7 Channel Types and Morphological Classification

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7.1 INTRODUCTION

River channel patterns are characterised by a range of forms and geometries. For engineering and management purposes it is often useful to classify channels using a range of geomorphological channel types that minimise variability within them and maximise variability between them. Most classification systems centre on the planform pattern of the river, but others include consideration of the cross-sectional geometry, longitudinal profile and type of bed material (gravel, sand, or silt/clay). The objective of this chapter is to review the basis for the identification of channel type and the classification of rivers and to examine briefly the utility of channel classification to engineers and river managers.

7.2 DRAINAGE PATTERNS: THE ROLE OF REGIONAL GEOLOGY AND TERRAIN IN INFLUENCING THE PATTERN OF CHANNELS AT CATCHMENT SCALE

Morphological classification must start by considering the geology and physiography of the river basin as they affect and, in some cases, control river form and processes. Examination of maps showing the topography, solid geology and surficial deposits is essential and assistance may be sought from the geologists and physical geographers in determining the significance to the river of various terrain features, rock formations, tectonic movements and sedimentary units. The influence and impacts of these factors on the fluvial system can also be gauged to some extent by tracing-out and interpreting the *pattern* of drainage channels in the catchment. For this purpose a topographic map covering the drainage basin (watershed), such as US Geological Survey quad sheets or their equivalent, is usually ideal.

A great deal of work on the analysis and morphometric interpretation of drainage patterns has been undertaken, a substantial proportion of which is concerned with topological analyses of channel networks that centre on the concept of 'stream ordering' (Strahler, 1964; Shreve, 1966). However, this type of approach is prone to subjectivity in the way that data are extracted from maps, and different operators invariably produce

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different statistical parameters such as drainage density and texture (see, for example, Chorley et al. (1984, p. 321)). In any case, such derived parameters have limited practical applications in river engineering and management. Direct examination of the overall pattern of drainage can be more useful. Howard (1967) grouped drainage patterns into eight categories which may be used to make useful inferences about the degree of influence of geology and terrain on the fluvial system (Figure 7.1). A summary of part of Howard's classification is given in Box 7.1.

Box 7.1 Drainage patterns and their geomorphic interpretation

A *dendritic* pattern is regarded as the simplest form of drainage system that results from the operation of fluvial processes in areas of homogeneous terrain with no strong geologic controls. Conversely, a *parallel* pattern develops where there is a steep regional dip (incline) to the terrain that imposes a preferred direction of drainage. A *trellis* pattern indicates both a regional dip and strong geologic control through the existence of folded sedimentary rock. A *rectangular* pattern is also associated with strong geologic control, this time through right-angled jointing and faulting. A *radial* pattern occurs around an eroded structural dome or volcano and is indicative of past or continuing tectonic and/or volcanic activity. Similarly, an *annular* pattern is associated with an eroded dome, the difference from the radial pattern being due to the channels forming where the fluvial system follows weaker strata in layered rocks. *Multi-basinal* drainage occurs in hummocky deposits such as those left by glacial deposition, and in areas of limestone solution. Finally, complex *contorted* drainage may be found where the terrain is heavily impacted by geology through structures produced by neotectonics and metamorphic activity.

7.3 THE CONTINUUM OF CHANNEL PATTERNS

7.3.1 Controls of Channel Form

The form, or morphology, of the channel (including its size, cross-sectional shape, longitudinal profile and planform pattern) is the result of processes of sediment erosion, transport and deposition operating within the constraints imposed by the geology and terrain of the drainage basin. Streams are constantly adjusting and evolving in response to the sequence of normal flow, flood flow and drought events which are associated with regional climate, local weather and catchment hydrology. In this respect, channel form can only be explained rationally if distinctions are made between those factors which drive the fluvial system (driving variables) in producing the channel, those which characterise the physical boundaries within which the channel is found (boundary conditions), and those which respond to the driving and boundary conditions to define the three-dimensional geometry of the channel (channel form) (Figure 7.2).

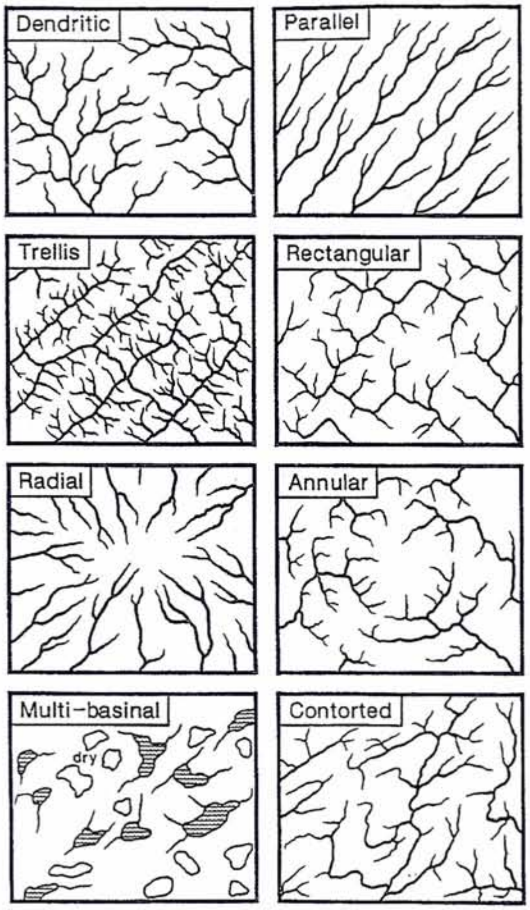

Figure 7.1 Basic drainage patterns (adapted from Howard, 1967)

Driving Variables

The inputs of water and sediment to the channel are not constant through time but vary widely. The input of water from drainage basin runoff drives the flow in the river, while the input of sediment from landscape erosion supplies some proportion of the sediment transported by the river. The balance between water and sediment inputs in turn controls the aggradation or degradational tendencies of the channel. Both the instantaneous values and time distribution of water and sediment are controlled by the climatic, terrain, geological and vegetational characteristics of the hydrological basin. These characteristics are themselves dynamic and they change in response to long-term climatic, geomorphological and biogeographical trends. However, such changes are not usually significant over human and engineering timescales. Fluvial processes may alter runoff characteristics over long timespans, as is clearly demonstrated in Chapters 2 and 3, but for the purpose of channel classification the inputs of water and sediment may be considered as *driving variables* which are effectively independent of channel morphology.

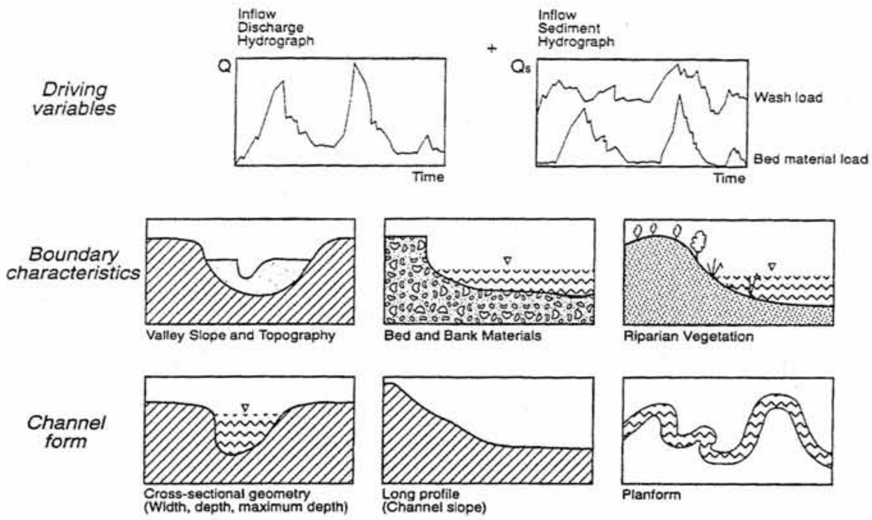

Figure 7.2 Independent and dependent controls of channel form

Boundary Conditions: Confined and Unconfined Channels; Bedrock vs. Alluvial Channels

The water and sediment inputs, or hydrographs, illustrated in Figure 7.2, interact with the landscape to form the channel. 'Landscape' in this respect can be defined in terms of the characteristics of the terrain and materials through which the river flows, and in which the channel is formed. These comprise the valley topography, and particularly the valley slope, together with the bed and bank materials and riparian vegetation.

Valley slope determines the overall rate of conversion of potential to kinetic energy and losses in the fluvial system and, hence, it controls the maximum stream power of a given water discharge, which is a function of the discharge–slope product. Stream power is a measure of the erosivity and sediment transport capacity of the flow for a given bed sediment size and input sediment load from upstream. The fact that it is a good parameter to represent the forces applied to the channel by the flow may explain why stream power is often used to classify channel type and to predict channel form, as discussed later in this chapter.

The bed and bank materials control the erosive resistance, or erodibility, of the channel boundaries. Here, important distinctions can be drawn between channels formed in bedrock and those formed in alluvium or sediment and, hence, between confined and unconfined channels. Channels formed in sediment that can be eroded, transported and deposited by the flow can be classified as 'self-formed', or *alluvial*. The nature and form of these channels is constantly being adjusted by the flow, and their dimensions obey the laws of hydraulic geometry or regime theory which are somewhat transferable between fluvial systems of various scales and geographical locations. Conversely, channels formed in bedrock only occasionally obey these laws because their forms and dimensions are governed directly by geological and structural influences.

A further distinction can be made between confined and unconfined channels. A channel flowing through a narrow valley interacts frequently with the valley sides.

Geomorphologically, fluvial and hillslope systems are closely coupled together. Hence, slope processes, such as soil creep and mass failure, may be driven directly by fluvial undercutting of the valley side by the river. Under these circumstances there may be a substantial supply of debris directly from valley-side processes into the stream channel. As a result, the morphologic development of the channel may well be confined by the valley sides in two ways. Firstly, if the valley sides are formed in consolidated, lithified materials such as rock, then outcrops of erosion-resistant materials in the channel bed and banks may restrict the development of a hydraulically 'self-formed' channel. Secondly, if the valley sides are formed in unconsolidated materials such as loose rock (talus) or soil, then mass failures may deliver such large volumes of sediment that the channel is unable to transport all of the debris away. Hence, the course and planform pattern of the river will be at least partly controlled by the spatial distribution of major sediment sources along the valley. Such streams, where the lateral development of the planform is restricted by interaction with the valley sides, are said to be confined.

Conversely, channels flowing through broad valleys with floodplains on either side rarely interact directly with the valley sides. The products of hillslope processes are stored as colluvium at the foot of the valley side and these are only attacked by the river infrequently during high out-of-bank floods or where in its lateral wanderings the channel encounters the edge of the floodplain. For the most part the channel is formed in erodible sediments and the river is said to be unconfined.

Floodplain vegetation, and most importantly bank vegetation, also plays a role in controlling the erodibility and stability of the channel boundaries. It is the balance between the erosivity of the flow and the erodibility of the boundary materials which controls the rate and direction of channel changes and the ultimate, stable form of the channel. Significant relationships between riparian vegetation and channel-forming processes have been demonstrated in hydraulic (Masterman and Thorne, 1992), geotechnical (Gray and Leiser, 1983) and geomorphological studies (Simon and Hupp, 1986) of channel flow and morphology. For example, research on the stable hydraulic geometry of gravel-bed rivers both in the USA by Andrews (1980) and in the UK by Hey and Thorne (1986) concluded that streams with heavily vegetated banks are narrower than those with thinly vegetated banks, for similar formative discharges. As the planform pattern of an alluvial channel is scaled closely on the width, the influence of vegetation on width will also, indirectly, affect the planform morphology and geometry of the channel.

7.3.2 Channel Morphology

The action of the driving variables of water and sediment inputs on the boundary conditions presented by the floodplain topography, bed sediments, bank materials and riparian vegetation produces the characteristic channel morphology of an unconfined, alluvial stream. Geomorphological classifications of channel type have established qualitative links between channel process, form and stability. In an important paper, Leopold and Wolman (1957) undertook a detailed examination of river form and concluded that natural channels form a continuous spectrum of patterns from straight, single-thread channels through to multithread, braided systems. The title of the 1957 paper by Leopold and Wolman, *River Channel Patterns – Braided, Meandering and Straight*, has been taken to infer that there are actually distinct types of pattern with clearly defined breaks between them, although the text of the paper actually stresses the continuity of channel planform geometries. In the paper an attempt was made to discriminate between meandering and braiding on the basis of formative discharge and channel slope.

The theory that there is a simple geomorphic threshold between meandering and braided planforms has been perpetuated through the quest for a numerical equation that can define this threshold quantitatively in terms of just two or three parameters representing the complex range of driving variables and boundary conditions responsible for controlling channel form. This quest is understandable from the point of view of the river engineer wishing to gauge the sensitivity of channel planform to engineering or river training, but it can obscure the fact that a distinct threshold does not actually exist. A more useful approach is to accept that there is a continuum of planform patterns and use an examination of the geomorphological features displayed by the channel to classify stream type. It is then possible to infer sensitivity from geomorphic classification. For example, Figure 7.3 shows a general relationship between sediment load, channel stability and channel form first proposed by Schumm (1977) that grades from straight, through meandering to braided channels with no abrupt breaks in between.

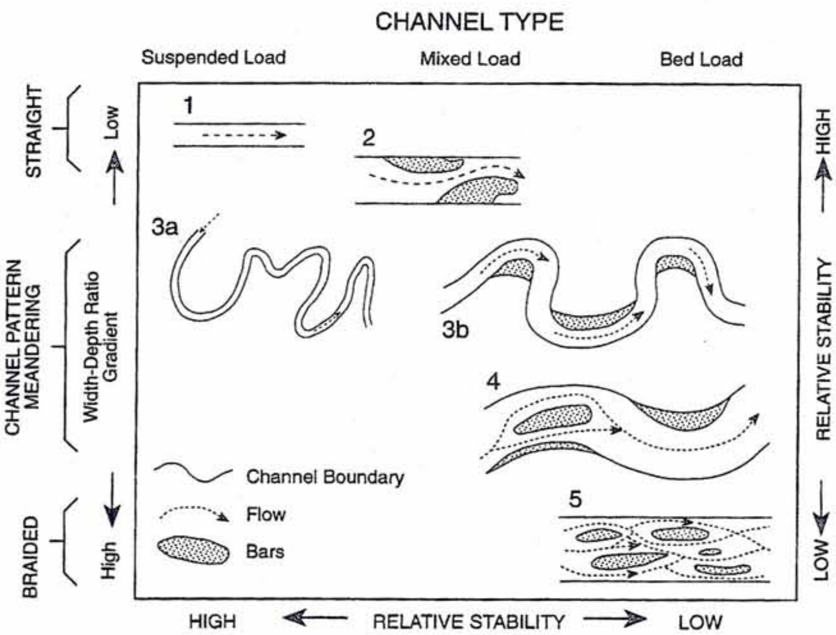

Figure 7.3 Classification of channel pattern based on sediment load and system stability (adapted from Schumm, 1977)

7.4 CHANNEL PLANFORM CLASSIFICATIONS AND CHARACTERISTICS

7.4.1 Channel Form and Processes

Channels with fine sediment moving in suspension and highly erosion-resistant boundary materials are relatively the most stable and follow straight and slightly sinuous courses (Types 1 and 2 in Figure 7.3). Such channels are often effectively confined by their bank materials and display rates of lateral shifting and planform evolution that are slow, or imperceptible. Leopold and Wolman (1957) classified a stream as straight if its sinuosity (ratio of channel length to valley length) was less than 1.1, sinuous if it was between 1.1 and 1.5 and meandering if it exceeded 1.5. Although these limiting values are somewhat arbitrary, they have become entrenched in the literature and remain widely accepted as the critical limits of sinuosity for a stream to be classed as straight, sinuous or meandering.

