Hydromorphological adjustment in meandering river systems and the role of flood events

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Abstract This paper takes a selection of meandering rivers in the UK to address issues of morphological adjustment and change. The occurrence of peak flow events over recent decades is analysed for patterns and trends. Certain hydrological phases are identifiable. Changes in morphology and activity of the channels are examined through repeat field and aerial photograph mapping and some detailed observations over a period of 20 years. These show major variations, some of which appear to be related to discharge fluctuations. The differing impact of the highest floods within the period of record is demonstrated. The state of the system, particularly the degree of meander development, is of crucial importance. A seasonal difference in the impact of high flow events is also detected. Relationships between morphological changes and discharge characteristics are complex and the effects of other factors, particularly growing season and ramped effects of growth of vegetation may be significant.

Key words channel changes; channel migration; discharge fluctuations; erosion; floods; hydromorphology; river meanders; temperature changes

INTRODUCTION

Understanding of the response of river channels to climate and land-use changes has become even more important under scenarios of global warming and with new legislation, particularly the EU Water Framework Directive (WFD). Sediment movement takes place almost entirely in peak flow events but these may be of varying magnitude depending on the hydrological regime and the size range of sediment available in the system. It is primarily coarse sediment, from sand size upwards, that contributes to channel morphology.

Meandering rivers are mainly developed in the flood plain zones of fluvial systems. Within these zones, the main source of coarse sediment to the channel system is erosion of the banks of the flood plains themselves, with occasional contributions from valley walls. Sediment supply from tributaries is localized in input. It is generally assumed that sediment has the potential to move down through the system. However, recent analyses have suggested that movement of the coarsest material may be much more localized in some systems and that there is not necessarily high connectivity between reaches, or that it may be operational only in very extreme events. (Fryirs & Brierley, 2001; Harvey, 2002; Hooke, 2003a). The incidence and impact of flood events in meandering rivers is examined here, through evidence of channel changes at a variety of spatial and temporal scales, to assess the conditions under which erosion and deposition take place and thus hydromorphological responses are brought about. The analysis focuses on the Rivers Bollin and Dane in northwest England (Hooke 1987, 1995a,b) with additional examples from the River Severn in Wales (Hooke *et al*., 1994), and the River Wey in southeast England (Hooke, 2002). The examples show that the relationships are not simple and that the complexity of meander behaviour and feedback effects must be taken into account.

HYDROLOGICAL VARATIONS

The occurrence of peak flows has been analysed for a range of rivers in England. The common perception is that the incidence of flooding is increasing and will do so under climate change scenarios. The annual peak flows for a standardized period, 1960–1999 are shown in Fig. 1 for four rivers from different regions of England and Wales, the Rivers Bollin and Dane in Cheshire, northwest England, the River Severn at Abermule in east Wales, and the River Wey at Tilford in Surrey, southeast England. These do have differing patterns, one showing a slight downward trend in annual maximum flow, one a decrease and the others no trend. However, far from the most recent period being one of destabilization, there seems to be some evidence to suggest that the period of the 1960s was even more extreme hydrologically on some rivers. Three out of the four rivers seem to show greater variation up until the early 1970s. There may be particular reasons for this on each river. Inferences made on data that exclude this period, e.g. analyses based on 1970–2000, can be very different from analyses that include it.

