayaka et al., 2022), and in Ethiopia Mulatu et al. (2018) found decreases in sediment transport capacity, leading to avulsions, mainly caused by multiple human interventions.

The historical analysis of meander dynamics in reaches over decadal timescales has shown that rates of development may vary spatially (Hooke, 2013, 2020). Stable sections or bends may be adjunct to very active bends, as exemplified in maps of historical sequences of change (e.g., Fig. 1) (Hooke, 2007b). At reach scale, annual monitoring of the intensity of erosion and deposition in each bend on the Bollin in the period 2001–2021 (Fig. 20) indicates a persistent higher rate of activity in some bends than others over time. However, these are not entirely the same bends for both processes, implying some differential change in width and form (Hooke, 2022). The role of mcbs (mid-channel bars) in the meander dynamics is also demonstrated. Overall, the sinuosity of the reach has been increasing since the major cut-offs of 2001, mainly by development of small new bends, rather than growth, as expected. Similarly, on the Dane, differences in erosion intensity between bends over the period 1981–2002 are apparent but the zones of high activity tend to remain the same, though intensity varies year to year (Fig. 21). Occasionally bends stabilise or zones of new activity develop. Similarly, on the Powder River in Montana, USA, the location and occurrence of bank erosion was extremely variable spatially and temporally year to year, with erosion maxima varying in position and being unsynchronized between bends (Moody, 2022). Averaging in reaches and over time tends to produce more systematic relationships as shown in measurements of widths, rates of erosion and erosion activity and their relation to discharge parameters (Fig. 22). Overall, this implies an adjustment and sensitivity on timescales of both a few years and annually (Hooke, 2012). Average annual maximum migration rate of erosion for the reach was modelled proportionally to peak discharge for the period 1984–1996, then this model tested against actual erosion/bankline movement for the period 1997–2002 and found to reproduce 76–87 % of the variation.

2.3.2. Spatial propagation of change

A key question on meander morphodynamics is the extent to which

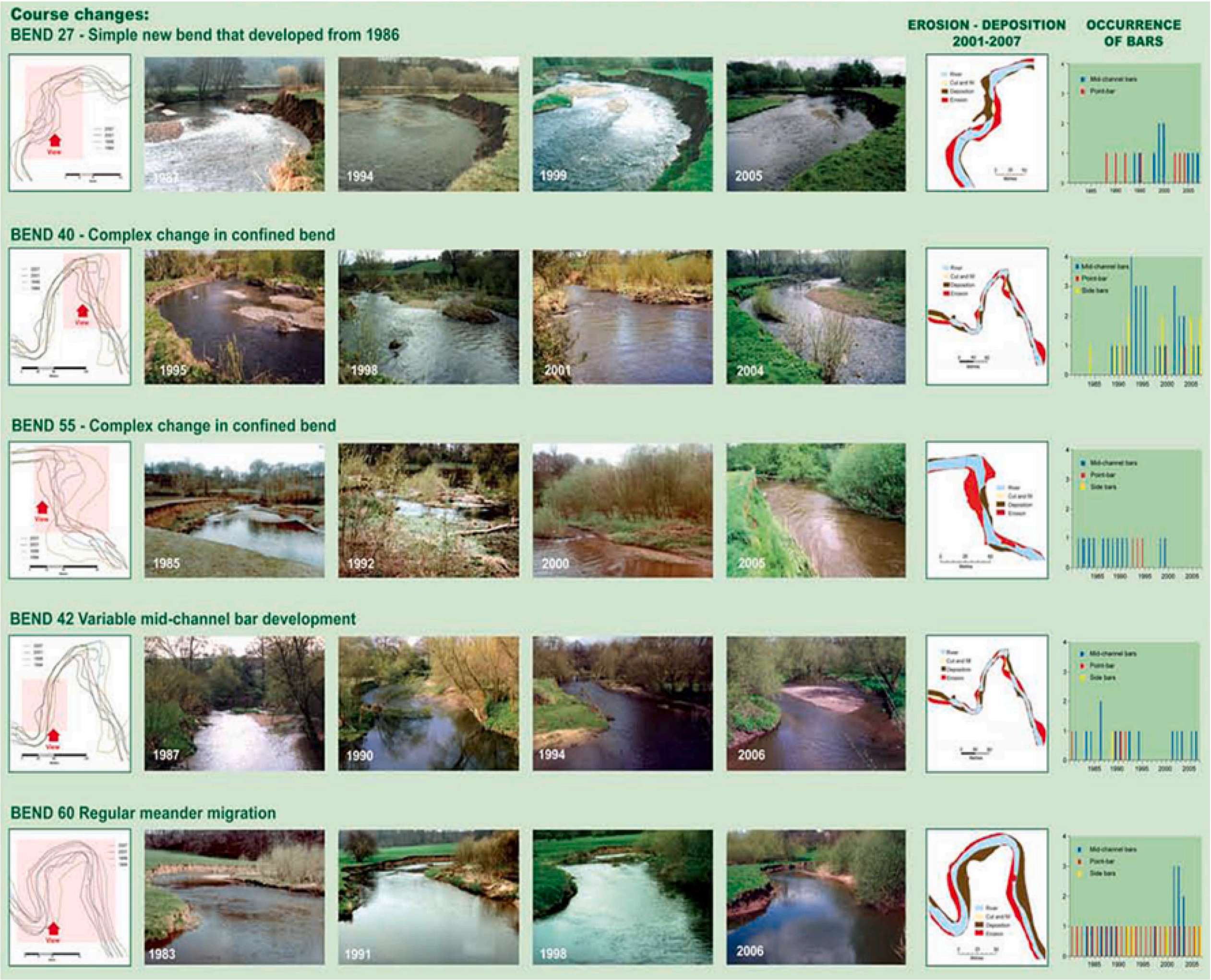


Fig. 16. Examples of evolution of bends of different types or stage, River Dane. (Partly based on Hooke and Yorke (2010, 2011)).

changes are propagated from bend to bend and through reaches. The analysis of cut-offs, above, begins to relate to this but the analysis is often only for the immediate upstream and downstream bends or sections. What emerges from contrasts of degree and type of change in adjacent bends on the Dane is that changes in individual bends may be quite localised (Hooke, 2007b). Lotsari et al. (2014) also found that changes are not propagated. This has implications for connectivity and systems analysis, the lack of propagation and the variation in occurrence of bars implying localised sediment sources (Hooke, 2003a). In several cases of cut-offs, obvious effects of a significant shortening of the course locally was limited in extent both upstream or downstream, for many years, once the initial phase of instability within the cut-through channel was completed (Hooke, 2007b). On the other hand, cut-off occurrence can have an important role to play in transmission of changes and overall planform evolution. A question is the length of reach and the time it takes for the effects to be transmitted. Micheli and Larsen (2011) studied channel migration and cut-offs on a 160 km meandering alluvial reach of the Sacramento River and identified 27 chute and 11 partial cut-offs occurred between 1904 and 1997 (averaging one cut-off approximately every 2.5 yr or 0.0029 cut-offs per kilometre per year). They attribute 20 % of the total floodplain area change between successive centrelines to cut-offs but most of the other change was caused by meander migration. Cut-off can be a major process by which an apparent dynamic equilibrium condition may be maintained, as shown for the Ucayali in which cut-offs occur in erosional phases and increased migration rates occur in depositional phases (Abad et al., 2012). However, Schwenk et al. (2017) later showed multiscale spatial and temporal variability on the same river, caused in part by variation in local inputs of sediment, cut-offs, and climate, which led to decadal trends in processes, migration rates, and channel widths. Cut-offs can act as perturbations that non-locally accelerate river migration and drive channel widening both upstream and downstream of the cut-off locations (Schwenk and Foufoula-Georgiou, 2016) producing "avalanche"-type behaviour in clustering of cut-offs. Adams (2020), in considering morphodynamics of gravel-bed rivers more generally, points out that reach averaging hides morphodynamics and that modelling without feedbacks suppresses certain effects and may not replicate the morphodynamics that typically occur in field conditions.