Mixed-load streams, with more mobile bed materials, greater sediment supply and resistant but somewhat erodible banks, adopt dynamic, meandering courses (Types 3 and 4 in Figure 7.3). These channels migrate freely across their floodplains through a combination of cut-bank erosion and point bar growth interspersed with neck and chute cutoffs of tight bends.

Rivers with sufficiently high energy to transport abundant, relatively coarse sediment moving as significant bedload, and with weak bank materials (which erode and thereby also contribute to the sediment load), tend to have very wide channels that feature multithreaded, braided patterns (Type 5 in Figure 7.3). Braided channels are made up of subchannels called *anabranches* which are separated by braid bars that are inundated at bankfull stage. Such channels are of low stability and they wander across their floodplains unpredictably through a combination of rapid, localised bank erosion and frequent anabranch avulsions. In some rivers the braid bars grow to the extent that they are not inundated even at bankfull stage, allowing them to vegetate and stabilise as semi-permanent islands. In this case the channel pattern is conventionally classified as *anastomosed.*

Anastomosing was for many years viewed as a particularly intense form of braiding (Leopold and Wolman, 1957). However, more recent research on anastomosed channels suggests that they may often in fact be geomorphologically distinct from braided systems. Work in the 1970s by Miall (1977) and by Smith and Smith (1980) showed that anastomosed rivers, with highly sinuous anabranches separated by large, vegetated areas of land at about the same elevation as the floodplain, are actually associated with low-energy fluvial systems. This led Rust (1978) to propose another qualitative diagram for the continuum of patterns, using sinuosity and degree of channel division as its axes and allowing subdivision of divided rivers based on their sinuosity (Figure 7.4). The forms and features of low-energy, anastomosing channels are now accepted as sufficiently different from conventional high-energy braided systems to merit a separate classification (Nanson and Croke, 1992). As a result there are now four generally accepted operational classes of channel, rather than Leopold and Wolman's original three.

Having recognised the fact that channel patterns form a continuum, when undertaking a closer examination of the geomorphological forms and features of alluvial channels it is still convenient to consider channels separately according to whether the channel at

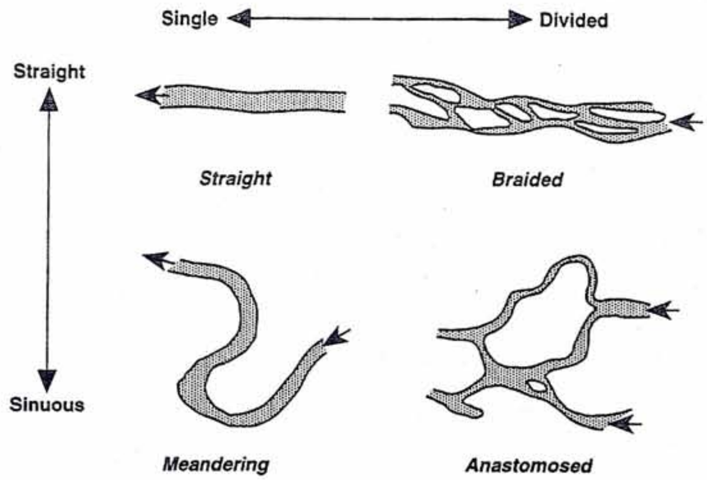

Figure 7.4 Classification of channel pattern based on sinuosity and degree of channel division (adapted from Rust,1978)

formative flow is straight, meandering, braided or anastomosed. This convention is therefore adopted here.

7.4.2 Straight Channels

The relative rarity of straight alluvial channels has been much commented on by geomorphologists. While this rarity may partly be attributed to variability in local floodplain topography, bank material properties and riparian vegetation that drive random bank collapses, there remains the fact that the vast majority of unconfined, single-thread streams follow a sinuous or meandering course. Even where a channel does follow a straight course for a significant distance, it is usually found that the paths of both the filament of maximum velocity and the line of the deepest point, or *thalweg*, oscillate across the width to describe a sinuous pattern within the straight alignment of the banks. The tendency to produce a sinuous thalweg is closely related to vertical oscillations in the bed elevation termed *pools* (deeps) and *riffles* (shallows) which are clearly defined in gravel-bed rivers but can also be detected in sand-bed streams.

The pool–riffle couplet represents the basic geomorphic unit of the straight river and the overall form and features of the stream can be explained in terms of pool–riffle combinations and their impacts on the channel geometry. Hence, a morphological description of the features of straight alluvial channels must still account for the presence of three-dimensional features and must explain the link between planform and cross-sectional geometries.

Relation Between Channel Pattern and Cross-sectional Geometry in Straight Rivers: Pool–Riffle Sequences, Channel Asymmetry and the Distribution of Bank Erosion

The bed topography in straight alluvial channels is non-uniform, especially where the bed material is sufficiently widely graded that selective entrainment, transport and deposition produces systematic sorting of grain sizes between scour pools and riffle bars. Riffles are the topographic high points in the undulating long profile, while pools are the intervening low points (Figure 7.5). In gravel- and cobble-bed streams it is generally found that bed materials on riffles are coarser than those in pools, at least at low flows when sampling usually takes place. Working on straight and meandering gravel-bed rivers, Hey and Thorne (1986) found that:

$$RD_{50} = 1.19\,D_{50} \qquad (r^2 = 0.95) \tag{7.1}$$

where, RD_{50} = riffle bed material median size (mm) and D_{50} = channel average bed material median size (mm). The occurrence of coarser bed materials with open structures and voids between them in riffles is not only important morphologically, but is also crucial in providing spawning habitat for fish.

At low and intermediate flows riffles act as natural, in-channel weirs that pond water in the pool upstream. The head of water in the pool upstream of a riffle drives flow through the bar that keeps the voids between coarse particles clear of silt. This, again, is not only important morphologically, but is also vital to oxygenate fish eggs buried in redds in the riffle. Flow in the pools is deeper and slower than would be expected in a channel of uniform cross-section, while flow over the riffle is shallow, rapid and tumbling. Pools not only tend to trap fine sediment during low-flow periods, but they also provide refuges for fish to rest and to hide from predators.

The details of flow behind, through and over riffles and the existence of local low-flow variability produced by pool–riffle bed topography are vital to providing a diverse habitat in the stream and in this respect the importance of these natural geomorphic bed controls in supporting valuable ecosystems cannot be over-emphasised.

Riffles are usually spaced fairly evenly along the channel at a distance scaled on the top-width. Leopold et al. (1964) noted that the riffle spacing was five to seven times the channel width. Thirty years of further observations and measurements has not altered this assertion. For example, Hey and Thorne (1986), working in British gravel-bed rivers with single-thread channels and a mixture of straight, sinuous and meandering planforms, found a strong correlation between width and riffle spacing (Figure 7.6a). They found that riffle spacing (measured along the line of the channel centreline) could be defined by:

$$z = 6.31w \tag{7.2}$$

where z = riffle spacing (m) and w = bankfull width (m). The coefficient of determination was 0.88 and the range on riffle spacing was between four and 10 times the width for the

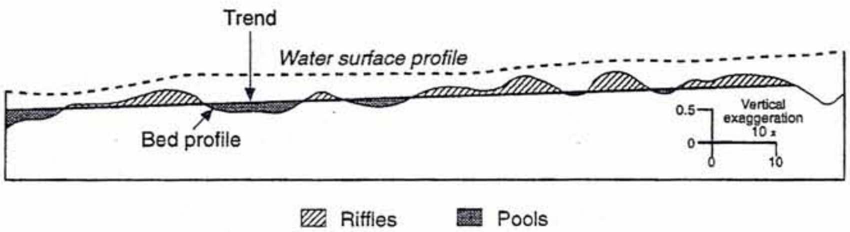

Figure 7.5 Pool–riffle sequence in a straight, gravel-bed channel: the River Fowey, England (modified from Richards, 1982)

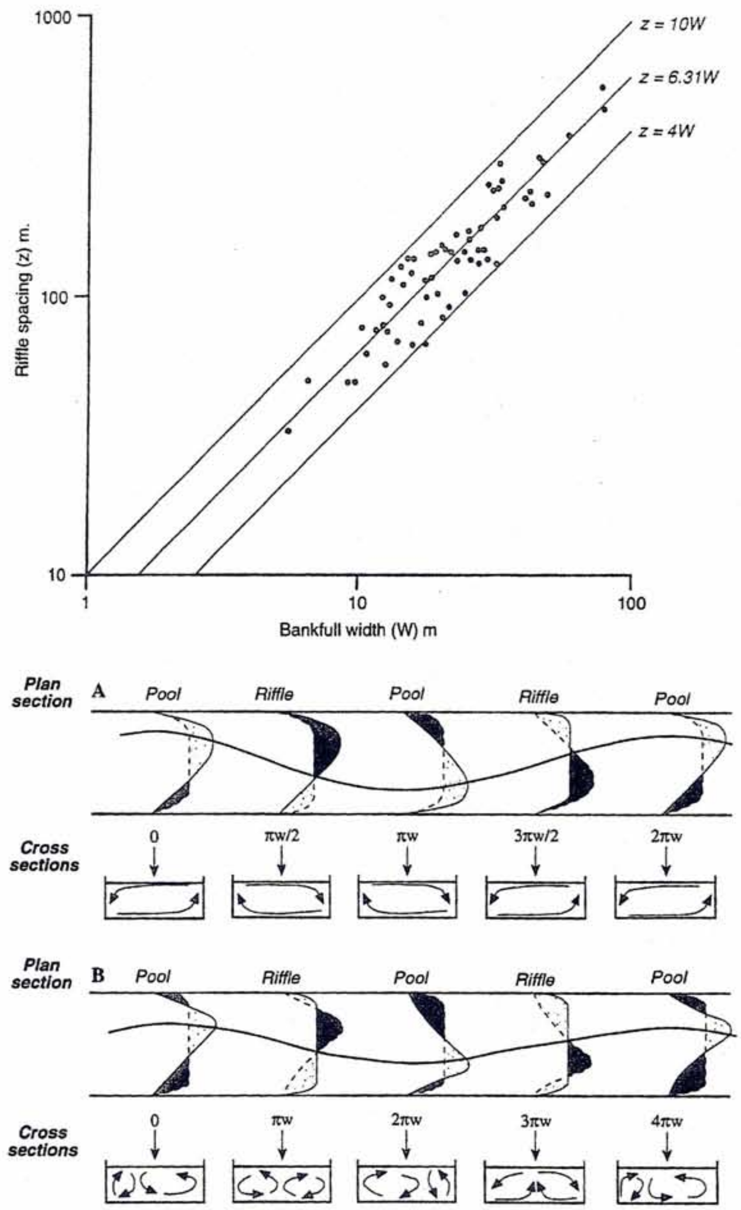

Figure 7.6 (a) Riffle spacing as a function of bankfull width (modified from Hey and Thorne, 1986). (b) Rational explanation of riffle spacing by Hey (1976) based on the theoretical work of Yalin (1972)

great majority of sites surveyed. However, the geometric regularity of pool and riffle spacing does not itself explain their formation.

It is generally accepted that pools and riffles are a dynamic response in the form of the channel to large-scale non-uniformity in the distributions of velocity, boundary shear stress and sediment transport. Theoretical work on the geometry and spacing of macro-turbulence and large-scale flow structures by Yalin (1972) suggested that riffle spacing should be π times the width, but this is half the observed spacing (Eqn 8.2). Hey (1976) re-examined Yalin's theory. He noted that while Yalin had assumed that secondary flow in straight channels was dominated by a single large cell extending across the whole width, field and flume observations showed that secondary flow in straight channels actually features twin cells of secondary circulation, which alternately dominate the pattern (Figure 7.6b). Based on Hey's reanalysis it would be expected that riffle spacing should be 2π times the width. The coefficient in Eqn 7.2 is in fact practically identical to 2π (6.28). This very strong periodicity in riffle spacing indicates a close analogy to meander arc length in sinuous streams (which is also about 2π times the width) and suggests that the processes responsible for meandering also operate in straight streams.

The local variability associated with pool–riffle bed topography in straight and meandering streams was also characterised by Hey and Thorne (1986) in the form of modifications to the equations defining the stable, or regime, hydraulic geometry of the channel as a whole:

$$R_w = 1.034w \qquad (r^2 = 0.97) \tag{7.3}$$

$$R_d = 0.951d \qquad (r^2 = 0.97) \tag{7.4}$$

$$R_{dm} = 0.912d_m \qquad (r^2 = 0.96) \tag{7.5}$$

$$R_v = 1.033v \qquad (r^2 = 0.92) \tag{7.6}$$

where R_w = riffle bankfull width (m), w = channel bankfull width (m), R_d = riffle bankfull mean depth (m), d = channel bankfull mean depth (m), R_{dm} = riffle bankfull maximum depth (m), d_m = channel bankfull maximum depth (m), R_v = riffle bankfull mean velocity (m/s) and v = channel bankfull mean velocity (m/s). These relationships show that, morphologically, riffles are a little shallower and wider than the average dimensions of the channel, even at bankfull stage. This variability is much greater at lower flows and accounts for many of the aesthetic features provided by natural alluvial channels that are often lacking in engineered channels. Differences between pools and riffles decrease as flow stage increases and probably disappear at about bankfull flow.

The pool–riffle sequence in the bed is generated by a combination of turbulent velocity fluctuations and large-scale, coherent flow structures which drive sediment pulsing and produce alternating areas of scour and fill along the axis of the flow (see Section III and the other chapters in this Section). These flow structures are three-dimensional and they generate lateral as well as vertical non-uniformity. The morphological result of this lateral non-uniformity of the flow is for pools to develop asymmetrically, with deep scour adjacent to one bank and a shoaling bar at the opposite bank, the sense of asymmetry alternating from one side of the channel to the other between consecutive pools (Figure 7.7). Riffles, between pools which are on opposite sides of the channel centreline, then become locations where the thalweg and maximum velocity filament cross the channel from one pool to the next.