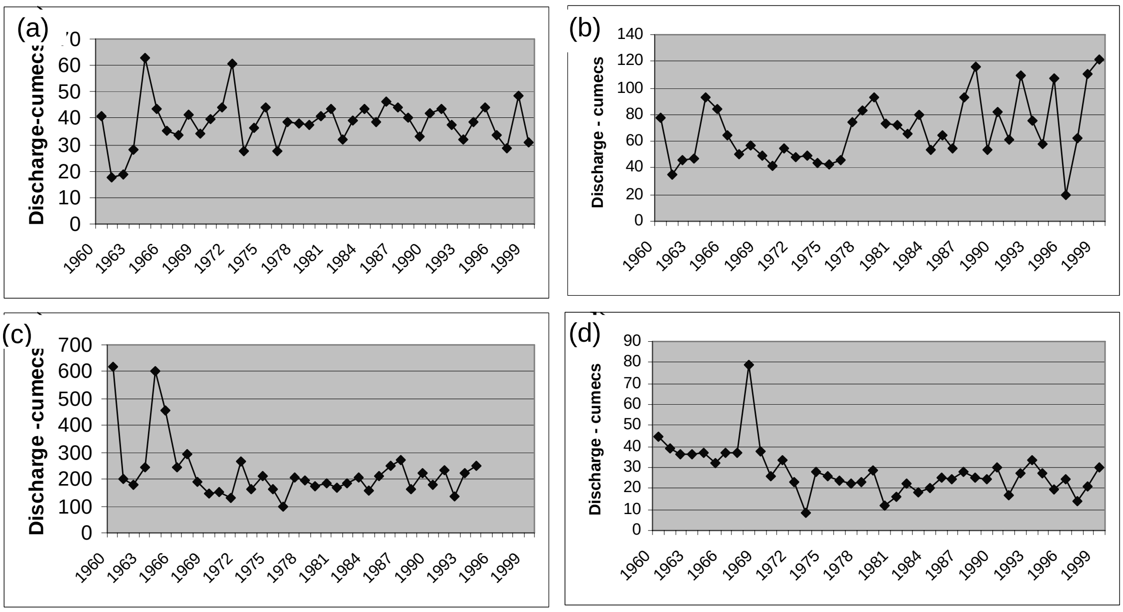

Fig. 1 Variations in annual peak discharge: (a) River Bollin, Dunham Massey, Cheshire; (b) River, Dane, Rudheath, Cheshire; (c) River Severn, Abermule, Wales; (d) River Wey, Tilford, Surrey.

MEANDER CHANGES

Evidence of the dynamics of some of these streams is exemplified in Fig. 2, based mainly on aerial photographic data and photogrammetric mapping. Additionally, the

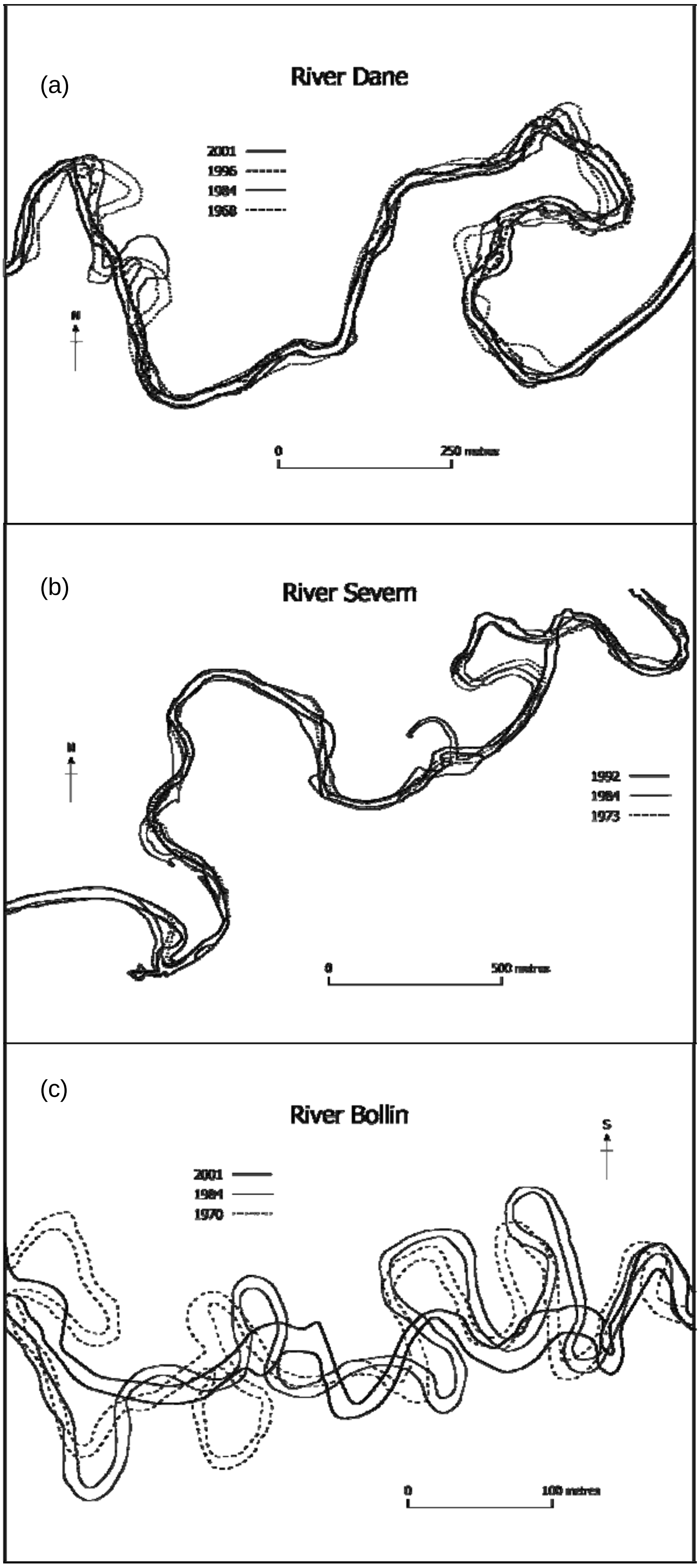

Fig. 2 Examples of channel changes: (a) River Dane, (b) River Severn, and (c) River Bollin.