2.3.3. *Thresholds, equilibrium and recovery*

In some situations, it has been demonstrated that a clustering of changes and transformation of patterns can occur, as in Schwenk and Foufoula-Georgiou's (2016) study. A major transformation of the River Bollin took place in 2000–2001, with multiple cut-offs in a highly sinuous 500 m channel reach (Fig. 23). A major question posed was the extent to which this was caused by the occurrence of flow conditions or the extent to which it was caused by autogenic changes in the bends, conditioning the meander forms such that major changes would have taken place anyway (Hooke, 2004). Continuous increase in sinuosity had taken place over the historical period since 1840, reaching a value of 2.92 by 1970 (Fig. 23d). The period 1998–2001 was a phase of particularly frequent and high peak discharges but it has been argued that the

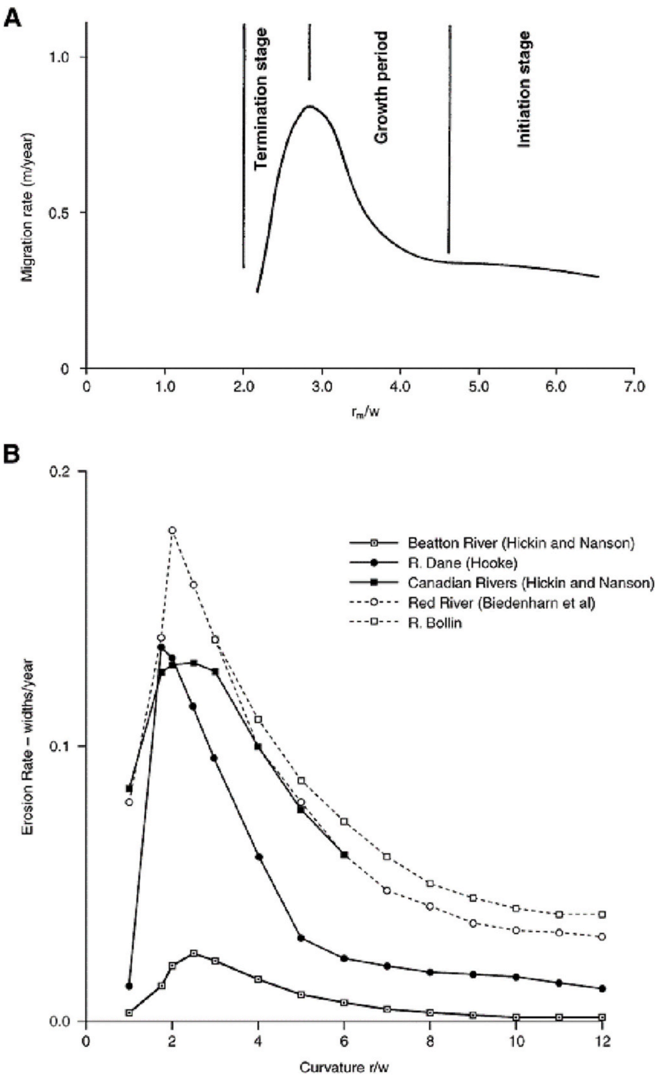


Fig. 17. a) Model of non-linear relationship and stages of change in meander evolution (Hickin, 1978), b) Compilation of plots of relationships between rate of meander movement and curvature (Hooke, 1997). (From Hooke (2003b), Fig. 8).

transformation took place in an avalanche type action because the sinuosity and bend curvatures were in a critical state such that they were going to cut-off anyway (Hooke, 2004). This argument is supported by the evidence from the River Dane in which a comparable pattern of peak discharges did not produce cut-offs, but the river had lower sinuosity and few very tightly curved bends at the time. This avalanche behaviour was recognised by Stolum (1996, 1998). Transformation and sudden changes of pattern can indicate that a geomorphic threshold (Schumm, 1979) or tipping point has been reached and that this process is autogenic. Gautier et al. (2007) also found a clustering of cut-offs on the Beni River, which they explain as autogenic behaviour. Ielpi et al. (2021) use the occurrence of 227 cut-offs in 25 yr on the Humboldt River (Nevada) to examine the distances between adjacent cut-offs and understand the mechanisms governing their clustering. They conclude that both local and nonlocal perturbations together trigger the clustering of new cut-offs, over distances limited by the backwater length and over yearly to decadal timescales. Some chute cut-offs were associated with upstream bend skewness. Paola (2016) considers autogenic influence may have been underestimated previously compared with allogenic responses and demonstrates that the two interact.

The occurrence of sudden changes, either from extreme events/ conditions or crossing of thresholds/ tipping points, raises the question of the extent to which recovery is apparent or whether a new equilibrium state develops. It may be that no equilibrium/steady state is apparent, rather continuous change prevails. This is difficult to detect because often it is accompanied by allogenic changes in inputs. Even without such changes the sequence of discharge events and conditions, combined with their feedback effects, may influence the trajectory and rate of 'recovery'. Lack of sufficient time between disturbance events such that transience is produced has long been recognised (Brunsden and Thornes, 1979) and many case studies on a variety of types of rivers have addressed these questions (Rhoads, 2020). Active meandering channels tend to be highly sensitive and exhibit high degrees of transience but even on these channels the challenge is obtaining the evidence over enough examples to identify the time periods and the controls. Hooke (2022) predicted some recovery after the series of cut-offs on the Bollin in 2001 but it did not occur quite as expected, though sinuosity increased (Fig. 23). Individual bends did not show the anticipated increase in rates. It is suggested this was because of the sequence of events, with some periods of lesser flow in which banks stabilized, vegetation increased and erosion decreased, thus also decreasing local sediment supply. Increase in vegetation has been demonstrated on the neighbouring River Dane (Hooke and Chen, 2016), though the increase on the Bollin is later and less marked. On an upland stream Milan and Schwendel (2021) found that, following an extreme flood in 2007 on Thinhope Burn, shear stresses were increased and recovery was not complete even 14 yr later.

The stability of widths and of rates over longer periods has been taken as evidence of a tendency towards a steady state or equilibrium but the period needed to exhibit or attain this varies. As shown in these examples, an apparent steady state and equilibrium may be misleading and caused by spatial and temporal averaging. However, adjustment to changes in effective discharges are more readily detectable and have commonly been identified in responses to allogenic alteration. These have been much analysed at reach scale and over decades in relation to effects of deliberate and narrowly-timed modifications of discharge regime and/or sediment supply, for example, in cases of dam construction (e.g., Magdaleno and Fernandez-Yuste, 2011; Legleiter, 2015; Garcia-Martinez and Rinaldi, 2022). Much research is ongoing into response of the Yangtze to the Three Gorges Dam (e.g., Lin et al., 2019). Responses to other changes in discharge have been identified; for example, extreme floods on the Squamish River, British Columbia, increased in magnitude, volume and duration, 1956–2007 (Bauch and Hickin, 2011). The rate of channel change accelerated through the 1980s–1990s, with erosion greater than deposition. Response in geometry was not uniform even though meanders straightened. Over the longer-term, some analysis has related such periodic variations to clustering of forcing events, with some causation attributed to major climatic fluctuations associated with El Nino or NAO variations (e.g., Suizu and Nanson, 2018). A strong tendency to variations over periods of a few decades has long been recognised, especially in drier environments, for example on the Gila in the SW USA (Hooke, 1996) and on Australian rivers (Warner, 1987). Now, anthropogenic climate change is superimposed on this but distinguishing clear trends from the complex patterns revealed by meandering channels is challenging as yet. The persistence of recent highly variable periods and extreme events remains to be seen but the response of active meandering rivers, which tend to be highly sensitive and responsive, needs to be carefully monitored. This is of vital importance in predicting impacts of climate change, the degree of variability in process, width and channel position, and the timescale of such variability.