Deep scour and high-velocity flow close to one bank in the asymmetrical pools and impinging flow attacking one bank just downstream of the riffles often generates bank instability and retreat. In such cases, the stream will not remain straight since retreat of alternate banks in pools along its length leads directly to the development of a sinuous

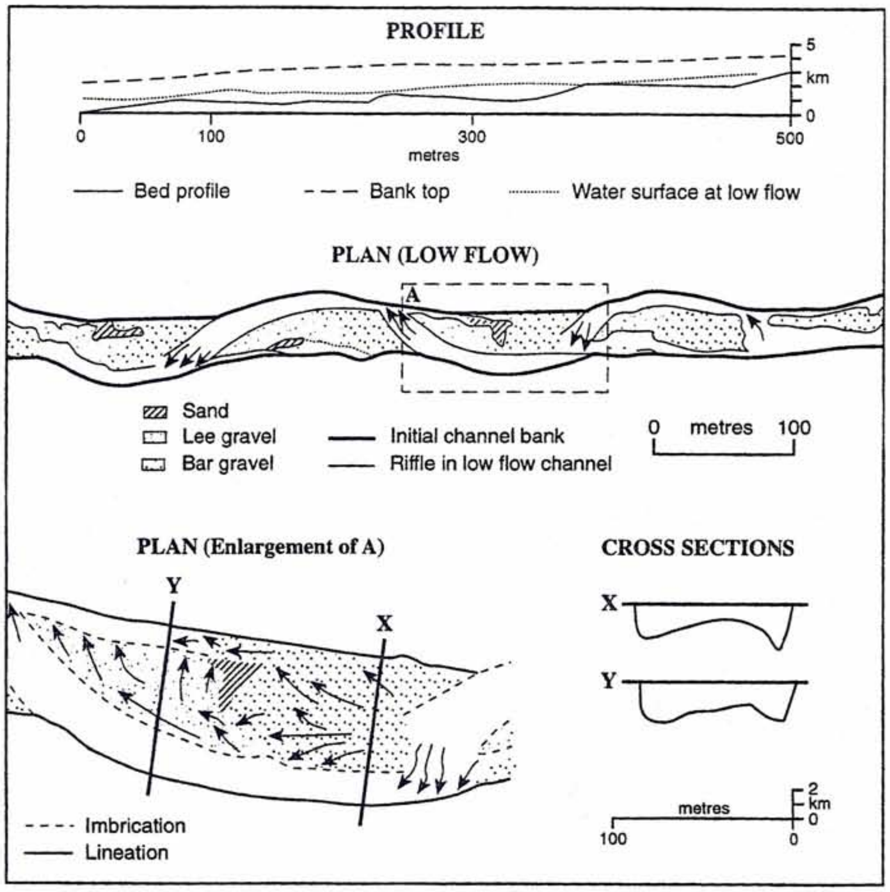

Figure 7.7 Formation of asymmetrical pools, alternate bars and riffle crossings in a straight alluvial channel (adapted from Richards, 1982)

planform. In most models of channel planform evolution the riffles become points of inflection in the sinuous pattern, with cut banks persisting at the outside of bends developing in the pools and the alternate bars growing at the inside of the bends becoming point bars (Figure 7.8). Since this development is the consequence on flow structures and bed asymmetry that definitely pre-existed in the straight channel, it is apparent that meandering is a natural progression of tendencies found even in entirely straight streams. This makes it hard to argue that an abrupt 'geomorphic threshold' exists between the straight and meandering forms, other than that the ability to erode the banks is essential if the planform as defined by the banklines is to be made sinuous.

The topics of bank erosion and retreat are dealt with in detail in Chapter 6, but it is relevant to point out here that, since bank stability and retreat are closely linked to processes operating at the bed through the concept of 'basal endpoint control', bank retreat adjacent to deeply scoured, asymmetrical pools is almost a certainty if the bank materials are alluvial. Only in confined channels can meandering tendencies due to active

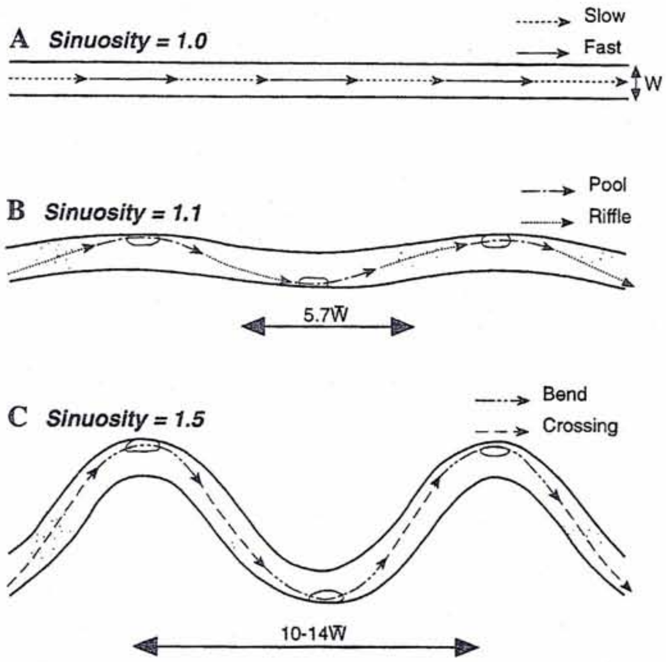

Figure 7.8 Transition from a straight to a meandering course through bank erosion and point-bar growth (adapted from Chorley et al. (1984)).

development of asymmetrical bed topography be frustrated by bank resistance to erosion and mass instability. However, the power of the flow to erode the channel boundaries must never be underestimated, and meanders incised into solid bedrock bear witness to the fact that flow scour and mass-wasting will usually prevail over bank resistance, given sufficient time. Viewed in this light, the rarity of straight, natural channels is no longer surprising.

7.4.3 Meandering Channels

Meander Planform Geometry

Meanders are usually defined geometrically in terms of their shape, bend radius of curvature and wavelength (Figure 7.9). The channel width at the dominant discharge or 'channel-forming flow' is used to scale the geometric relationships.

The vast majority of streams follow a winding, more or less sinuous course and are usually morphologically classified as meandering. However, it is important to recognise at the outset that not all sinuous channels with bends are necessarily actively meandering through cut-bank erosion and point-bar growth. Unless a further distinction is made by classifying sinuous channels as exhibiting either *active* or *passive* meandering, then correct interpretation of the morphological forms and sensitivity of the channel will be difficult. The remainder of this discussion of meandering channels is relevant to active meandering.

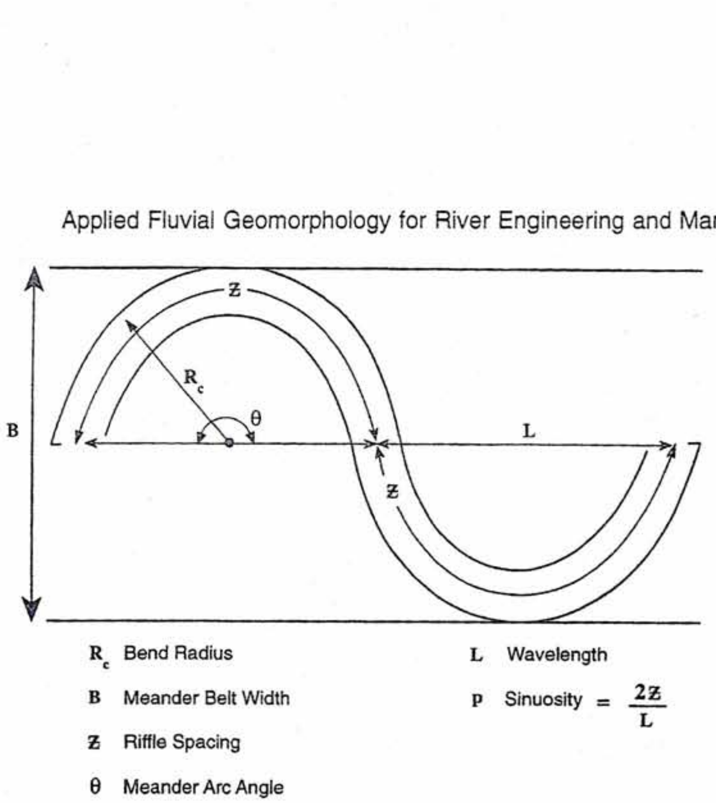

Figure 7.9 Definition diagram for meander planform

A brief outline of active and passive meandering, and how to tell the difference in the field, is given in Box 7.2.

Studies of meander shape were initiated by Leopold and Langbein (1966) who attempted to characterise the planform of meanders in terms of a generalised geometric shape. Figure 7.11 shows the four types of curve proposed by Leopold and Langbein.

Box 7.2 Active versus passive meandering

Active meandering is the result of on-going bed and bank deformation by the flow in a self-formed alluvial channel. The topography of pools and riffles in the bed is matched to the pattern of bends and crossings in the planform, with pools being located at bends and riffles being found at crossings. The riffle spacing (five to seven times the width) is very close to half the meander wavelength (10 to 14 times the width), so that there is in general only one deep pool in each bendway and only one distinct riffle in each crossing reach.

Streams with sinuous courses which do not meet these criteria should be classified as having *passive meandering*. For example, Richards (1982) used the Afon Elan in Wales to show how an apparently meandering stream may actually be following a sinuous course only because of planform patterns imposed by the local terrain. The Elan (Figure 7.10) is an underfit stream (see Chapters 2 and 3) which no longer has the stream power necessary to deform its channel boundaries through active bed scour and bank erosion. The channel follows a sinuous course, but meander wavelength is much greater than 10–14 times the width and there are several pool–riffle units in each bendway. Bends occur because the bluffs confining the stream deflect it back and forth across the comparatively narrow floodplain. Morphologically, passive streams of this type are distinct from freely meandering systems which are more actively forming the landscape. They have more in common with straight streams and are better classified as either confined, or geomorphologically straight.

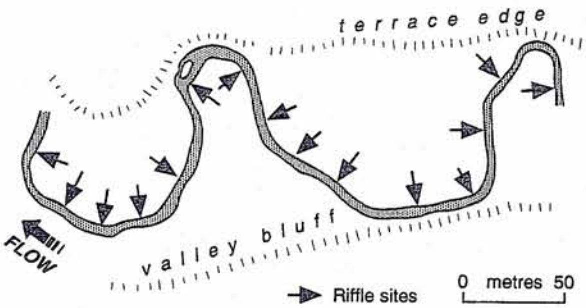

Figure 7.10 Planform of the Afon Elan, Wales. The sweeping bends appear to be classic alluvial features but are in fact the result of diversions of the stream by valley side bluffs. The channel is more properly classified as confined with passive meandering (adapted from Richards, 1982)

They found that a sine-generated curve resembled an idealised meandering river. This curve closely approximates the curve of least work in turning around the bend and they put this forward as an explanation of the form of natural meanders. The path of the river following a sine-generated curve is defined by:

$$\phi = \phi_{\max} \sin[(x/T)2\pi] \tag{7.7}$$

Leopold and Langbein (1966) noted at the time that real bendways are asymmetrical and deviate significantly from the idealised, perfect symmetry of the sine-generated curve. This asymmetry is associated with the fact that the points of deepest bed scour and of maximum attack on the outer bank in bends are usually located downstream of the geometric apex of the bend, so that through time the bends migrate downstream, becoming skewed in the downvalley direction as they shift. Several researchers, including notably Ferguson (1973)

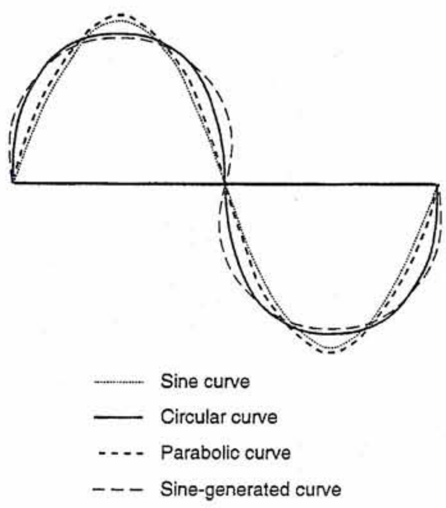

Figure 7.11 Geometric curves investigated by Leopold and Langbein to define meander shape in terms of minimisation of work (adapted from Leopold, 1994)

and Carson and Lapointe (1983), have examined many models of bend shape and concluded that symmetrical models cannot correctly reproduce the downvalley asymmetry that is an essential feature of real meanders.

In nature, every meandering river has a pattern made up of a complicated and unique series of bends connected by short, more or less straight, intervening reaches. If valley terrain and sedimentary variability were the primary controls on meander form then it would be expected that meander patterns would produce random planform attributes. However, while irregular planform paths do occur, in general this is not the case. Leopold and Wolman (1957, 1960) produced graphs linking meander wavelength to channel width over several orders of scale of flow (Figure 7.12) and in a variety of natural environments. They found that power law relationships described the range of wavelengths observed and these were defined by:

$$L = 7.32w^{1.1} \tag{7.8}$$

to

$$L = 12.13w^{1.09} \tag{7.9}$$

where L = meander wavelength measured along the axis of the channel (m), and w = channel top width at the dominant discharge (m). It is important to note the range in the multiplier of width, which indicates that there is real variability in the wavelength to width relationship of natural meanders.

Subsequent reanalysis of Leopold and Wolman's data has shown that because the exponents in Eqns 7.8 and 7.9 are not significantly different from one another, a linear function fitted through the data is acceptable. This has been defined by Richards (1982) as:

$$L = 12.34w \tag{7.10}$$

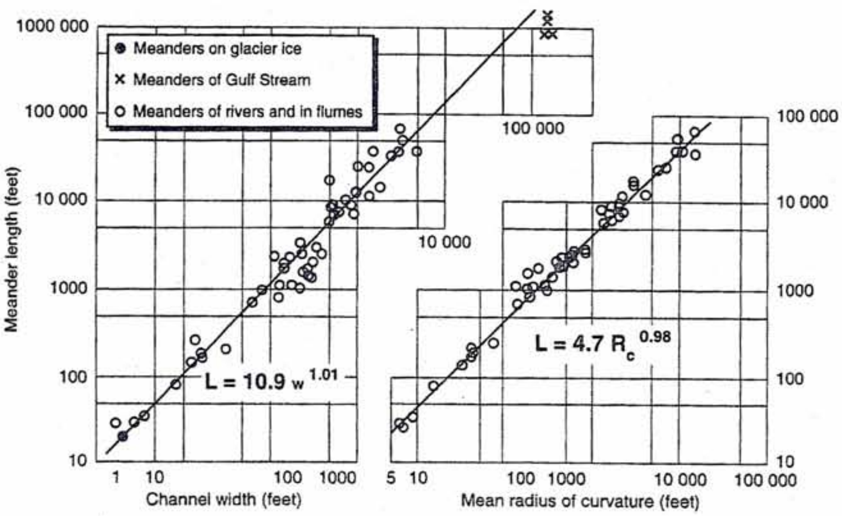

Figure 7.12 Relationship between meander wavelength and channel width (adapted from Leopold, 1994)

In this equation the coefficient is numerically very close to 4π (12.57), which is twice the riffle spacing in a straight channel. Although, strictly, the riffle spacing in a meandering channel should be measured along the channel rather than along the axis of the meanders, this matching of waveforms in the bed topography and planform is almost certainly related to turbulent flow structures and secondary currents in the flowing water that are responsible for the genesis of non-uniformity in the channel in both straight and meandering channels.