Bollin and Dane in northwest England have been mapped and monitored annually for the last 25 years. The Bollin and Dane and Caersws section of the River Severn are highly dynamic and respond readily to flood events, with active erosion and deposition usually occurring several times a year, as was shown earlier by intensive measurements of bank erosion on several dynamic meandering streams in southwest England (Hooke, 1979). Likewise, intensive measurements of movement of coarse material using tracing techniques on the River Yarty in Devon, southwest England, show that large cobbles are transported in events that occur on average several times a year (Barker, 2000). Thus the thresholds in relation to peak flow for coarse sediment transport are relatively low. Rates of erosion on the most active meander bends of these systems are of the order of 0.5–1.0 m year^{-1} and it is these bends which lead the hydromorphological response. Such systems are highly sensitive.

RELATIONSHIPS OF CHANGE TO PEAK FLOWS

The relationships between channel change or processes and the magnitude and frequency of peak flows have been analysed in various ways. Measurements of rates of erosion and of channel width derived from aerial photographs for available epochs are tabulated together with data on average mean annual flood and number of Peaks over Threshold (POT). Care must be taken in comparability of data but distinct differences in channel width are apparent for some epochs on some rivers (Table 1(a)). Data on areas or erosion and deposition derived from GIS analysis of the changes on the Dane and Severn show changes in the ratios of erosion and deposition (Table 1(b)). However, data on rates of movement of meanders of different type (Table 1(c)) show that this also has a profound influence on actual behaviour at any time, the different types of bend evolving and changing in different ways (Hooke, 1987). For the River Dane, annual observations have also been made of the occurrence of bank erosion, locations and amounts of deposition on bars, and calibre of sediment deposited on bars. These data, from a reach of ~10 km and comprising ~80 meander bends, have been amalgamated into indices of erosion and deposition. Sediment calibre is assessed by percentage of bars with dominantly cobble size material deposited. The annual data show considerable variability as would be expected and some general relationships but the correlation coefficients indicate that the occurrence of peak flows is not the complete explanation (Fig. 3).

IMPACT OF LARGE FLOODS

Much fluvial literature documents the impacts of extreme flood events and there is much discussion of the role of different magnitude–frequency events. The 2000–2001 peak flows in Britain were the highest on record for several decades on some rivers and were thought to have had a large impact. Comparison of both the magnitude–frequency of the event and the morphological impacts on the two neighbouring rivers, the Bollin and Dane, which are very similar in morphology and behaviour, is very instructive. On the River Dane, gauge records from 1949 show that the peak flow in November 2000 was the highest since records began. However, detailed ground field

Table 1(a) Changes in width of channels.

River Dane	1984	1996	2001
Width (m)	18.6	15.7	17.2
Last peak Q ($m^3 s^{-1}$)	79.4	20	130.7
River Bollin	1970	1984	2001
Width (m)	10.3	8.0	9.85
Last peak Q ($m^3 s^{-1}$)	39.56	38.91	48.65
River Severn	1973	1984	1992
Width (m)	21.0	25.5	26.5
Last peak Q ($m^3 s^{-1}$)	131.18	207.11	230.97

Table 1(b) Areas of change in relation to discharge characteristics for period.

River Dane	1984–1996	1996–2001
Erosion (m^2)	43 122	31 735
Deposition (m^2)	60 779	24 490
Erosion & Deposition (m^2)	89 060	104 074
Ratio erosion /deposition	0.71	1.30
Mean annual max Q ($m^3 s^{-1}$)	77.4	88.9
Mean no. peaks	6.7	15.9
River Severn	1973–1984	1984–1992
Erosion (m^2)	7785	15 089
Deposition (m^2)	14 779	11 385
Erosion & deposition (m^2)	1716	5821
Ratio erosion /deposition	0.53	1.33
Mean annual max Q ($m^3 s^{-1}$)	174.85	192.06
Mean no. peaks over threshold	1.36	2.89

Table 1(c) Rates of erosion on different types of meander, River Dane.