2.3.4. Timescales of bend and floodplain turnover

By analysis of many bends in a reach and comparison between reaches and between rivers then the extent of an overall pattern of evolution of bends becomes apparent. Degree of autogenesis and consistency can be assessed and the fit to evolutionary models evaluated. It is

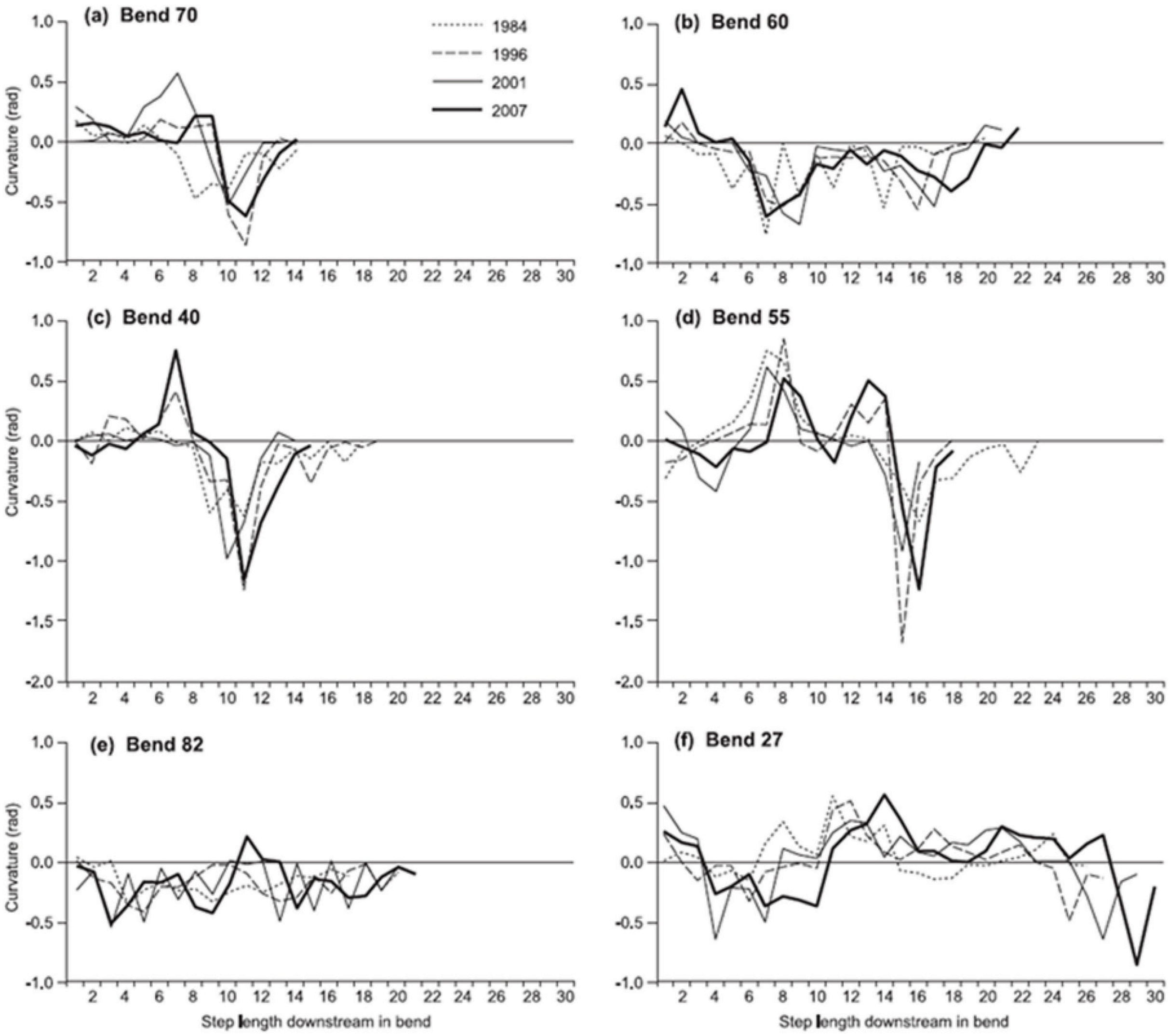


Fig. 18. Examples of curvature distributions for individual bends for four mapped dates, 1984, 1996, 2001 and 2007, River Dane. (a) Bend 70 – simple migrating and developing bend; (b) Bend 60 – large, migrating and growing bend; (c) Bend 40 – sharp-angle, rotating bend; (d) Bend 55 –sharp-angle, rotating bend; (e) Bend 82 – large, simple, growth bend that has become compound; (f) Large migrating bend with new, rapid growth loop on upstream limb. (From Hooke and Yorke, 2010, Fig. 4).

concluded that a high degree of autogenesis is evident in the behaviour of the most active meanders. Timescale for full sequence will vary from reach to reach and river to river, depending mainly on resistance factors, thresholds and occurrence of effective events. Questions arise of rapidity of turnover of bends and reworking of floodplains, for example, on the timescales of meander development in the multiple traces seen in many lowland, particularly tropical, rivers. Whether the evidence of high morphodynamics is caused by rapidity of meander development or to long timescales without major incision and alteration of loads needs further investigation. Likewise, are tortuous but now inactive rivers the product of rapid development then stabilisation or slow development over a long time (Hooke, 2003b, 2007a)? Candel et al. (2020) have recently proposed that a process of self-constraining of low-energy rivers explains low channel mobility yet tortuous planforms. Hooke (2007a) and others have posed the question in relation to bedrock meanders where compound morphology can be seen. Some timescales for bend evolution and floodplain turnover have been identified (Table 1) revealing some similarities of timescales of bend development even on rivers of vastly differing size. Similarly, the reworking or overturning of the floodplain varies considerably in timescale, even within the same region (e.g., Amazonia, Table 1).

2.4. Controls on meander morphodynamics

Major controls on morphodynamics of meanders at reach scale and between rivers include stream power. Much research has shown that the degree of activeness depends on stream power, which in turn relates to discharge magnitudes and gradient (relief), so settings within and between rivers are.

very important. Discharge is the major scaling factor of activity, though questions arise such as which are the key parameters, as demonstrated earlier. Spatial variability of channel migration rates in the Rhone Basin, France, were primarily explained by the gross stream power, but also scaled with drainage basin area (Alber and Piegay, 2017). Guo et al. (2021) compared two rivers in the same region and found the differences in meander behaviours were caused by gradient and discharge, i.e., stream power. They compare published values of scaled rates of mean and maximum migration in different hydrogeomorphological settings. Grenfell et al. (2012) found chute dynamics related to stream power in different rivers. Gradient strongly influences stream power and therefore overall behaviour of rivers, but in meandering rivers it may also have an influence at more local scale. For example, Hooke analysed the relationship of each bend to gradient on the River Dane (Hooke and Harvey, 1983; Hooke, 1984a) and found that