Because the channel top width of an alluvial channel is closely related to discharge through hydraulic geometry relationships, it follows that there should be a relationship between discharge and wavelength. Allen (1970) found such a link and suggested the equation:

$$L = 168Q_{\mathrm{a}}^{0.46} \tag{7.11}$$

where Q_{a} = the mean annual discharge ($\mathrm{m^3/s}$). In fact, mean annual discharge has little or no geomorphic significance and so a relationship based on bankfull discharge (often taken as the channel-forming flow) is more meaningful, morphologically. Dury (1956) suggested:

$$L = 54.3Q_{\mathrm{b}}^{0.5} \tag{7.12}$$

where Q_{b} = bankfull discharge ($\mathrm{m^3/s}$). However, it is known that sediment load and boundary materials have real impacts on channel geometry as well as discharge (see Chapter 8). While the use of channel width as a scaling factor for meander wavelength to some extent incorporates these impacts implicitly, the use of discharge alone ignores them completely. This may explain why the relationships based on discharge are less general and much less popular than those based on width.

Schumm (1968) attempted to take account of the effect of boundary materials on meander wavelength explicitly by using a weighted silt-clay index of the bed and bank sediments. He analysed large empirical data sets for sand-bed rivers and streams to produce:

$$L = 1935Q_{\mathrm{m}}^{0.34}M^{-0.74} \tag{7.13}$$

$$L = 618Q_{\mathrm{b}}^{0.43}M^{-0.74} \tag{7.14}$$

$$L = 395Q_{\mathrm{ma}}^{0.74}M^{-0.74} \tag{7.15}$$

where Q_{m} = mean annual discharge ($\mathrm{m^3/s}$), Q_{b} = bankfull discharge ($\mathrm{m^3/s}$), Q_{ma} = mean annual flood ($\mathrm{m^3/s}$), and M = weighted silt-clay index. As expected, each equation shows that as the proportion of fine material in the bed and banks increases, the meander wavelength for a given discharge decreases. This is taken to indicate that the greater erosion resistance of silt-clay banks allows a narrow cross-section with steeper banks and tighter, shorter wavelength bends to develop than is the case for friable, easily eroded banks in sand.

Schumm (1963) had already demonstrated that channel sinuosity was related to the weighted silt-clay index and the form ratio (width/depth) using the relations:

$$p = 0.94M^{0.25} \tag{7.16}$$

$$p = 3.50F^{-0.27} \tag{7.17}$$

where p = planform sinuosity and F = width/depth ratio. These relationships form a rational and logical set of empirical equations linking the characteristic wavelength of meandering channels to the formative flow in the channel, its width and the nature of the boundary sediments.

Meander wavelength and bend radius of curvature are closely related, since as the wavelength shortens, bends, necessarily, tend to tighten. Leopold and Wolman (1960) derived an equation describing this relationship:

$$L = 4.59R_c^{0.98} \tag{7.18}$$

where R_c = bend radius of curvature (m). Combining the wavelength relations with width and with bend radius, it follows that:

$$R_c \approx 2 - 3w \tag{7.19}$$

This morphological relationship, arrived at empirically by Leopold and Wolman, was shown at the same time by Bagnold (1960) to have a basis in the theory of physics. Bagnold's work on flow hydraulics and energy losses at bends indicated that at a bend radius-to-width ratio of 2 to 3, energy losses due to the curving of flow in the bend were minimised. Tighter bends produced extensive areas of flow separation at both the outer bank at the bend entrance, and the inner bank at the bend exit. Separation produced large energy losses due to flow constriction, large-scale eddying and distortion of the free surface (Bagnold termed this spill-resistance) so that bends tighter than an R_c/w of 2 exhibited a disrupted flow pattern and high flow resistance. Plots of both meander migration rate and bend scour depth as a function of bend tightness also peak sharply at an R_c/w of between 2 and 3, indicating that such bends are the most effective at eroding their bed and banks (see below and Chapter 9). The fact that in nature many bends develop to an R_c/w value of 2 to 3 and then retain that form while migrating across the floodplain may, therefore, be consistent with their conforming to the most efficient hydraulic shape, which also maximises their geomorphic effectiveness. However, Hey (1976) pointed out that the relationship between width and bend radius also depends on the arc length of the bend. He plotted a graph which generalises Leopold and Wolman's relationship for bends with various arc angles and in various intermediate stages of evolution from meander genesis to loop cutoff and abandonment (Figure 7.13). Data from the Rivers Tweed and Wye were used to validate the geometric relationship between these bend parameters. The data also illustrate the fact that an R_c/w of 2.4 combined with an arc angle of 150° forms a boundary to bend evolution for these particular rivers. This geometry is typical of many natural, alluvial streams with freely meandering planforms.

Figure 7.13, taken together with the various equations and rules-of-thumb for meander morphology quoted here, could be used to assess the form of existing meander bends in engineering-geomorphic studies, or could form the basis for restoring a straightened

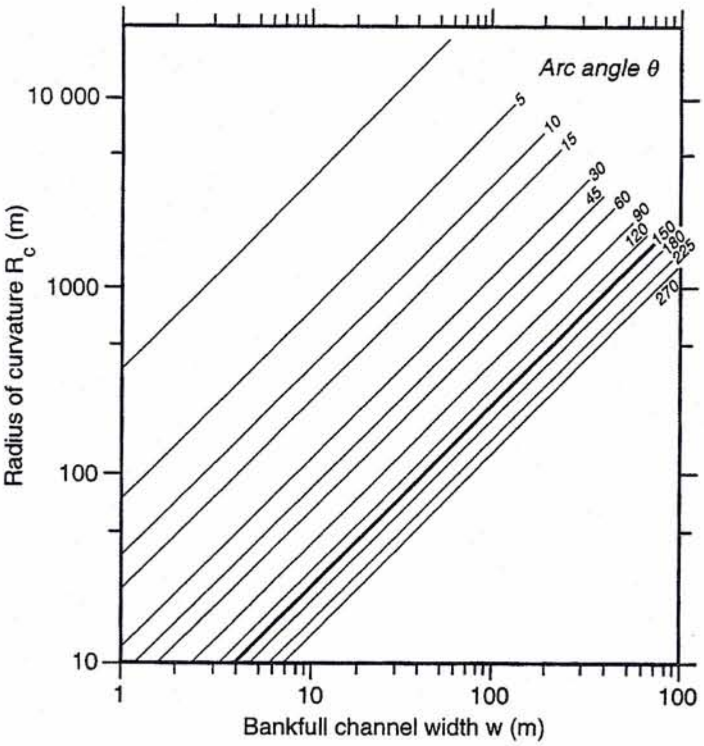

Figure 7.13 Relationship between bankfull width, meander bend radius and bend length (represented by meander arc angle) (after Hey 1976)

stream to a sinuous pattern that mimics the planform of a natural single-thread channel. But it is important to remember that despite such generalities of alluvial meander geometry, in real rivers perfectly formed meanders are, in fact, the exception rather than the rule.

Fisk (1944,1947), working on the Lower Mississippi, identified that the form of most meanders was influenced by variations in the erodibility of the materials encountered in the outer bank. He concluded that outcrops of erosion-resistant clays in the bank have the strongest influence and that such outcrops slowed bank erosion locally, distorting the curve of the outer bank, changing the flow direction and inducing a decrease in the bend radius of curvature. 'Clay plugs' are frequently encountered by rivers meandering across alluvial floodplains. They are produced by infilling of old meander bend scars and abandoned channels by overbank and backswamp deposition of fine sediment. Fisk (1944) set out examples of the effect of clay plugs on meander form and Schumm and Thorne (1989) suggested how these can be used to identify the presence of a resistant hard point in the bank, in the field, from channel maps or from aerial photographs (Figure 7.14b). Thorne (1992) described specific examples of bend deformation by clay plugs and other resistant outcrops. Salient points from these papers are given in Box 7.3.

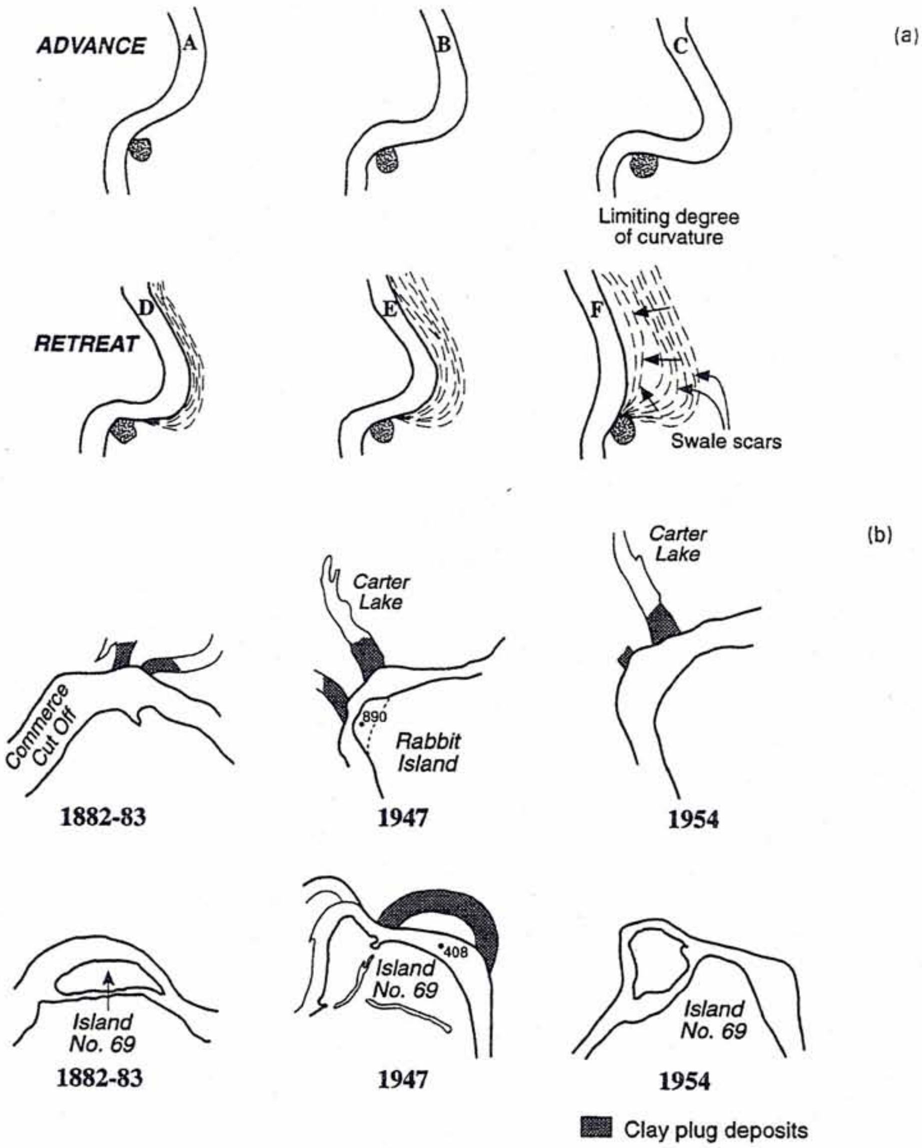

Figure 7.14 (a) Theoretical impact of a hard point on meander morphology and evolution (after Reid, 1984). (b) Empirical impact of hard points on meander morphology and evolution: examples from the Lower Mississippi (after Schumm and Thorne, 1989)

Relationship Between Channel Pattern and Cross-sectional Geometry in Meandering Rivers

The hydraulics and morphology of meandering rivers have received close attention from fluvial geomorphologists over many years. Although much is now known about the flow processes, sediment dynamics and morphological features of actively meandering

Box 7.3 Deformation of meander bends due to clay plugs and hard points

When the river encounters erosion-resistant material in the outer, retreating bank, there are morphological responses both locally and throughout the bend. Irregularities in the planform of the bend can, therefore, be used to detect the influence of resistant materials and their presence can then be taken into account when analysing and predicting channel evolution and sensitivity to river engineering and management.

The immediate effect of resistant material is to slow the local rate of bank retreat. If the longstream extent of the resistant material is short compared to the length of the bend then the outcrop constitutes a *hard point*. As the surrounding bank continues to retreat, the hard point develops into a local bank promontory. This deflects the flow, inducing local acceleration of the primary flow, intense turbulence and strong secondary currents which cause deep bed scour and increased erosion of the surrounding, weaker bank materials. This usually leads to flanking of the hard point. However, in cases where the hard point cannot be flanked easily, the bend may become so deflected that flow adjacent to the outer bank stalls and separates, leading to bar deposition of an outer bank bench and flow attack of the point bar opposite. This in turn leads either to the active channel progressively 'backing out' of the bend, as described by Reid (1984) (Figure 7.14a), or to a chute cutoff across the point bar at the inner bank.

If the resistant material is more extensive, as in the case of most clay plugs, this may be identified as a convexity in the otherwise concave curve of the outer bankline. This deforms the planform of the bend, with particular impacts that depend on the location of the clay plug in the bend. Fisk (1944) described two basic patterns of deformation: when a clay plug is encountered at the bend apex, the apex is flattened and in many cases a compound or double-headed bend develops; if the clay plug is encountered downstream of the bend apex, the downstream limb is fixed in position while the upstream limb continues to shift downvalley, compressing the bend and leading to a neck cutoff. If the presence of a clay plug directs the flow into highly erodible adjacent sediments, a bend of abnormally high amplitude develops that will eventually cutoff. Numerous clay plugs flanking a channel can inhibit meander development and a relatively straight channel will be confined to a narrow zone of the floodplain.