Rates of erosion Bend	 Type	1968–1984 m $year^{-1}$	1984–1996 m $year^{-1}$	1996–2001 m $year^{-1}$
27a	New	0	1.41	3.17
28	Bedrock compound	1.56	0.92	1.24
40	Constrained	3.67	1.81	1.93
55	Constrained	0.39	3.10	1.52
58	Migration	2.03	1.50	1.52
60	Migration	2.50	1.41	2.07
63	Developing	0.47	1.47	2.97
82	Lobing	1.56	1.15	0.69

mapping and accurate photogrammetric plotting of the course from aerial photographs, especially flown for the purpose in May 2001, show that the changes were in no way abnormal from other years. Rates of erosion and amounts of movement may have been slightly higher but the types of change were consistent with previous behaviour. In contrast, the monitored reach of the River Bollin upstream of Wilmslow, Cheshire, was transformed by the floods (Hooke, 2004). Several cut-offs took place within a 1 km reach, with a domino-like effect. The hydrological records (Fig. 1) show that this was not even the highest flow in recent years, with the peak in 1998 almost equal;

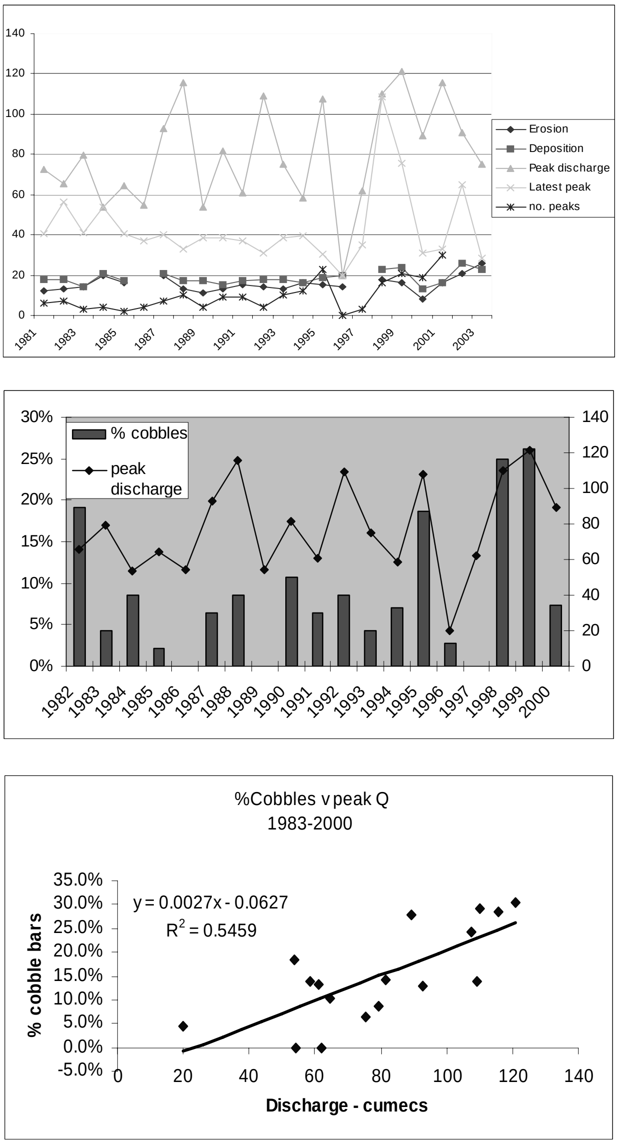

Fig. 3 Annual changes in erosion, deposition and proportion of bars dominantly cobbles on the River Dane in relation to discharge characteristics.

much higher peaks occurred in 1964 and 1972. It is suggested that the difference in response of these two rivers was because of the state and condition of meandering. On the Bollin, the meander course was near the critical threshold of sinuosity; this threshold was crossed and the cut-offs occurred as a catastrophic adjustment in a self-organizing system (Hooke, 2003b). The Dane has not yet reached that critical sinuosity and spacing of meander loops such that the effects are catastrophic and propagate rapidly.

On the much less dynamic system of the River Wey, the 2000–2001 were the highest flows for five years but not extreme. The duration of high flows and number of peaks that winter was high. The peak flows had little noticeable impact except for slightly higher rates of erosion and deposition.

A differing effect of high peak flows in different seasons can also be distinguished. Twice within the 25-year period of monitoring on the Dane, very high summer floods have occurred. However, these have not had the proportional effects that would be expected from a simple relationship of erosion to peak flow. For example, the peak flow of 1988 in Fig. 3 is an August flood and is the data point showing least relation with activity. Observations soon after the event showed that the main effect was a slight bending of vegetation and thin veneers of fine deposition. It is suggested that vegetation in summer has a marked effect in reducing the impact of floods, with much lower amounts of erosion and sediment transport. It is possible also that the duration of flood events has an influence and that these summer floods are highly peaked, resulting from summer thunderstorms. Further investigation of the effects of duration of events and of flows is taking place. Earlier research on bank erosion showed that the amount of bank erosion in an event is not correlated simply with peak flow but is strongly influenced by soil moisture (Hooke, 1979). Thus, the dry riverbanks in summer are also much less easily eroded than the wet ones in winter.