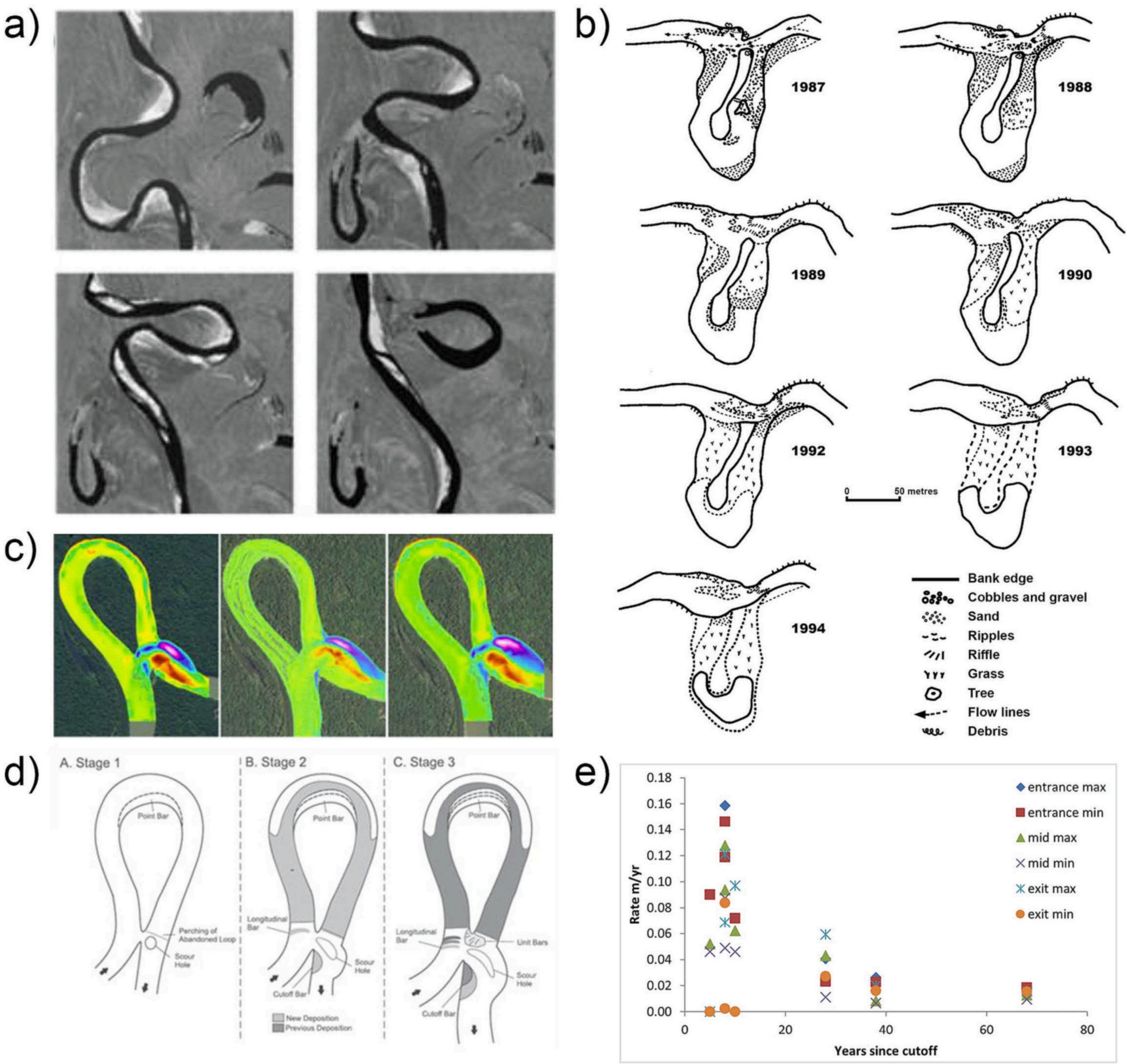


Fig. 19. Evolution of cut-offs and oxbow lakes. A) Examples from the Rio Beni, Amazonia (Gautier et al., 2007, Fig. 13), b) Stages of development immediately after neck cut-off, R Dane (Hooke, 1995a, Fig. 7), c) Example of stages after cut-off, White River, Arkansas (Richards and Konsoer, 2020, Fig. 5), d) Conceptual model of neck cut-off development, based on the White River, Arkansas (Richards and Konsoer, 2020, Fig. 14) e) Rate of infill of entrance and exit of cut-off (Hooke, ICG poster 2013).

bends exhibiting growth had higher gradient than those migrating. The stable reaches had lower gradients. The occurrence of mcbs is closely related to steeper bends (and widening because of higher stream power) and sections with bars were found to be near Leopold and Wolman's (1957) threshold for braiding (Hooke, 1986).

Valley confinement also has a profound influence on meander activity. Nicoll and Hickin (2010) report that confined meanders in Taiwan do not develop cut-offs and that migration rate is most closely related to stream power. In contrasting two cohesive channels in Ottawa, Parsapour-Moghaddam and Rennie (2018) found the unconfined sub-reach has a typical channel migration pattern of outer bank erosion and inner bank deposition whereas in the confined sub-reach, bank instabilities were greater and had an irregular meandering pattern development. Joyce et al. (2020) showed that meanders are more stable in confined sections at the upstream ends of basins.

A major control on meander morphology and dynamics is that of sediment supply. Dingle et al. (2019), in a decadal-scale study of morphological adjustment of a lowland tropical river in the Philippines, indicate that sediment transport and deposition are key drivers of the observed tropical channel morphodynamics in that region. They suggest that lateral migration rates of tropical rivers are typically greater than those of temperate rivers. In the Amazon, rivers with high sediment loads were found to exhibit higher annual migration rates than those of rivers with lower sediment loads and meander cut-offs were also more frequent (Constantine et al., 2014). Furthermore, sinuosity increases more rapidly in higher sediment load rivers in the region, especially in downstream-rotating meanders, which establish large point bars (Ahmed et al., 2019). Donovan et al. (2021) consider that sediment

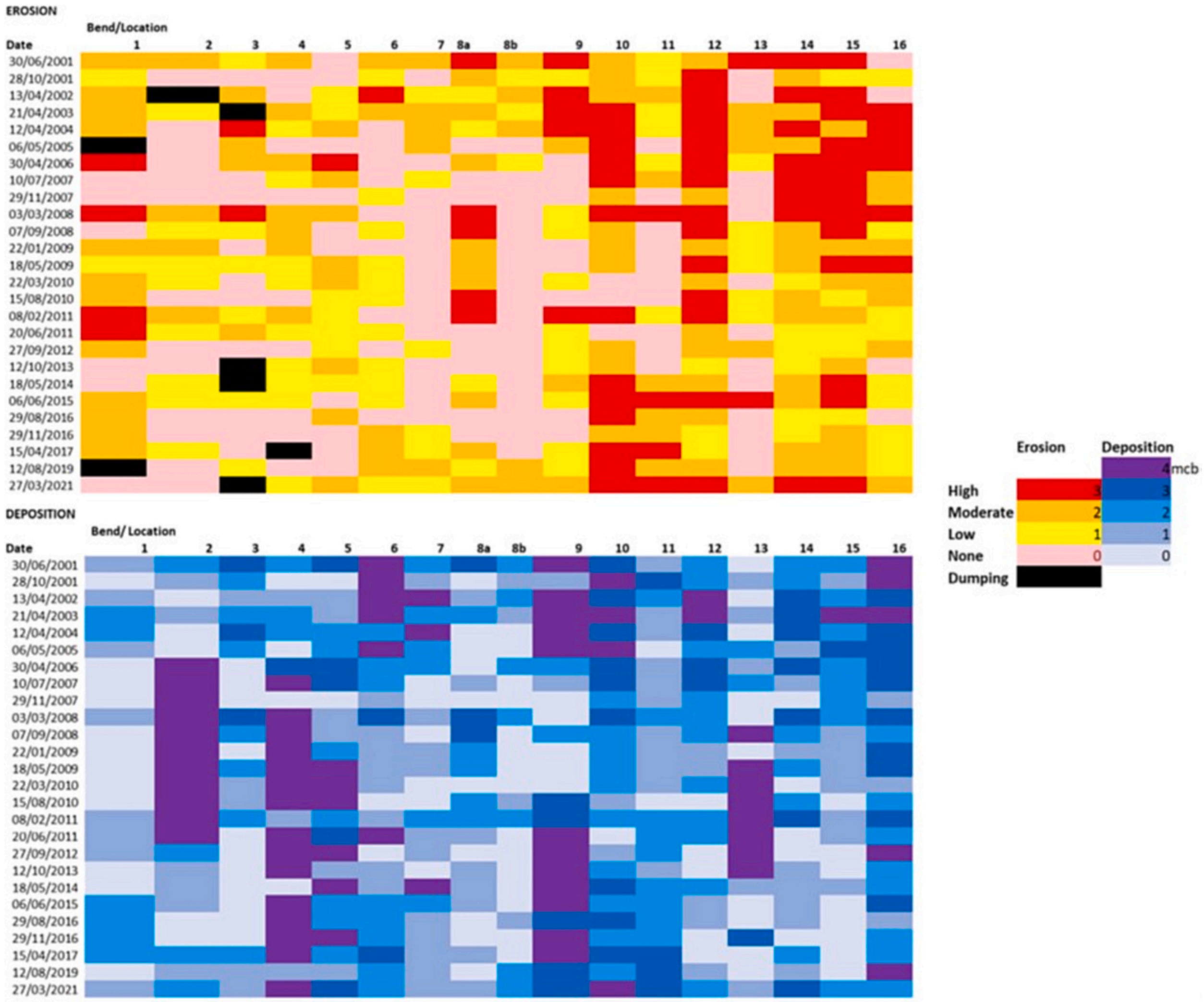


Fig. 20. Index of erosion and deposition at each bend at each survey date on study reach of the River Bollin, NW England. In erosion, black is occurrence of dumping of rubble on the bank. Purple in deposition indicates a mid-channel bar, with much deposition. (From Hooke, 2022, Fig. 8).

supply drives migration, though they suggest that the migration–curvature relationship breaks down under low sediment supply. The situation may be rather different in some smaller rivers, especially gravel-bed rivers and those with higher bedload. Evidence increasingly indicates the importance of the channel sources in fluvial systems (e.g., Al-Ghorani et al., 2021; Hughes et al., 2022). Once sediment is supplied from bank erosion then this provides material for bars and sedimentation. This relates to the issue of connectivity and the close association of mobility of meanders to occurrence of erosion and bars (Hooke, 2003a).