If the resistant material is very extensive, as is the case where a migrating bend comes up against rock or consolidated materials in the valley side, deep scour may develop all along the bank, effectively locking the channel against the valley side for a considerable period until the bend is overtaken by a more mobile bend from upstream.

channels, there remain severe limitations to the applicability of this knowledge in predicting channel cross-sectional parameters such as scour depth for practical river engineering and management (see, for example, publications by Ikeda and Parker (1989) and by Markham and Thorne (1992)).

The topography of the bed and pattern of the planform are closely related, at least for rivers which are freely meandering. It is well known that pools usually occur in bendways and riffles occur in the intervening straight reaches or crossings. It is further known that the depth of pool scour is in some way related to the geometry of the bend. Data assembled from hydrographic surveys of the meandering Red River in Louisiana and Arkansas are typical (Figure 7.15). Scour depth is a function of river size as well as bend geometry and in Figure 8.15 the scour depth is made non-dimensional by dividing the maximum scour depth (BD_m) and the mean scour depth in the bend (BD_b) by the mean depth at the crossing

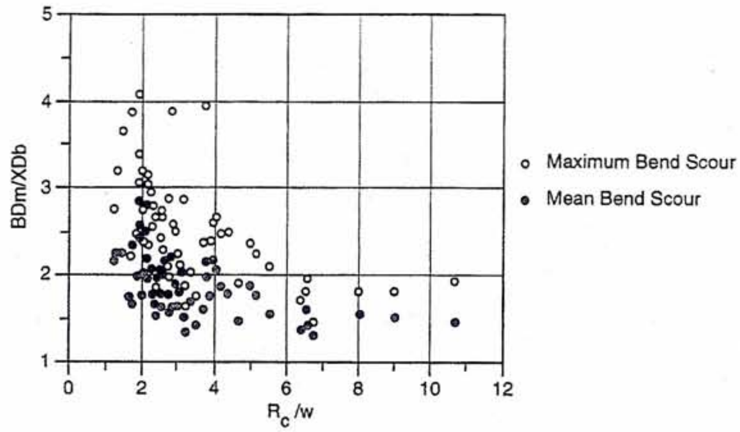

Figure 7.15 Bend pool depths from the Red River, USA (after Thorne, 1989)

upstream (XD_b). The geometry of the bend is represented by the ratio of meander bend radius (R_c) to the channel top width (w), measured at the inflection point upstream. It is important to use the crossing width to non-dimensionalise the bend radius, rather than the width at the bend, because the wide expanse of the point bar at the inner bank often makes it difficult to identify the top bank width in a bend. Also, a reference discharge and associated water level must be used to define the channel dimensions. Ideally, this should be the geomorphologically important 'formative flow', that is the discharge responsible for forming most of the features of the channel. This may be taken as the dominant flow, bankfull discharge or two-year flow. In the case of the Red River data, the two-year flow was used (Biedenharn et al., 1987).

In a study of the Red River, Thorne (1988, 1992) examined the distribution of bend scour with bend geometry and found that in very long radius bends ($R_c/w > 10$) mean scour pool depth is about 1.5 times the mean riffle (crossing) depth and the maximum scour depth is between 1.7 and 2 times the mean crossing depth. This geometry is probably representative of local variability in the parabolic, 'regime' cross-section of the alluvial channel when bend effects are small.

The data from free alluvial meanders show how both the mean and maximum scour depths in the bendway pools increase as a long radius bend becomes tighter and more pronounced. The relationship is non-linear, with scour depths increasing markedly once the R_c/w value decreases to a value below about 5.

For bends with R_c/w values between 2 and 4, scour depths may be anywhere between two and four times the mean crossing depth, with the deepest scour being associated with an R_c/w of about 2. For extremely tight bends with R_c/w less than 2, there is evidence that maximum scour depths decrease with decreasing bend radius. This is consistent with the theoretical and empirical work of Bagnold (1960) which showed that at an R_c/w a distinct change in bend flow hydraulics took place. He found that energy losses at a bend were minimised and the flow efficiency of the bend maximised. For tighter bends the flow pattern broke down to produce large-scale separation at both the outer bank near the entrance and the inner bank at the exit, leading to gross changes in the pattern of erosion, transport and deposition of sediment. Leopold and Wolman (1960) found that most natural bends tend towards R_c/w values in the range 2 to 3, which is consistent with Bagnold's findings. These results also demonstrate the significance of an R_c/w value of about 2 to bend morphology, and suggest that bends with R_c/w values less than 2 must be treated separately when analysing or predicting scour depth. In his study of the Red River, Thorne (1989, 1992) fitted a semi-logarithmic function to the data for maximum scour depth in bends with $R_c/w > 2$. The resulting equation is defined by:

$$(BD_m/XD_b) = 2.07 - 0.19\ \log_e((R_c/w) - 2) \tag{7.20}$$

where BD_m = maximum scour depth in bendway pool (m), XD_b = mean depth at crossing (m), R_c = bend radius of curvature (m), and w = channel width at the crossing (m). This curve fitted the Red River data, from which it was derived, with a statistically significant r^2 of 0.66, but a more stringent test is required if the relationship is to be applicable to any other rivers. In a subsequent study, Thorne and Abt (1993) compiled data from 256 bends on a wide variety of rivers, streams and flume channels. They then used the analytical bend-flow models of Bridge (1982) and Odgaard (1989) and the empirical equation of Thorne (1988) to predict the expected scour depth and compare the results to observed scour depths. The results are plotted in Figure 7.16a. The empirical relationship clearly performs more reliably than the analytical methods, with the great majority of the predictions being within $\pm 30\%$ of the observed value. Figure 7.16b shows the errors plotted as a function of R_c/w. This diagram shows that Odgaard's model actually does quite well for very tight bends with $R_c/w < 2$, although errors of up to 80% may still occur. The empirical equation is inapplicable to these bends. Bridge's model should not be used for such tight bends as it is liable to produce errors of as much as 300%. For longer radius bends Odgaard's model systematically under-predicts scour depth, while Bridge's model is prone to over-prediction. The empirical equation tends to over-predict somewhat, which puts it on the safe side in engineering terms.

It is perhaps disappointing that in 1997 a relatively crude empirical equation can outperform more process-based analytical models. Hopefully, as our ability to model bend flow and sediment interactions improves, this situation will change. At the moment, however, the extremely stringent data requirements of sophisticated and conceptually strong models of bend flow, such as the model of Smith and McLean (1984), make them impractical for day-to-day use as bend scour predictors.

7.4.4 Braided Rivers

Braiding Forms and Processes

Compared to single-thread, meandering channels, much less is known about the morphology of braided rivers. This is partly due to the fact that they have, until recently, received less attention from fluvial geomorphologists, but mostly because their morphology is much more complicated and, therefore, more difficult to define and classify.

The origins of contemporary morphological descriptions of braided rivers may be traced back to Leopold and Wolman's paper *River Channel Patterns – Braided, Meandering and Straight* of 1957. Their paper reported the results of a laboratory flume experiment to

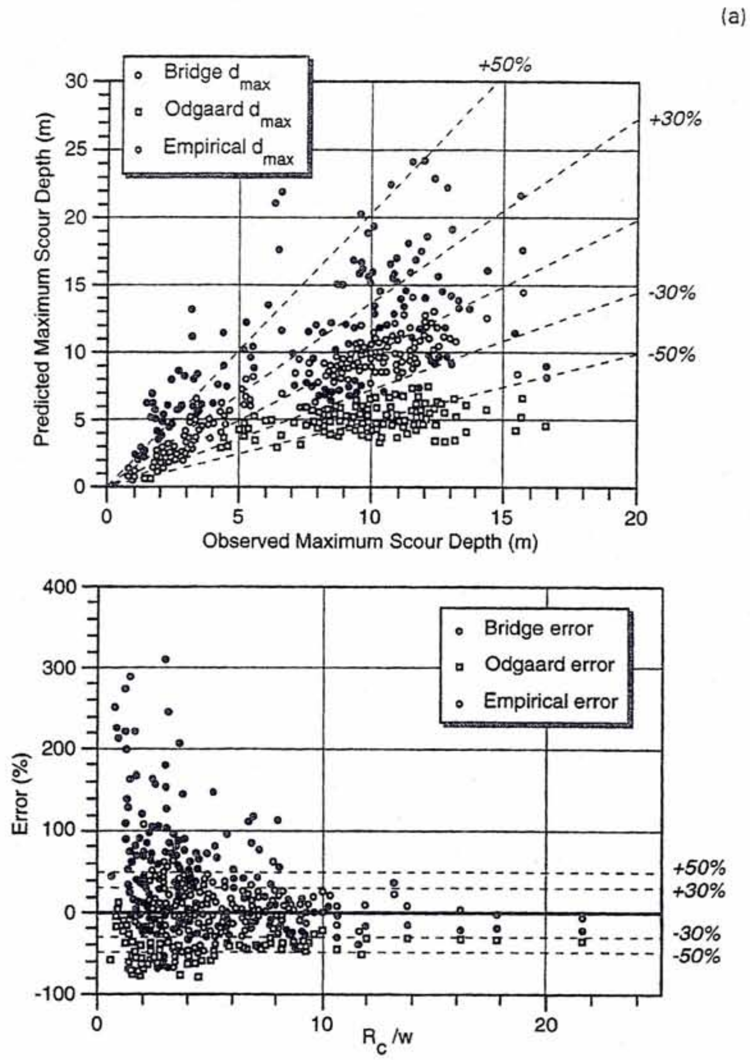

Figure 7.16 (a) Observed and predicted maximum bendway scour depths, and (b) errors as a function of bend geometry (after Thorne and Abt, 1993)

simulate the processes by which a single-thread channel evolved into a multithreaded, braided channel. Figure 7.17 shows the sequence of observed channel changes.

In a channel with abundant bedload, deposition of a mid-channel bar deflects the flow first to one side and then the other, to attack and erode the banks (Figure 7.17, A). The resulting bank retreat feeds sediment to the channel, supporting further bar growth. It also produces a lenticular planform shape to the channel that creates space for lateral expansion of the mid-channel bar (B). As the bar grows and the banks retreat, the subchannels on either side of the bar become increasingly curved, inducing strong secondary currents. The curved flow scours the bed and further erodes the banks at the outer margins of the channel

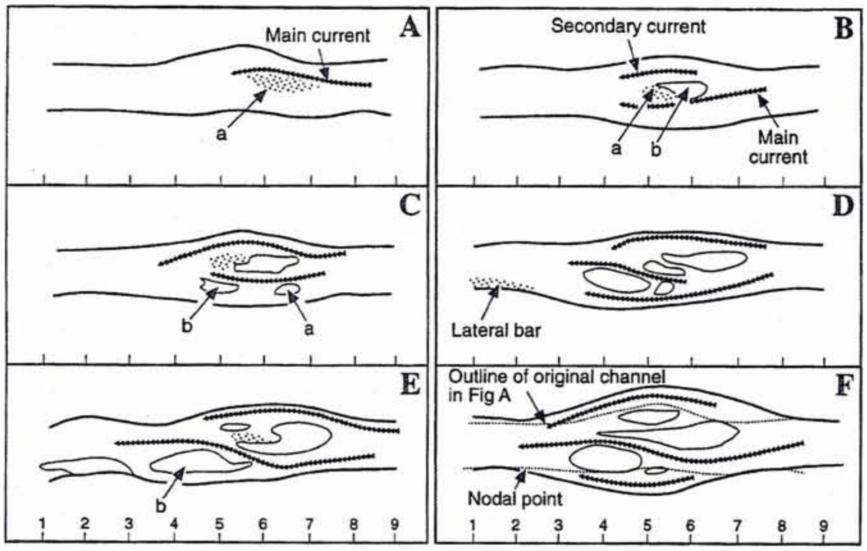

Figure 7.17 Progress in the development of a braided channel (after Leopold and Wolman, 1957)

while driving bed deposition along the inner margins of the anabranches (C). Bed scour in the divided reach lowers the water surface elevation so that the top of the mid-channel bar emerges as an island. Through time, a bar–island complex develops, with multiple flow divisions and subchannels (D and E). Eventually, as the width increases, the bar–island complex may coalesce to form a much larger, semi-permanent island. Mid-channel bar formation in each of the anabranch channels on either side of the island may then lead to further braiding through division of the flow following the same sequence of events. The resulting planform morphology resembles a string of beads, with relatively long, wide, multithreaded island reaches interspersed with shorter, narrower, single-thread nodes (F).

Differentiation of Islands and Bars

Brice (1964) built on Leopold and Wolman's identification of the difference between bars and islands to define these two features of braided river morphology. Bars are defined as dynamic features which are unvegetated and submerged at bankfull stage. Islands are more stable features, emergent at bankfull stage and vegetated. In practice, it is usually possible to differentiate between islands and bars although, as pointed out by Bridge (1993), the terms used to define them are purely qualitative and should be replaced by quantitative terms based on their rates of creation, migration and destruction.

The Braided Pattern: Nodes and Island Reaches

The idea that braided rivers display a node–island pattern was taken up by Coleman (1969) in an important paper describing the morphology of the Brahmaputra River in

Bangladesh. He generalised Leopold and Wolman's findings to produce a generic diagram for the planform/cross-section associations in braided channels that draws parallels with the geometry and wavelength of meandering channels (Figure 7.18).

Coleman's diagram shows how braid bars, asymmetrical cross-sectional geometries in the flanking anabranches, and deep scour holes at confluences combine to link planform geometry to cross-sectional shape in braided rivers. At a node (a–a′ in Figure 7.18), the single-thread channel is narrow and relatively deep owing to confluence scour, although often there may be a pronounced medial bar. At an island reach, the multithread channel is very wide, with deep scour in some anabranches due to flow curvature and shallow channels running across the intervening islands.

The spacing of nodes along the length of the river appears to be scaled on the channel width, although this relationship is not nearly so well established as that for meander wavelength in single-thread channels. For example, in a morphological study of the Brahmaputra River in Bangladesh, Thorne et al. (1993) identified seven islands and eight nodes somewhat evenly spaced along a 220 km reach (Figure 7.19). The average node spacing was about 30 km, which approximates to about six times the 5 km average width of the braided channel. This finding is consistent with the theory of Yalin as modified by Hey (1976), which predicts that nodes should be spaced at about 2π times the width.