EXPLANATION AND DISCUSSION

The evidence indicates that on the active meandering channels there is an underlying basic relationship between the magnitude of a peak flow event and the amount of erosion and deposition and therefore sediment dynamics. In certain systems, thresholds for transport of the dominant sediment size can be identified. In general, there also tends to be more erosion in the higher events and relatively more deposition in the lower events, which carry more sand and gravel. Thus a sequence of high flow years will tend to lead to a widening of a channel but lower, still competent peak flows for finer fractions, will result in more deposition. However, there are two major complications to these relationships.

The first, as has been shown by the example of the Bollin, is that the response and behaviour of the system depends on its overall state, particularly the degree of meandering. Much research has now shown that these active meanders exhibit an evolution of form from low sinuosity bends through to compound forms that then tend to cut off. If the sinuosity becomes so high and the meander loops so closely spaced, then the adjustment can be sudden and catastrophic and lead to a wholesale transformation of the pattern. In the case of the Bollin, it is now returning to a meandering state through moderate floods and has not permanently crossed a threshold to a braided state. Similar kinds of effects of sudden inputs of sediment temporarily transforming a system have been demonstrated by Harvey (2002). The importance of thresholds in the system and the influence of the state of the system have long been recognized (Schumm, 1979; Wolman & Gerson, 1978).

The second complication is the effect of sequences of events and phases of flood occurrence. A neglected factor in this type of stream is that of vegetation. Presence of riparian vegetation can markedly reduce bank erosion and reworking of coarse deposits on bars. Vegetation tends to encourage fine deposition. Vegetation can be removed in high peak flows and trees are regularly brought down on the River Dane, though the thresholds for such effects are relatively high. The annual monitoring on the Dane has shown that if a sequence of relatively low flood years occurs then vegetation can colonize and build up on the bars and banks. These then raise the thresholds for further erosion and so a ramped effect could be expected. However, preliminary analysis and modelling of this effect also does not provide the whole explanation of a prolific growth in vegetation on several of these channels in recent years, which is now having a stabilising effect. It is hypothesized that the increased vegetation growth may be due to the higher winter temperatures, which have been identified (Mitchell & Hulme, 2002). Analysis of the growing season for the Dane does not show much change over the past 20 years but an analysis of the number of frost days for the period 1980–1999 shows a very marked decrease (Table 2). Thus the dieback of vegetation in winter, particularly on channel bars, is not as great as in cooler periods. It is suggested that any hydromorphological modelling of responses to changes in magnitude and frequency of floods must take these factors and feedback effects into account.

Table 2 Number of frost days in each month at Knutsford, Cheshire, 1980–1999.

Year	Oct	Nov	Dec	Jan	Feb	Mar	Total
1980–81	2	10	7	10	19	1	49
1981–82	4	3	21	16	9	2	55
1982–83	0	4	13	2	21	5	45
1983–84	5	5	7	12	10	7	46
1984–85	0	2	5	26	12	13	58
1985–86	2	14	6	15	24	7	68
1986–87	1	1	6	20	14	12	54
1987–88	1	3	10	3	5	5	27
1988–89	2	11	2	5	7	5	32
1989–90	0	8	11	2	2	3	26
1990–91	0	4	9	17	20	1	51
1991–92	1	4	9	15	5	1	35
1992–93	5	2	13	4	6	4	34
1993–94	5	13	7	6	9	2	42
1994–95	1	0	5	8	2	9	25
1995–96	0	6	14	6	19	7	52
1996–97	0	10	14	15	1	1	41
1997–98	4	0	4	7	4	2	21
1998–99	0	4	9	6	6	0	25
Average							41.4

CONCLUSIONS

Variations in magnitude and frequency of peak discharges are apparent. Analysis of morphological changes on several meandering rivers reveals significant fluctuations within periods of a few years, including changes in width and in the ratio of erosion to deposition. There appears to be a general relation to variations in peak discharges but more detailed data show complex relationships. The impact of large floods is seen to vary with state of the system in terms of the degree of meandering and sinuosity. Both seasonal and longer-term trends in vegetation growth may also have an effect on the impact of floods.

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