By comparing a series of bends in a reach experiencing the same hydrological conditions, spatial factors of control can be identified. Curvature has been shown to be a strong control, as indicated earlier, but questions arise of cause and effect and of feedbacks. The evidence is that once curvature develops then erosion and migration are enhanced and accelerate, hence the contrast in the stability of straight sections and more sinuous ones However, differences in resistance may explain much spatial variation. It has long been recognised that heterogeneity of bank material, such as from clay plugs in meander cut-offs, can alter rates and morphology of adjacent meanders (Fisk, 1944). Guneralp and Rhoads (2011) advocated that resistance of materials needs to be in models and several models recognise that (e.g., Motta et al., 2012, da Silva and Ebrahimi, 2017) but Schwendel et al. (2015) were still saying that few researchers have quantified the feedbacks. They demonstrated that the presence of clay-rich floodplain deposits on the Rio Beni produces reduction in channel migration rates and styles of channel evolution that include straightening and narrowing (Fig. 24). Similarly, others have shown the effects on migration rates and morphology (e.g., Bogoni et al., 2017; Wolfert and Maas, 2007). Konsuer et al. (2016) acknowledge that much research has shown the effects of variability of resistance of material on meander dynamics for small streams but consider large rivers are underrepresented (though the first notable paper on this subject was for the Mississippi (Fisk, 1944)). They made detailed measurements of sediment resistance and of vegetation cover and properties such as root strength and identify considerable variability both within and between bends. Material included bedrock outcrops. In large rivers the vertical heterogeneity is also important. Once material fails from bank erosion, blocks can be left at the base of the bank and this can then add resistance, particularly if they can become stabilized by vegetation, and thus affect flow patterns (Rhoads, 2020).

Arguments have also been made about the role of vegetation, including whether it is necessary for meandering (Tal and Paola, 2007; Braudrick et al., 2009; Kleinhans et al., 2018; Rhoads, 2020). Santos et al. (2019) questioned whether meandering develops in deserts and found that it does, as had Billi et al. (2018), exhibiting a range of morphology. Likewise, on ephemeral rivers in the hyperarid environment of the middle Tarim River, northwestern China, Li et al. (2017) found the planform attributes of that meandering river are similar to those found in other environments and that migration and cut-offs

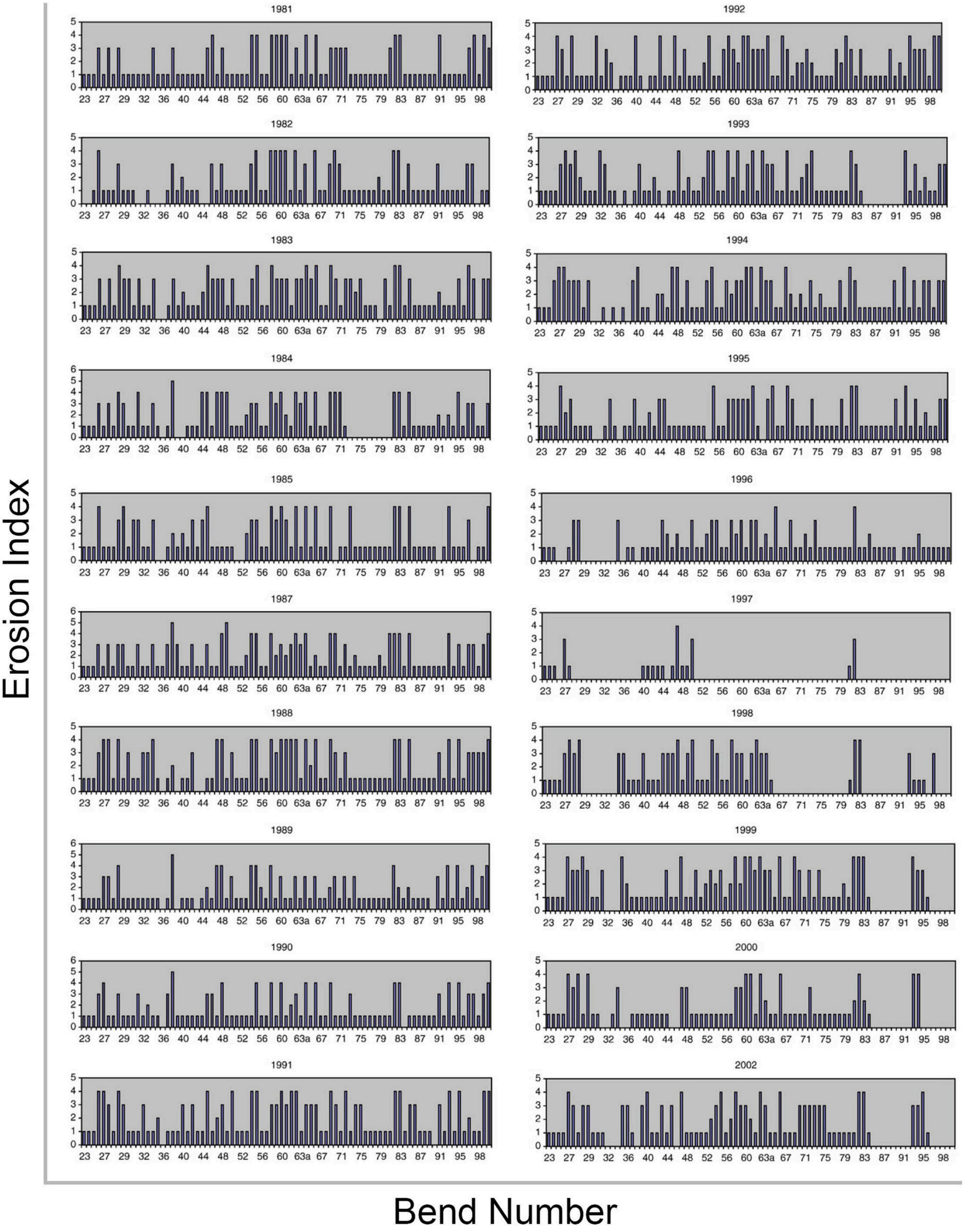


Fig. 21. Occurrence of erosion in each bend in each year, 1981–2002, in the River Dane study reach, coded by intensity of erosion (0 = no observation, 1 = stable, 2 = slight, 3 = moderate, 4 = severe, 5 = cut-off). (From Hooke, 2007b, Fig. 5).

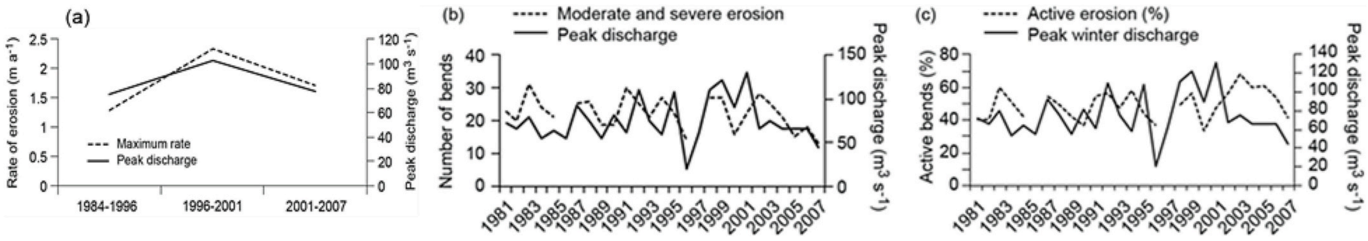


Fig. 22. Erosion activity on the study reach of the River Dane, a) Mean maximum erosion rate and mean annual peak discharge in each epoch of measurement from aerial photographs, b) number of bends with moderate and severe erosion, and (c) % active bends, in relation to peak winter discharge. (From Hooke, 2012, Figs. 3 and 4).