Braiding Intensity

Leopold and Wolman (1957) noted how division and subdivision of the channel into increasing numbers of anabranches continued until the flow in the outer, flanking channels was no longer able to erode the banks, input sediment for bar building or increase the braid

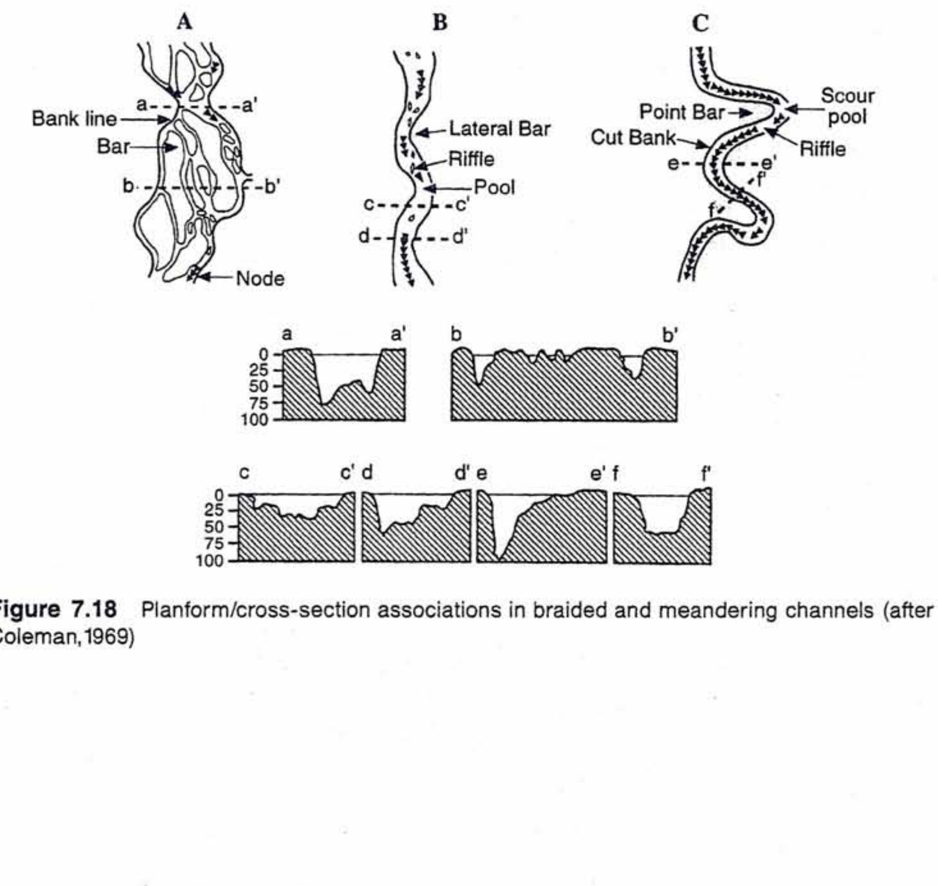

Figure 7.18 Planform/cross-section associations in braided and meandering channels (after Coleman, 1969)

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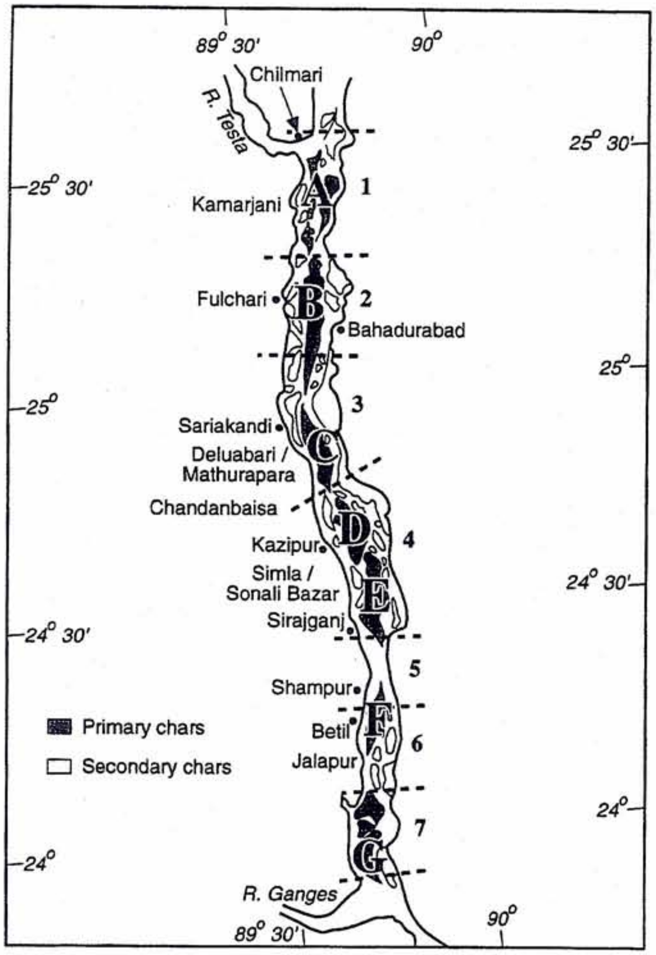


Figure 7.19 Islands, nodes and morphological reaches in the braided pattern of the Brahmaputra River, Bangladesh (after Thorne et al., 1993)

belt width. This infers a relationship between the competence of the stream to erode and transport sediment and the degree of braiding. On this basis researchers have subsequently attempted to develop a quantitative index of braiding intensity to characterise the degree of braiding. Bridge (1993) presented a useful summary of some of the more commonly used indices (Table 7.1).

These indices generally fall into two categories: those based on the number of active subchannels or braid bars at a section across the braid belt; and those based on the ratio of the sum of the channel lengths within a reach to a measure of the reach length. These latter types are actually measures of total sinuosity (as noted by Richards (1982)). In fact, these two types of index are measuring different aspects of braiding, both of which are informative in their own way.

Table 7.1 Braiding indices (modified from Bridge, 1993)

Author	Braiding index
Brice (1960, 1964)	$\text{Braid index} = \dfrac{2(\text{sum of lengths of all bars + islands in the reach})}{\text{centreline length of the reach}}$
Howard et a. (1970)	Braid index = (Av. no. of anabranches per cross-section) − 1
Engelund and Skovgaard (1973), Parker (1976), Fujita (1989)	Mode = number of rows of alternate bars (and sinuous flow paths) = 2 × the number of braid and side bars per cross-section
Rust (1978)	Mode = number of braids per meander wavelength
Hong and Davies (1979)	$\text{Total sinuosity} = \dfrac{\text{length of channel segments}}{\text{channel belt length}}$
Mosley (1981)	$\text{Braiding index} = \dfrac{\text{total length of bankfull channels}}{\text{distance along main channel}}$
Richards (1982)	$\text{Total sinuosity} = \dfrac{\text{total active channel length}}{\text{valley length}}$
Ashmore (1991)	Mean number of active channels per transect, or Mean number of active channel links in braided network
Friend and Sinha (1993)	$\text{Braid channel ratio} = \dfrac{\text{sum of mid-channel lengths of all channels}}{\text{length of mid-line of widest channel}}$

Generally, the first type of braiding index is preferable because it is a measure of the intensity of flow division that is the essence of braiding. This type of index can be used to characterise and compare the intensity of braiding in adjacent reaches and to identify time trends in braiding intensity of particular reaches. For example, Figure 7.20 shows the results of an engineering-geomorphic study of the Brahmaputra River in Bangladesh which were used to establish spatial variations in Howard et al.'s (1970) braiding intensity upstream and downstream of Sirajganj and to identify contrasting time trends in braiding intensity within morphologically defined subreaches (see Figure 7.19 for the locations of the reaches).

The second type of index (based on total sinuosity) combines the intensity of splitting of the flow with a measure of the sinuosity of various channels and subchannels which is, in fact, an entirely different morphological characteristic. Such indices are indeterminate morphologically because (as Bridge (1993) points out) it is possible for a braided river with a large number of relatively straight subchannels to have the same total sinuosity as one with a few, highly sinuous subchannels. Ideally, both a measure of flow division and a measure of total sinuosity should be used to define the planform morphology of a braided reach.

Braiding as an Equilibrium Channel Form

The shifting, changing nature of braided channels and the fact that they are often generated by sediment deposition and bed aggradation has led many engineers and river scientists to associate them almost exclusively with disequilibrium in the fluvial system. Yet Leopold

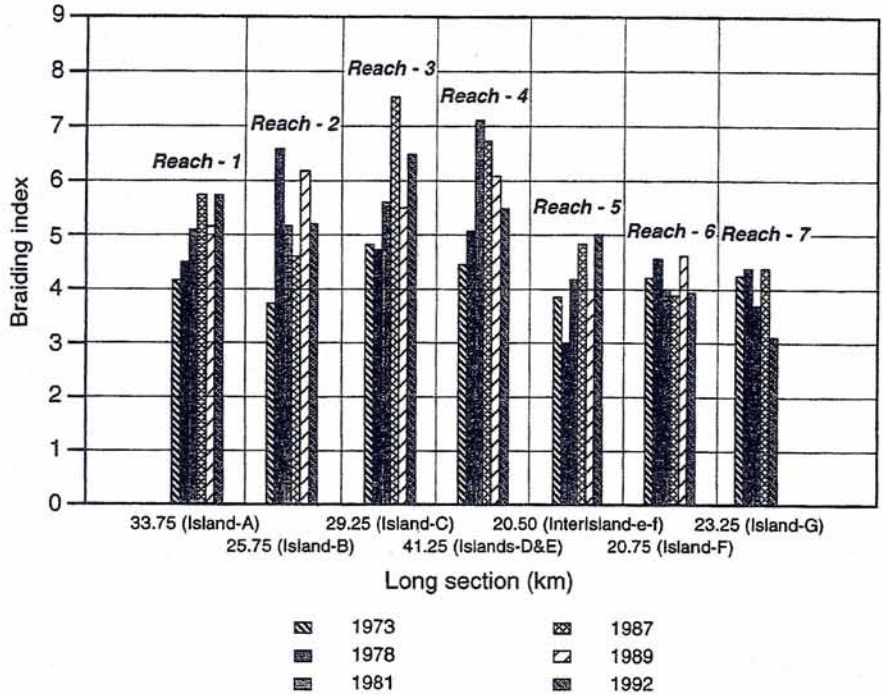


Figure 7.20 Spatial and temporal changes in the braiding intensity of the Brahmaputra River, Bangladesh, measured using the index developed by Howard et al. (1970). Locations of study reaches are marked in Figure 7.19 (after Sir William Halcrow and Partners, 1992)

and Wolman were at pains to point out as long ago as 1957 that braided rivers are a distinct and viable category of dynamically stable planform, along with straight and meandering configurations. The fact is that it is difficult to recognise this stability in systems which exhibit rapid and unpredictable channel changes owing to high mobility of bed and bank sediments and frequent adjustments of the positions and patterns of bars and anabranches. For example, specific gauge analysis of the records for Bahadurabad, on the braided Brahmaputra River in Bangladesh, indicated no significant change in stage levels over a 30 year period during which around 15 billion tonnes of sediment was transported through the section (Sir William Halcrow and Partners, 1992). This demonstrates that it is possible for a braided pattern to be associated with a graded profile, at least over engineering timescales.

Similarly, if a global view is taken of channel pattern, then the state of adjustment of channel form can be revealed. Analysis of satellite images of the Brahmaputra River, using LANDSAT images covering the period 1973–1992, has allowed insights into the overall adjustment of the system that were previously impossible using ground-based observations. In the study, the area of the braid plain was categorised from false-colour images as being water, sand, vegetation or cultivation. Taken together, water and sand represent the active channels and bars of the river, while the areas covered by vegetation and cultivation represent islands. A plot of the areas covered by active channels and bars and by islands reveals organisation and progressive change where formerly there was thought to be disorganisation and disequilibrium (Figure 7.21). The data show how, as the overall area of the braid plain has increased progressively due to widening, the area of active channels and bars has been maintained at between 48% and 52% of the total area. That is, it has been constant to within $\pm 2\%$. This is certainly a form of dynamic equilibrium quite different to that found in single-thread channels, but nevertheless it displays a degree of mutual adjustment not usually recognised in braided channels.

There is a great deal of fundamental research that must be performed before the fluvial forms and processes of braided channels will be properly understood. Until this work has been completed, morphological classifications and characterisations will remain sketchy at best.

7.4.5 Anastomosed Rivers

Differences Between Anastomosed and Braided Rivers

Anastomosed rivers are the fourth and most recently recognised type of channel pattern. The term 'anastomosing' comes from medicine and is used to describe a distributary system of arteries in the body at locations such as the back of the hand. The term seems first to have been applied to rivers by Lane (1957), but it only came into wide usage following work by Miall (1977), Rust (1978) and Smith and Smith (1980). Like braided

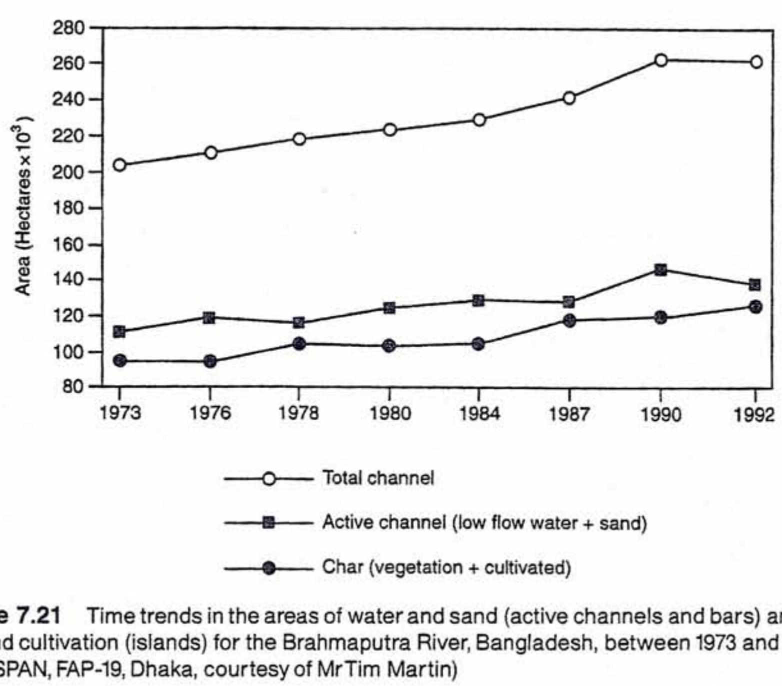


Figure 7.21 Time trends in the areas of water and sand (active channels and bars) and vegetation and cultivation (islands) for the Brahmaputra River, Bangladesh, between 1973 and 1992 (data from ISPAN, FAP-19, Dhaka, courtesy of Mr Tim Martin)

rivers, anastomosed rivers are multithreaded, but they differ fundamentally in at least two important respects.

The first distinctive difference relates to channel morphology (Ferguson, 1987). Braided rivers have a straight or slightly sinuous channel in which the flow diverges, divides and converges around relatively small, mobile, unvegetated sand or gravel bars. The highest elevations of the bars are, on average, a little less than that of the surrounding floodplain so that the bars are submerged and the anabranched flows combined at stages approaching bankfull. Anastomosed rivers have two or more channels, each of high sinuosity, separated by large, semi-permanent, vegetated islands capped by fine-grained sediments such as silts and clays. The highest elevations of the islands are about equal to those of the surrounding floodplain, so that the pattern remains multithreaded even at bankfull stage.