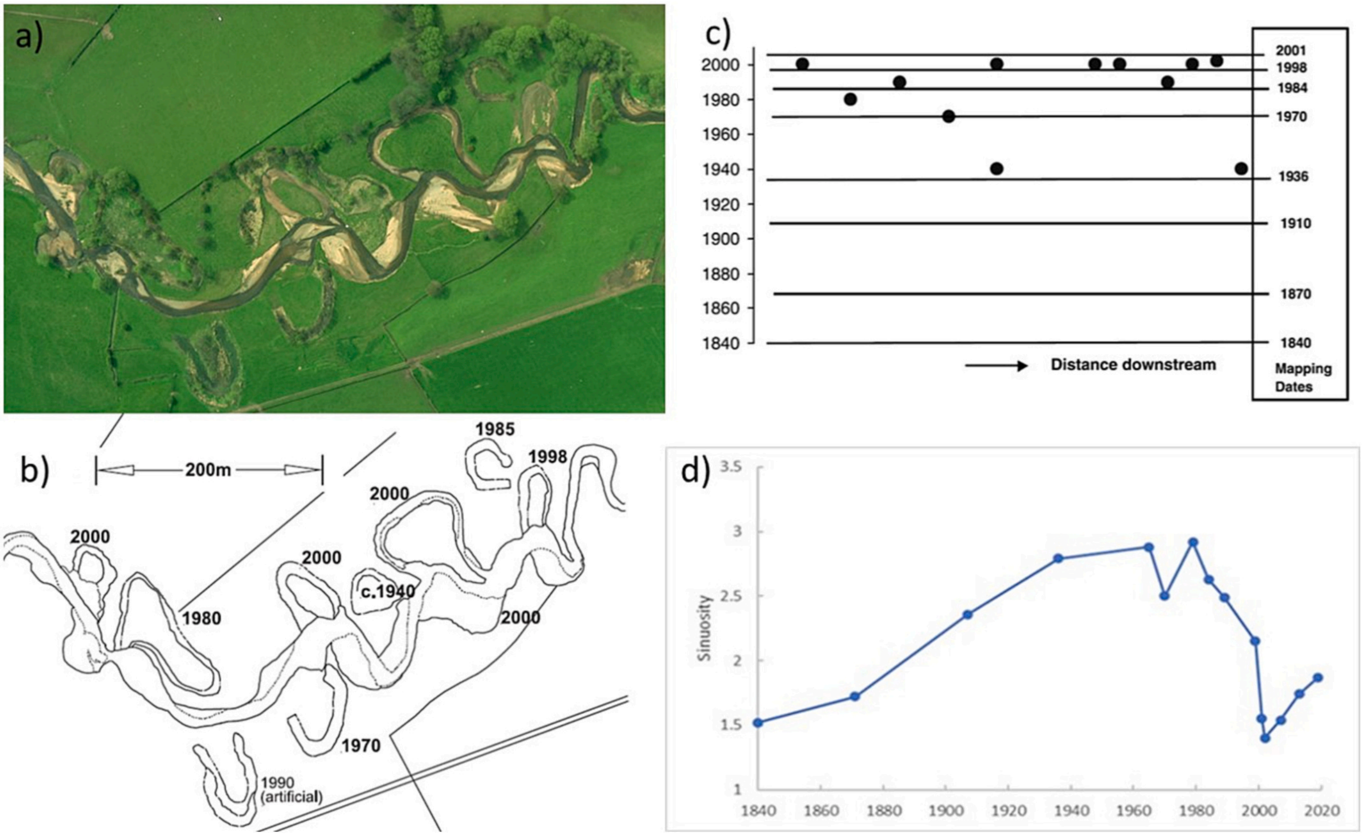


Fig. 23. Cut-offs on the study reach of the River Bollin. a) Aerial photograph of the reach in 2001, b) dates of cut-offs in the reach, c) dates and distribution of cut-offs, d) changes in sinuosity over time. (Based on Hooke, 2003b, 2004, 2022).

occurred. In the sparsely vegetated environment of Iceland, Ielpi (2017) showed well-developed point bars were present and concluded that vegetation was not a major control, rather that stronger controls were from discharge regime and alluvial morphology on sinuous rivers. The important stabilising role of vegetation has been demonstrated in restoration of meandering (e.g., Vargas-Luna et al., 2018).

Most research indicates that presence of vegetation at scales from individual trees or patches within bends to differences between different fluvial environments, increases resistance and slows down activity. Quantification of vegetation effects is challenging but modelling indicated that presence of trees doubles the cohesive strength of the material alone on banks of the Wabash River (Konsuer et al., 2016). Trimble (2004) debated whether grass-covered banks were more resistant than forested banks. Individual trees can often produce a lobing type effect from increased resistance locally for a time but then can take more material when the resistance is overcome and it falls. Likewise, the effects of cattle grazing are debated (Trimble and Mendel, 1995). Rates of erosion and meander mobility are often higher in pasture (Micheli et al., 2004). Stable reaches are often tree-lined (Hooke and Redmond, 1992), but vegetation can be a response and therefore lead to apparent association of resistance and mobility, rather than it being causal. The woody debris itself can affect fluvial processes and planform development. It can cause blockages and obstructions from fallen and transported wood. Daniels and Rhoads (2003) demonstrated the difference that presence of woody debris makes to the circulation in meander bends compared with bends free of obstruction, particularly affecting the position of the high-velocity core and the helical flow patterns.

3. Synthesis and implications

Active meandering channels exhibit high mobility of position and various dynamics of morphological change. These channels are characterised by both temporal and spatial variability. From the intensive field measurements and from longer-term evidence it emerges that relations of rate and type of movement do not tend to exhibit simple relationships to discharge dynamics, even using a range of parameters and

Table 1
Published timescales of bend and floodplain turnover.

Author	River	Width m	Timescale
Dort (2009)	Kansas River, USA	150–450	Bend initiation to cut-off - <a few decades
Harmar and Clifford (2006)	Lower Mississippi	1500	Meander train development – 120 yr
Beechie et al. (2006)	Pacific NW streams, USA	10–50	Turnover recurrence – 60 yr
Hooke (2004)	Bollin	10	Bend initiation to cut-off –120–150 yr
Hooke and Yorke (2010)	Dane	15	Bend initiation to cut-off –120–150 yr Development to compound 50–100 yr
Hooke, 1980	Devon rivers, SW England	10–30	Full floodplain width reworking –7000 yr
Mertes et al. (1996)	Solimões–Amazon	4000	Floodplain recycling –1000–4000 yr
Gautier et al. (2007)	Beni, Amazonia	600	Floodplain recycling –10 K–40 K yr

timescales. The relations are complicated by complex temporal feedbacks, which are often ignored or underestimated in modelling. However, it does appear that, although correlations between annual discharge peaks and rates of movement or process are not high, a series of wetter or drier years, of even as few as 2–3 yr, can produce a distinctive signal. It is suggested that over such timescales the channel processes can produce adjustments in width and form. It may be that the feedback effects need this timescale for the channel adjustment. A cluster of high flows or high flow years may produce a more consistent response and successive high flows may enhance instability. A series of lower flow years will increase stability, causing thresholds to increase and thus further lengthening the period of greater stability/ less activity. Thus, response becomes delayed and smoother, and this may not simply be an artefact of averaging. Such hypotheses need much further testing with greater amounts of data; data availability and computational ability are advancing rapidly to facilitate this. Some extreme high flows do cause transformations and morphological thresholds to be crossed, and these thresholds need to be identified for individual reaches. Again, long records are needed to encompass the occurrence of the rarer events.

Spatial variability in meander behaviour, even in reaches affected by the same discharge events and conditions, is apparent in many examples. Changes are not synchronous. Different types of temporal variation in meander behaviour can be recognised that may occur simultaneously in one reach, as indicated in Fig. 16 on the River Dane. Types of temporal pattern include consistent high rate, decline then stabilisation, stable then initiation, variable but continuous activity, episodic activity. A longer record may reveal phases of activity. These variations are different from, but can be related to, type of morphological change, previously recognised as part of the common sequence of bend evolution. Bends or sections of channel can go in and out of activity. Likewise, persistence of position of erosion and deposition within bends can vary. It is partly explained by flow patterns at different discharges, but also with feedback effects of the morphology and of obstructions and resistance such as from vegetation. However, the consistency of the overall bend evolution indicates that this combines over a few years to produce the morphological changes. Again, more evidence on the dynamics at this scale is needed.

Much of the spatial variation in meander dynamics is probably caused by heterogeneity in boundary materials and in vegetation, though this still seems to be underestimated and often not captured in modelling. A major challenge is in acquiring relevant data on resistance and boundary conditions without time-consuming and resource-demanding detailed sampling. It is suggested that techniques of mapping different zones of the valley floor by topography and elevation from remote sensing data, then simple characterisation of material into sediment types and bedrock categories in each type of zone by some sample field mapping may, at least, provide a framework for analysis. The effects of varying resistance need to be combined with effects of width and curvature and the feedback effects on morphology and channel position incorporated in analysis and modelling.