The second distinctive difference relates to channel slope (Ferguson, 1987). Braided rivers generally have relatively steep slopes compared to rivers with similar discharges and single-thread, meandering channels. The steep channel slope is closely associated with the abundant, relatively coarse sediment load which is another characteristic of braided rivers. Anastomosed rivers have slopes which are as low or lower than those associated with equivalent meandering rivers. This fact was first noted by Lane (1957), although the significance of the fact that there were two suites of multithread channels in his plots was not fully realised at the time.

Morphology of Anastomosed Rivers

It is now recognised that anastomosed rivers represent a channel type that is genetically different from braiding. Anastomosed systems comprise of a number of sinuous, low-energy anabranches following paths across the floodplain that, although they cross occasionally, operate independently over considerable distances. In an anastomosed system the lengths of anabranches between junctions is much longer than the characteristic bar length, so that individual anabranch reaches contain their own bars, scaled on the width of that particular anabranch. Anabranches usually meander, often with the highly sinuous, even tortuous, planform associated with low-energy streams flowing through cohesive sediments. On this basis, use of braiding indices based both on flow division and a measure of total sinuosity should allow quantitative differentiation of braided and anastomosed rivers. Braided rivers will display a high degree of flow division and a low total sinuosity, while anastomosed rivers will characteristically have a low degree of flow division and a high total sinuosity. In practice, however, many large alluvial rivers display elements of both braiding and anastomosing at the same time and in the same reaches (Coleman, 1969; Bristow, 1987; Bridge, 1993; Thorne et al., 1993).

Anabranch meanders share the same geometric relationships between channel width, meander wavelength and bend radius as those for single-thread meandering channels. Compared to both single-thread meandering channels and the subchannels in a braided system, anabranches are relatively stable. Rates of bank erosion, bend migration and planform evolution are characteristically small. The channel dynamics, floodplain environment and sedimentary deposits associated with anastomosed rivers are sufficiently distinguishable for them to be classified separately to those of other systems (Nanson and Croke, 1992).

Floodplain Classification of Anastomosed Rivers

In their genetic classification, Nanson and Croke (1992) define anastomosed rivers as producing low-energy, cohesive floodplains. Braided rivers form high-energy, non-cohesive floodplains and meandering systems form medium-energy, non-cohesive floodplains. Consequently, floodplain deposition is dominated by vertical accretion during overbank flows, setting anastomosed systems apart from meandering and braided systems which both tend to build floodplains by lateral point-bar accretion, mid-channel bar accretion and infilling of abandoned channels, as well as vertical accretion.

7.4.6 Prediction of Channel Planform Morphology

Given the marked contrasts of geometry, sedimentology and stability between rivers with different channel types and morphologies, it is not surprising that engineers and scientists need to predict channel pattern and channel pattern changes that might occur in response to changes in the river regime, engineering or management practice. This chapter has emphasised that, notwithstanding the usefulness of considering channel patterns under the headings straight, meandering, braided and anastomosed, there is actually a continuum of planform morphologies. In practice, it is probably the intermediate and transitional forms that occur most frequently, with easily classified forms being the exception rather than the rule. Hence, it is not meaningful to search for sharp dividing lines or geomorphological thresholds between different patterns because, in reality, a range of transitional patterns exists. This is not really a problem; in fact it actually makes life easier for professional engineers. As pointed out by Ferguson (1987), if a river is actually susceptible to pattern transformation from, say, meandering to braided (with serious implications for bankside and floodplain structures and human activities on the floodplain), this should be apparent through the prior existence of a range of channel forms and features that are recognisably transitional between meandering and braiding. If the channel displays only the features of an archetypal meandering stream then geomorphologically it is probably safely remote from the braided threshold in any case.

It is, however, unlikely that such qualitative arguments will convince team leaders, planners and managers and, usually, recourse to a quantitative analysis will be unavoidable. Several criteria exist and Bridge (1993) summarised many of them in a table which is reproduced, in modified form and with some additions, in Table 7.2.

Predictors such as those listed in Table 7.2 are currently out of fashion with geomorphological thinking and are subject to heavy criticism in learned journals and texts. Despite this, they can be used to add a quantitative dimension to qualitative arguments concerning planform evolution and the potential for climate change, sea level rise or engineering intervention in the fluvial system to trigger abrupt changes in channel planform type and morphology. Accepting this, the problem which remains is that of selecting the appropriate predictor for a given situation. A number of studies have been performed to evaluate these predictive models (Julien, 1986, 1987).

Ahmed (1986) used a hydrodynamic stability analysis to predict whether an initially straight channel would remain straight or would tend to either meander or braid. Re-examining the stability approach of Fredsøe (1978), he found that a channel will remain straight if its width/depth ratio is less than 8 and will always braid if its width/depth ratio is greater than 60. Diagrams based on Ahmed's analyses are reproduced in Figure 7.22. His

Table 7.2 Predictors of Channel Pattern (modified from Bridge, 1993)

Author	Function*	Explanation
Lane (1957)	$S < 0.007 Q_{\mathrm{m}}^{-0.25}$	Meandering, sand-bed channels
	$0.0041 Q_{\mathrm{m}}^{-0.25} > S < 0.007 Q_{\mathrm{m}}^{-0.25}$	Meandering–braiding transition
	$S > 0.0041 Q_{\mathrm{m}}^{-0.25}$	Braided, sand-bed channels
Leopold and Wolman (1957)	$S = 0.013 Q_{\mathrm{b}}^{-0.44}$	Meandering–braiding threshold
Henderson (1961)	$S = 0.000196 D^{1.14} Q_{\mathrm{b}}^{-0.44}$	Meandering–braiding threshold
Antropovsky (1972)	$S = 1.4 Q_{\mathrm{ma}}^{-1}$	Meandering–braiding threshold
Parker (1976)	$S/Fr \approx d/w$	Meandering–braiding threshold
Fredsøe (1978)	$\theta = (\tau/(s-1)) D_{50}$	Straight–meandering–braided thresholds (see Figure 7.22)
Begin et al. (1981)	$S = 0.0016 Q_{\mathrm{m}}^{-0.3}$	Meandering–braiding threshold for a standard channel with $\tau = \tau_{\mathrm{ave}}$
	$S = 0.0016 (\tau/\tau_{\mathrm{ave}}) Q_{\mathrm{m}}^{-0.3}$	Relations for non-standard channels (braided channels: $\tau > \tau_{\mathrm{ave}}$; meandering: $\tau < \tau_{\mathrm{ave}}$)
Ackers (1982)	$S = 0.0008 Q^{-0.21}$	Meandering–braiding threshold for sand-bed flumes and rivers
Bray (1982)	$S = 0.07 Q_{2\mathrm{f}}^{-0.44}$	Meandering–braiding threshold for gravel-bed rivers
Ferguson (1984)	$S = 0.042 Q^{-0.49} D_{50}^{0.09}$	Meandering–braiding threshold for gravel-bed rivers
	$S = 0.056 Q^{-0.5}$	Meandering–braiding threshold for any river
	$S = 0.0049 Q^{-0.21} D_{50}^{0.52}$	Meandering–braiding threshold based on Parker's theory and hydraulic geometry
Chang (1985)	$S \approx a Q^{-0.5} D^{0.5}$	Meandering–braiding threshold
Robertson-Rintoul and Richards (1993)	$\Sigma P = 1 + 5.52 (Q S_{\mathrm{v}})^{0.38} D_{84}^{-0.44}$	Meandering–braiding threshold for gravel-bed rivers (Figure 7.23)
	$\Sigma P = 1 + 2.64 (Q S_{\mathrm{v}})^{0.4} D_{84}^{-0.14}$	Meandering–braiding threshold for sand-bed rivers (see Figure 7.23)

*SI units

analyses did not, however, establish whether these findings were a cause or an effect of planform development.

Stubblefield (1986) tested the methods of Lane (1957), Leopold and Wolman (1957) and Parker (1976) using information for 56 streams extracted from a database published by Church and Rood (1983). His overall finding was that each of the methods was of limited accuracy and suggested that in practice all three should be used and the results combined to increase confidence in the predictions. Lane's (1957) method was found to give the best results for sand-bed streams.

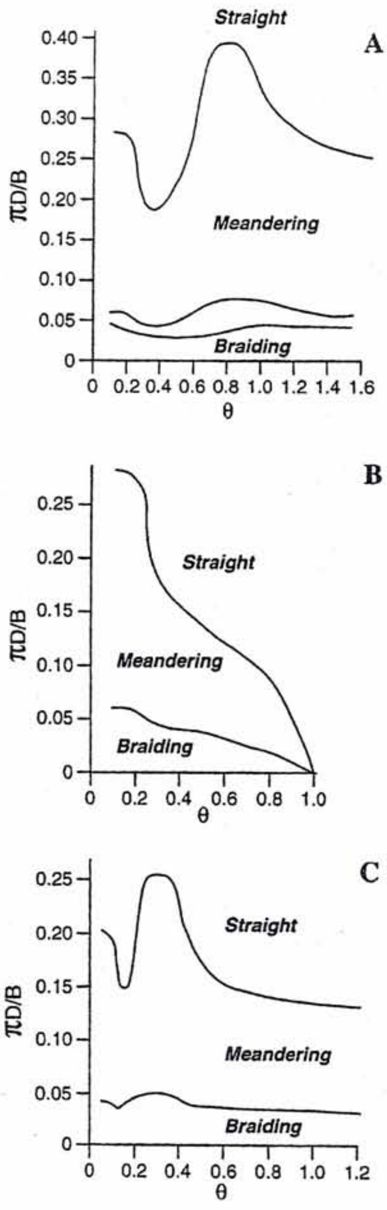


Figure 7.22 Fredsøe's stability diagrams for planform prediction in: (A) a sand-bed river with dunes ($s=2.65$, $d/D=1000$, $Cd=7$); (B) a flat-bed channel; and (C) a dune-bed with suspended load neglected (modified from Ahmed, 1986)

Smith (1987) used a more extensive data set from 101 channels to investigate the accuracy of nine methods in defining the meandering/braiding threshold in alluvial rivers. The methods tested were the empirical relations of Lane (1957), Leopold and Wolman

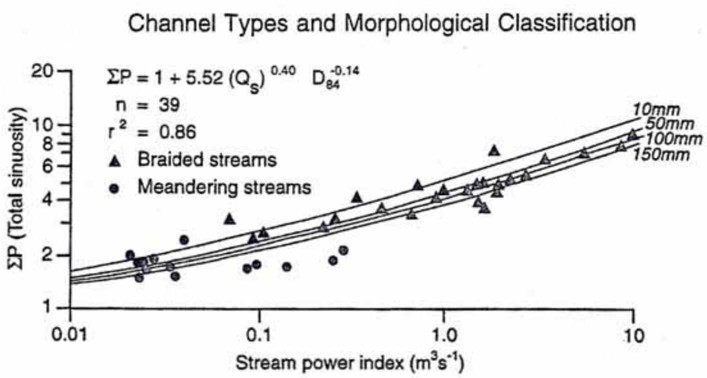


Figure 7.23 Relationship between total sinuosity and stream power for single-thread and multi-thread channels (adapted from Robertson-Rintoul and Richards, 1993)

(1957), Henderson (1961), Osterkamp (1978), Begin et al. (1981), Bray (1982) and Ferguson (1984), and the theoretical relations of Parker (1976) and Fredsøe (1978).

Smith's results emphasised the importance of considering the size of the bed sediment when attempting to predict channel planform. In practice this may be achieved either by selecting a method which was developed for river conditions similar to those being studied, or by using a method which explicitly accounts for bed material size. Smith confirmed Stubblefield's finding that Lane's (1957) method gave the best results for sand-bed rivers, but also demonstrated that it must *not* be applied to gravel-bed rivers. Ferguson's (1984) method was the most reliable for gravel-bed rivers. Fredsøe's (1978) method was, overall, the best predictor for streams of all types, although the requirement that width and depth be specified as input parameters limits its applicability compared to that of both Lane's and Ferguson's methods, which do not require the user to specify a cross-sectional geometry. This is potentially a great advantage, as the cross-sectional geometry may well be unknown when predictions are being made of channel planform response to changes in the driving variables or to the impacts of engineering intervention.

Most recently, van den Berg (1995) has re-examined the prediction of alluvial planforms and presents a new method which uses as input variables the bed material median grain size and the potential specific stream power based on bankfull discharge and valley slope. A data set of 228 streams was used to develop a discriminant function between meandering rivers with sinuosities greater than 1.5 and less sinuous, braided rivers. It is defined by:

$$\omega_{vt} = 843 D_{50}^{0.41} \tag{7.21}$$

where ω_{vt} = specific stream power at the transition between meandering and braiding (W/m^2). Specific stream power (stream power per unit bed area) is defined by:

$$\omega_v = 2.1 S_v Q_b^{0.5} \quad \text{for sand-bed rivers} \tag{7.22}$$

$$\omega_v = 3.3 S_v Q_b^{0.5} \quad \text{for gravel-bed rivers} \tag{7.23}$$

This reflects the different cross-sectional geometry for the same discharge in sand-bed and gravel-bed rivers. Streams with potential specific stream powers greater than the threshold value will braid and those with values less than the threshold value will meander. The limits to the applicability of the function are $Q > 10 m^3/s$ and $0.1\ mm < D_{50} < 100\ mm$. The data and threshold line are shown in Figure 7.24.

van den Berg's approach takes into account bed material size and, by using stream power in place of discharge, it better accounts for the competence of the river to entrain and transport bed sediment. A discriminant function of this type may well represent the logical endpoint of the line of investigation into the meander/braiding threshold begun by Lane and by Leopold and Wolman nearly 40 years ago.

7.5 STREAM CLASSIFICATION FOR ANALYSIS, ENGINEERING AND MANAGEMENT: THE FUTURE?

In terms of channel pattern classification, the diagram produced by Brice (1975) covers the entire range of planforms identified in this paper and is recommended for use in engineering geomorphic studies (Figure 7.25). However, planform is only one aspect of channel form and the cross-sectional and longitudinal dimensions should also be considered for completeness.

Perhaps the most comprehensive system for classification yet devised is that of Rosgen (1994). This divides streams into seven major types on the basis of degree of entrenchment, gradient, width/depth ratio, and sinuosity. Within each major category there are six subcategories depending on the dominant type of bed/bank materials.