These temporal and spatial variations are superimposed on underlying autogenic trends in bend development and evolution. The autogenic sequences have now been demonstrated to have considerable commonality and consistency in a wide range of fluvial environments

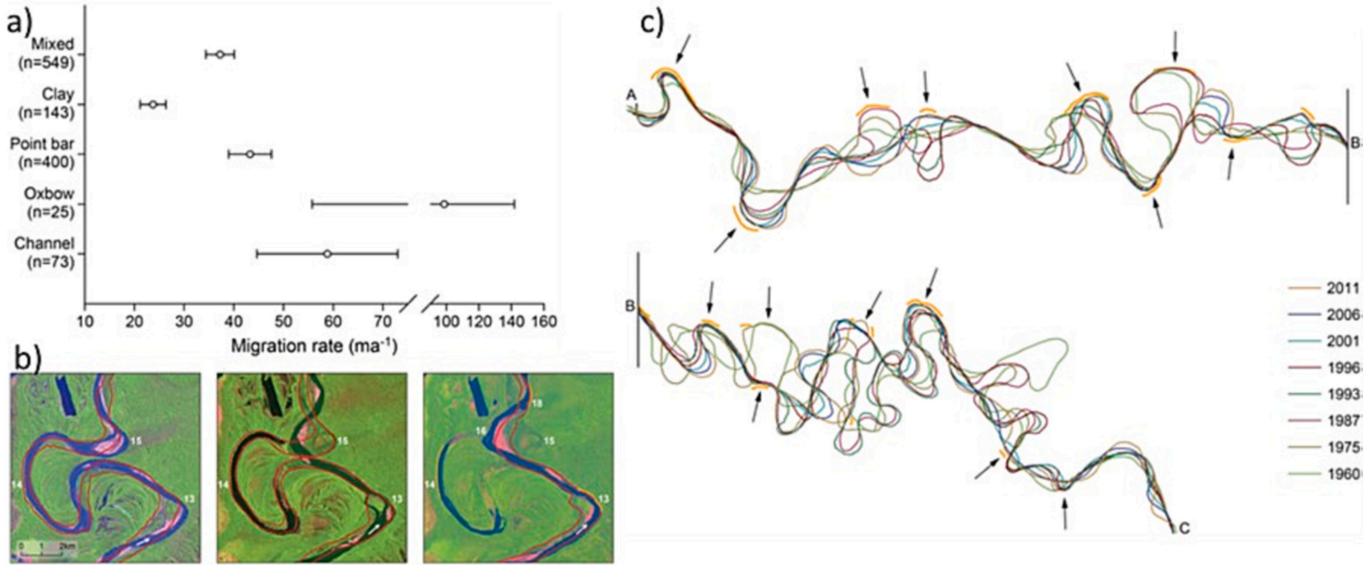


Fig. 24. Interaction between meander dynamics and floodplain heterogeneity on the Rio Beni, Amazonia. a) Mean migration rates of bends between 1960 and 2011 (95 % confidence intervals shown as error bars); bends are classified by the substrate or the morphological feature into which they are migrating, b) Typical sequence of channel migration influenced by clay-rich banks 1975–1987, 1987–1993, 1993–1996 (panels left to right); Landsat image dates correspond to the end of each time period, banklines shown in red represent the start of the time period in each panel. c) Channel centre lines between 1960 and 2011, with arrows marking the bends in more resistant materials, which are relatively immobile over >50 yr and act as fixed 'hinges' between more mobile reaches. (From Schwendel et al., 2015, Figs. 4, 6 and 16).

and types of active meandering channel. Less active meandering may not exhibit this complete sequence, or not within the timescale of evidence. The timescale of full bend development from initiation to cut-off needs to be identified in a reach. In addition, these sequences may also be underlain by some trends in vegetation growth or ecological succession, some of which are associated with the changes, but others may be induced by wider environmental and climatic changes. Thus, these different temporal patterns combine to produce the complexity of outcomes.

In many cases it is found that adjacent bends are not exhibiting synchronous changes but that these are also not simply explained as the stage in the autogenic sequence. Yet, it is also difficult to detect a direct transmission of effects and a propagation of change from one bend to the next. Conditions need to persist long enough to identify specific types and magnitude of response and that is increasingly challenging in the more rapidly changing climate. The long-term but detailed studies, notably on the Powder River in Montana, USA, and on the Dane and Bollin in the UK, have provided invaluable insights into morphodynamics, particularly highlighting the variability and complexity. The availability of much more data covering sequences of bends at greater temporal resolution and the greater capabilities of analysis may reveal the degree of connection or association. Much more analysis of the meander change records is needed, especially in regions of rapid movement and multiple former channels and scroll bars, such as on many tropical rivers. The use of Artificial Intelligence and Big Data analytics combined with the satellite imagery, offers much potential for unravelling the complex combinations, sequences and interactions. The morphological change data need to be complemented by discharge, local gradient and resistance data. A checklist of steps and components in analysis of morphodynamics is provided in Table 2. Many techniques and software, with increasing automation, are now available for the data compilation and analysis at the various stages.

Understanding the morphodynamics of active meandering rivers has practical implications for river management. Long ago, Hooke and Redmond (1989) advocated that room should be left for these active channels to meander but much research in the last two decades has developed the idea of making space for the river to move and freedom space in floodplains (e.g., Piégay et al., 2005; Biron et al., 2014). In strategies of management, it is now widely appreciated that, for a range of reasons associated with sustainability and adaptability, and with biodiversity, ecological and landscape value, meandering rivers need to be left alone and those modified, be restored to more natural functioning. Much management has been for flood risk purposes but active meandering channels with their high mobility present particular challenges. Channel movement can place assets, infrastructure and activities at risk so predictions of the zones of movement and timescales of effects are needed. In zones of active meandering rivers, whether more natural or restored, prediction of likely movements and future positions of the channel are needed to facilitate detailed planning. For example, Nagel et al. (2022) discussed the impact of meander migration on riverine communities in Amazonia. Ideally, predictions of trajectory of position would be highly beneficial. These are high energy rivers and thus have high potential to reassert their natural dynamics even when controlled. This needs to be allowed for. Opening up of corridors of mobility and re-establishing more natural channels is proving feasible and enormously beneficial in many ways (e.g., NWRM, n.d http://nwrm.eu/measure/re-meandering). Of course, implementation of such strategies is not simple and must take into account the social and economic context, but public perception and attitudes towards the acceptance of such approaches are changing (Newson, 2022).

Table 2
Methodological template – framework and checklist of analysis stages.

1. Compile longer-term historical evidence – historical maps, aerial photographs.
2. Identify zone of movement and stability. Measure sinuosity and average width. Relate to valley characteristics -gradient, materials, confinement, vegetation/land use
3. Extract mobile reaches and bends
4. Compile detailed evidence over recent decades from satellite imagery, Google Earth (GE), LiDAR, air photos
5. Extract individual bends
6. Analyse bend movement and change. Measure maximum rates, average rates. Plot and classify type of meander change.
7. Plot rates over time. Identify patterns of variation and phases. Assess synchronicity.
8. Compile discharge record for period of evidence. Analyse key discharge parameters.
9. Analyse relation of rates of movement to discharge parameters, including peak magnitudes, clustering and periodicity.
10. Identify threshold flows, key events and phases.
11. From phase of bend evolution, project likely trajectory.
12. From topographic maps, LiDAR, GE and other sources, map valley floor topography. Divide into zones of different elevation. From RS imagery, map riparian vegetation. Examine geology and soil maps.
13. Visit active reach. Examine bank composition in zones of different topography – bedrock and sediment type (gravels, sand, silt and clay). Apply a resistance category to each valley floor zone.
14. Modify autogenic trajectory for resistance elements.
15. Digitise or automatically generate channel centreline. Calculate curvature at steps. Calculate migration rate for each step along course using Hickin and Nanson relation and resistance category or other reduced-complexity models.
16. Map the prediction of changes. Plot the corridor of mobility required for sustainable functioning.
17. Consider consequences for settlements, infrastructure and activities in the valley flood zone.

Much restoration is involving reconnection of floodplains to channels so that, in these naturally active meandering rivers, former channels and floodplain lakes can function again. However, such actions also cause controversy, especially in relation to oxbow lakes and wetlands and their valued biodiversity. Arguments have arisen over the extent to which the features should be preserved in these dynamic environments. Many ecologists wish to preserve them as valuable aquatic habitats and early thinking was on strategies to do so (Shields and Abt, 1989). It was a contentious issue in planning of extension of Manchester airport runway into the Bollin valley where oxbow lakes contained red-species insects. However, on these rivers the natural dynamics need to be recognised and that former channels will tend to infill, even if at varying rates. It is not sustainable to preserve them. If a channel is allowed to be mobile and dynamic then it is likely that more cut-offs will be created as older ones are obliterated and thus new habitats formed. Understanding of dynamics of cut-offs and wetlands needs to be appreciated and incorporated into management, as emphasised by Piégay et al. (2002).

A major question is how predictable are the channel movements. Much modelling has been undertaken to understand fundamental principles and controls (see Hooke, 2020) but, inevitably, applies simplified and idealised conditions. For realistic predictions, particularly for specific locations, then the complexities, both in time and space must be incorporated. Suitable methods need to be available that are accessible to river managers. Sophisticated numerical modelling is often not feasible for managers and simpler approaches may provide the basis for outline decisions on strategies. From an early stage, specific tools and models were developed to aid in restoration of meandering of streams (e.g., Abad and Garcia, 2006). Some simple approaches may be quite successful. For example, application of the Hickin and Nanson relation of rate to curvature, incorporating a lag and a spatially varying resistance function, can provide outcomes that are quite close to reality (Hooke, 2003b). Some other empirically based techniques have been developed, for example, the project by Lagasse et al. (2004), which uses circular fits to the meander morphology and follows an evolutionary sequence, but it generalises the bend form. Feeney et al. (2020), using the Caesar-Lisflood model, found reasonable predictions of rates of meander movement for reaches but that reach-specific calibration is needed to produce accurate simulations. The analysis of the morphodynamics presented here indicates the importance of the details and the complexity of morphology, boundary conditions, sequences of flow events and of feedback effects. Initially, the evidence of the context and past trajectory and behaviour of the channel needs to be assembled and analysed. Detailed analyses of meander morphodynamics can aid in river management by identifying rates and sequences of change in different reaches and also the effects of management actions (e.g., Bertalan et al., 2019). Likewise, Hasanuzzaman et al. (2022) demonstrate that even quite simple methods of data extraction and analysis can provide valuable data for channel management and river restoration. Thus, research of the types reviewed here is required to provide the necessary information and to try to project future trajectories. A framework of steps and components in analysis of morphodynamics is provided in Table 2. Such data can provide the validation for more sophisticated modelling.

Very few rivers in the world are unaffected by human activities, not only by deliberate and direct alterations of flow regimes and of channels, but also indirect effects of land use change. Anthropogenic climate changes now present additional major challenges in prediction and management. Understanding of the dynamics is required both for establishing principles and relations for modelling and for the validation of models. Long detailed records of both the drivers and the river morphodynamics are needed to distinguish tends and patterns. Shifts to persistently changed morphology (e.g., of channel size and wavelength) can be identified and compared with phases of human actions. Much research is ongoing into analysis of climate signals and the extent of anthropogenic modification, with a clear anthropogenic signal becoming apparent. The impact of the teleconnections of major variations in the past such as associated with El Nino have been identified (e.g., Suizu and Nanson, 2018). Wetter and drier periods on the timescale of a few years to a few decades have long been recognised and are well known, particularly in drier environments and in some regions. For example, the flood-rich and flood-poor phases in Australia have effects on management of channels such as in design of infrastructure like bridges (Warner, 1987). The analysis here has suggested that clustering of years has important effects on morphodynamics, so if the periodicity of the contrasting periods is shortened and the amplitude increased then this could have significant effects on the morphodynamic response of channels. Few rivers can act as completely natural baselines but those lacking major deliberate intervention, and particularly those for which evidence has been accumulated for periods of many years, provide a very valuable basis for assessing both past and future responses.

The rapidity and high variability of change and morphology in these active meandering channels also has implications for frequency and areas of flooding. On these rivers, much of the floodplain area is often relatively low in elevation because of the rate of overturning of floodplains. This contributes to the high frequency of overbank flows that is quite common on these rivers. The large morphological changes, indicated by width and planform characteristics, have implications for the geometry and therefore the channel capacity and thus may have large effects on inundation, which could be as great as the climatic and land use signals (Hooke, 2022). Other research on changes in channel capacity and feedback effects of discharge variations and morphological change have indicated the magnitude and rapidity of such adjustments (Slater et al., 2015, Slater et al., 2019, Li et al., 2020b).

Scenarios of anthropogenic climate change for prediction of river channel morphological responses are mostly still not very detailed and management authorities, such as the Environment Agency in the UK, have been using projections of, for example, +20 % in the controlling peak flows. A new hydrological service has just been launched, Climate Change Allowances of Peak River Flow by Management Catchment, for individual river flow predictions based on climate change scenarios (https://www.data.gov.uk/dataset/5d9c75a9-4554-455c-96ff-8fd814c317dd/climate-change-allowances-peak-river-flow-by-management-catchment, n.d.) in UK. Future scenarios are further complicated because vegetation and land use may adapt to the climate changes. The main concern is with flooding but research is beginning to use modelling to anticipate erosion and channel changes (Feeney et al., 2022).

4. Conclusions

High process and morphological variability, both temporally and spatially, are characteristic of active meandering channels but they combine over longer periods to produce a high degree of systematic behaviour and autogenic evolution. These channels have high sensitivity, with changes in position and morphology taking place each year even in moderate, frequent peak discharge events. Rates and amounts of change can be very high and not systematically related to various discharge parameters alone. Identification of the controlling discharges still requires more analysis to distinguish effects of peak magnitudes, number of peaks, persistence of wet periods, flow duration or sequences of conditions. Evidence suggests that channels adjust over periods of 2–5 yr, especially if clusters of events occur. Adjustment takes place locally by widening and narrowing through erosion and bar deposition, but destabilising or stabilising feedbacks act over a series of events to produce a coherent response at bend scale. Feedback effects are very important at bar scale as well as bend scale, particularly in the case of mid-channel bars, common on this type of river. The responses may be further complicated by trends in vegetation growth, with its feedback effects on resistance and on sediment supply. The effects of an extreme flow event tends to straighten a channel temporarily but will be highly dependent on the state of morphology (curvature and sinuosity) and of vegetation and resistance. Averaging over periods of a few years and over reaches of several bends tends to show specific responses to relatively short wet and drier periods. Analysis at longer timescales blurs the variations and also produces lower rates of movement.

Overall, even with the high variability of response to individual events, these active channels tend to exhibit transience of morphology, which emerges as an autogenic evolutionary behaviour. Many bends, given the freedom to move, exhibit a common sequence in which rate of change accelerates over time, bends increase in curvature, become more complex (compound form) and then cut-off. This sequence may be modulated by local variations in resistance as the banklines shift, producing a pulsed or phased response over time and a modification and skewing of smoothly curving bend morphology. In these active meanders, full sequence of bend development to cut-off can take place in as little as one or two decades on the most active rivers.

Spatial variations in rates of movement and changes in bend morphology are influenced by heterogeneity in bank resistance from scales of short lengths of higher resistance sediment or vegetation within bends to greater lengths of constraint at bend and reach scales. Meander movement has a high component of downstream migration, especially in early evolutionary stages of bend development but spatial propagation of changes in process rates and bend morphology are not necessarily transmitted from bend to bend. Some evidence points to lack of propagation of change, with very active bends adjacent to much more stable ones. Much adjustment and absorption takes place locally. However, on some rivers, the effects of cut-offs can be transmitted along the course. Analysis indicates the importance of considering a hierarchy of both temporal and spatial scales to understand the mechanisms and periodicity of change and how small-scale variations integrate into more coherent behaviour.

The high variability, spatially and temporally, poses challenges for predictability. The actual trajectory of individual bends will be a product of short-term variability underlain by longer-term autogenic bend development and influenced by local constraints of boundary resistance and gradient. Nevertheless, the high degree of consistency and autogenesis underlying the morphodynamics means that, given enough evidence, it should be possible to model the complex combinations of conditions. Technological advances are facilitating data collection and analysis at an enormous rate and application of Artificial Intelligence and Big Data should enable the unravelling of these complexities. Remotely sensed imagery of channel and floodplain morphology still needs to be complemented by discharge and ground measurements, and data on boundary resistance. The dynamics of these highly active river channels should not be underestimated and must be allowed for in any management strategy, including possible increased dynamics with climatic trends. Understanding of the morphodynamics of these rivers is vital for such management. Lack of interference with the channels, and restoration of meandering channels that allow natural functioning will mean the channels can adapt to variable and changing conditions and be sustainable, with added advantages of high biodiversity and amenity value.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: I have served on the Editorial Board of Geomorphology for several years.

Data availability

Data will be made available on request.

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