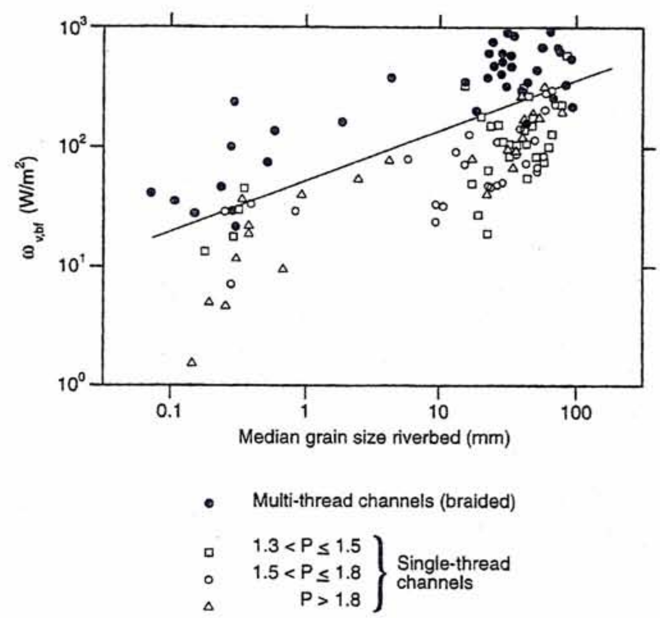


Figure 7.24 Planform prediction diagram developed by van den Berg (1995)

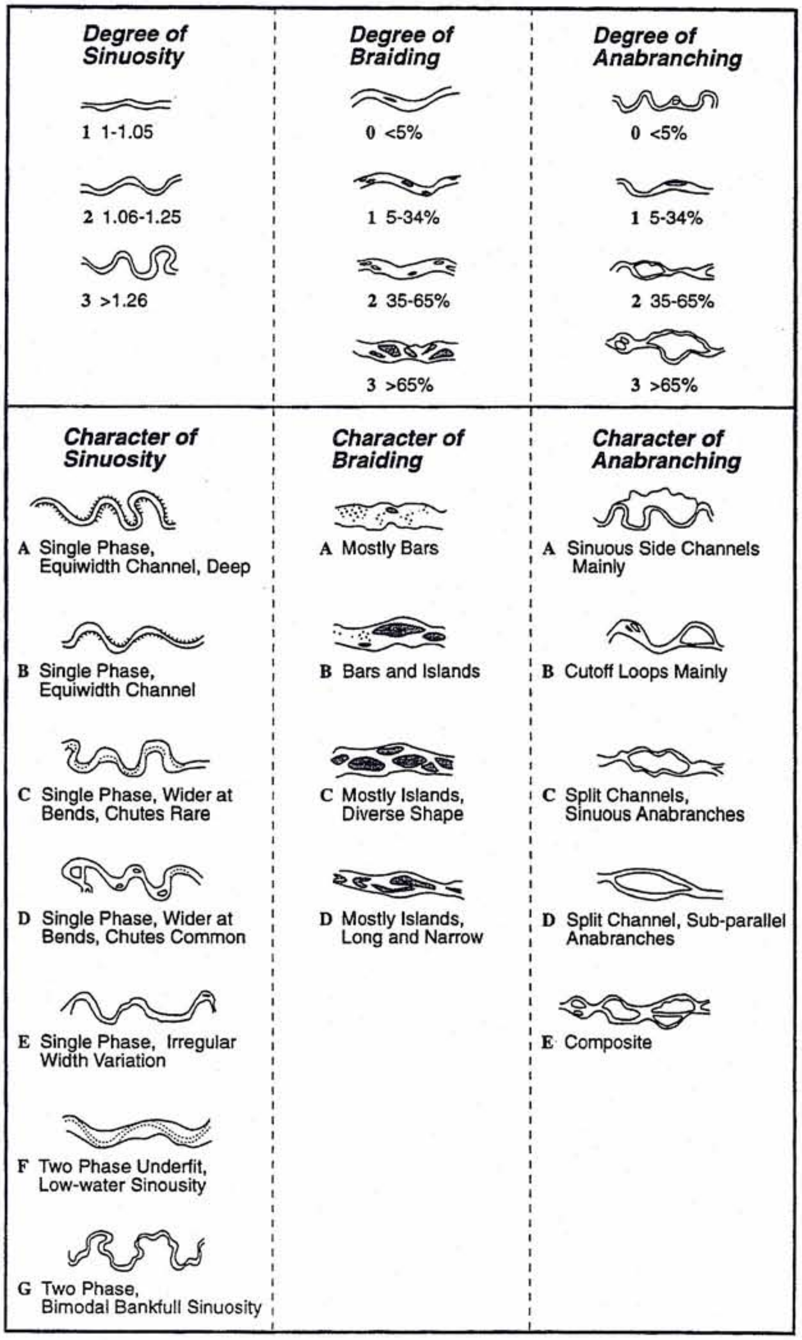
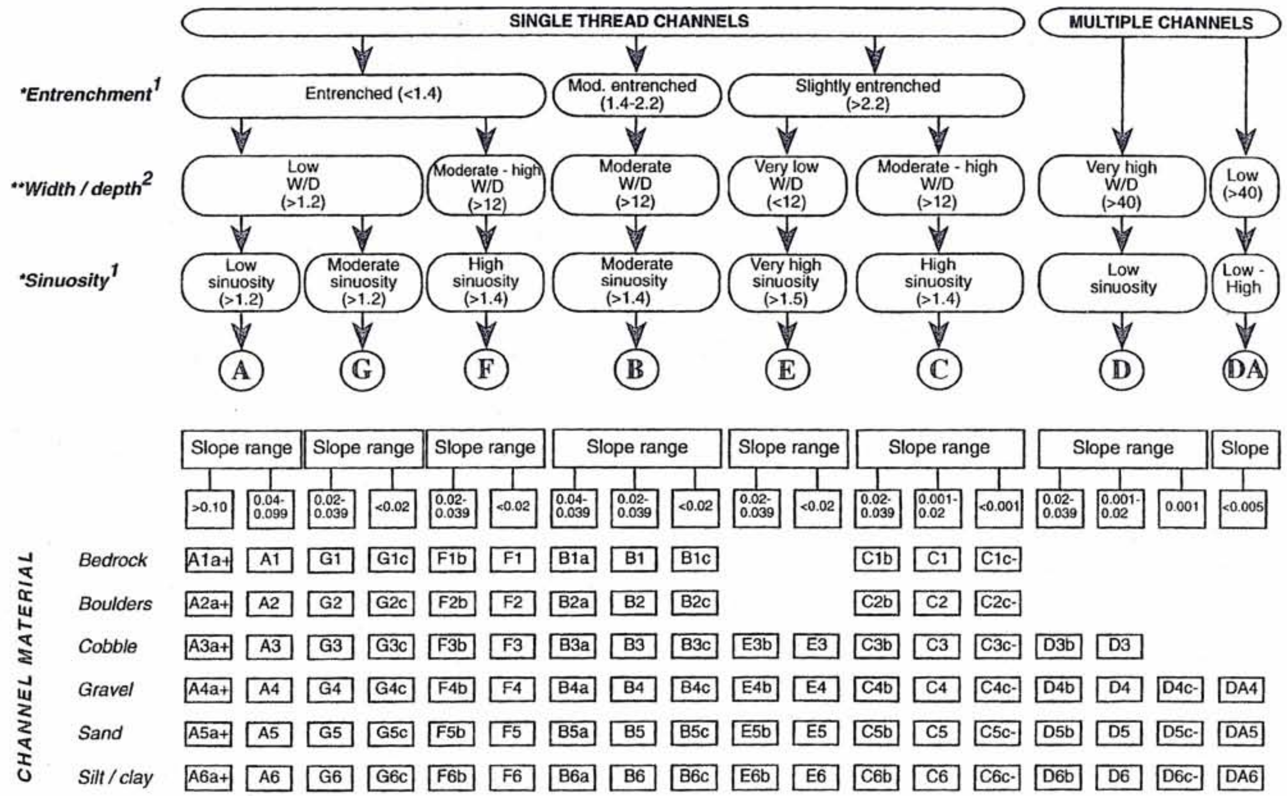


Figure 7.25 Channel pattern classification devised by Brice (after Brice, 1975)



[1] Values can vary by ±0.2 units as a function of the continuum of physical variables within stream reaches

[2] Values can vary by ±0.2 units as a function of the continuum of physical variables within stream reaches

Figure 7.26 Key to classification of rivers in Rosgen's method (modified from Rosgen, 1994)

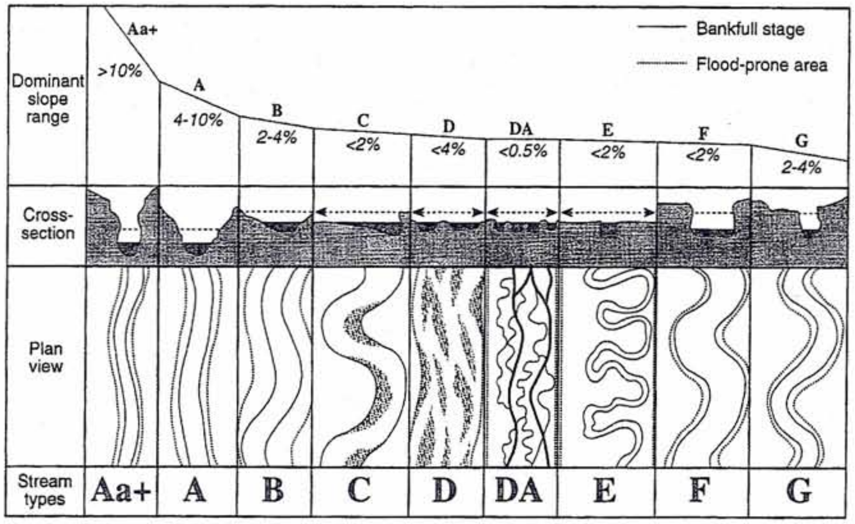


Figure 7.27 Longitudinal, cross-sectional and planform views of major stream types in Rosgen's method (modified from Rosgen, 1994)

The basic framework of Rosgen's method is set out in Figures 7.26 and 7.27. Criteria for the classification system and descriptions of the salient forms and features of each type are listed in Table 7.3. Examination of the criteria, forms and features listed in Table 7.3 illustrates that Rosgen has synthesised much of the material covered in this chapter. The result is a classification which is comprehensive in its scope, but which requires a strong geomorphological insight and understanding to apply consistently and usefully. It is at present too early to judge the usefulness and reliability of Rosgen's method when applied by engineers and managers with only a limited background in fluvial geomorphology, although indications are that users can gain the knowledge required through intensive, short-course training.

A more serious problem with all classifications based on existing channel morphology is that they fail to account for dynamic adjustment or evolution of the fluvial system. Increasing recognition of the fact that rivers are seldom in dynamic equilibrium has driven a desire on the part of engineers and managers to be able to predict channel changes in the short and medium term. In response, geomorphologists have begun to develop new schemes of river classification based on adjustment processes and trends of channel change rather than existing channel morphology and sediment features. The relatively simple adjustment classification of Brice (1981) identified channels as degrading, aggrading, widening, shifting at both banks, or shifting laterally at points of flow impingement. Brookes (1988) accentuated instream adjustments with adjustment classes that accounted for bed degradation, armouring, thalweg sinuosity, bar development and bank erosion. Downs (1995) developed a comprehensive system that incorporates the classifications of Brice and Brookes but builds on their earlier work by linking observed trends and patterns of adjustment to the fluvial and sediment processes responsible for driving channel change (Figure 7.28).

Figure 7.26 Key to classification of rivers in Rosgen's method (modified from Rosgen, 1994)

Table 7.3 Summary of criteria used for broad level classification in the Rosgen method (redrafted from Rosgen (1994))

Stream type	General description	Entrenchment ratio	*W/D* ratio	Sinuosity	Slope	Landform/soils/features
Aa +	Very steep, deeply entrenched, debris transport streams.	<1.4	<12	1.0 to 1.1	>0.10	Very high relief. Erosional, bedrock or deposition features; debris flow potential. Deeply entrenched streams. Vertical steps with deep scour pools; waterfalls.
A	Steep, entrenched, cascading, step/pool streams. High energy/debris transport associated with depositional soils. Very stable if bedrock- or boulder-dominated channel.	<1.4	<12	1.0 to 1.2	0.04 to 0.10	High relief. Erosional or depositional and bedrock forms. Entrenched and confined streams with cascading reaches. Frequently spaced, deep pools, associated step-pool bed morphology.
B	Moderately entrenched, moderate gradient, riffle-dominated channel, with infrequently spaced pools. Very stable plan and profile. Stable banks.	1.4 to 2.2	>12	>1.2	0.02 to 0.039	Moderate relief, colluvial deposition and/or residual soils. Moderate entrenchment and *W/D* ratio. Narrow, gently sloping valleys. Rapids predominate with occasional pools.
C	Low gradient, meandering, point-bar, riffle/pool, alluvial channels with broad, well defined floodplains	>2.2	>12	>1.4	<0.02	Broad valleys with terraces, in association with floodplains, alluvial soils. Slightly entrenched with well defined meandering channel. Riffle–pool bed morphology.
D	Braided channel with longitudinal and transverse bars. Very wide channel with eroding banks.	n/a	>40	n/a	<0.04	Broad valleys with alluvial and colluvial fans. Glacial debris and depositional features. Active lateral adjustment, with abundance of sediment supply.
DA	Anastomosing (multiple channels) narrow and deep with expansive well	>4.0	<40	variable	<0.005	Broad, low-gradient valleys with fine alluvium and/or lacustrine soils. Anas-

	eroding banks.					features. Active lateral adjustment, with abundance of sediment supply.
DA	Anastomosing (multiple channels) narrow and deep with expansive well vegetated floodplain and associated wetlands. Very gentle relief with highly variable sinuosities. Stable streambanks.	>4.0	<40	variable	<0.005	Broad, low-gradient valleys with fine alluvium and/or lacustrine soils. Anastomosed (multiple channel geologic control creating fine deposition with well vegetated bars that are laterally stable with broad wetland floodplains.
E	Low gradient, meandering riffle/pool stream with low width/depth ratio and little deposition. Very efficient and stable. High meander width ratio.	>2.2	<12	>1.5	<0.02	Broad valley/meadows. Alluvial materials with floodplain. Highly sinuous with stable, well vegetated banks. Riffle–pool morphology with very low width/depth ratio.
F	Entrenched meandering riffle/pool channel on low gradients with high width/depth ratio.	<1.4	>12	>1.4	<0.02	Entrenched in highly weathered material. Gentle gradients, with a high *W*/*D* ratio. Meandering, laterally unstable with high bank-erosion rates. Riffle–pool morphology.
G	Entrenched 'gulley' step/pool and low width/depth ratio on moderate gradients.	<1.4	<12	>1.2	0.02 to 0.039	Gulley, step–pool morphology with moderate slope and low *W*/*D* ratio. Narrow valleys, or deeply incised in alluvial or colluvial materials, i.e. fans, deltas. Unstable, with grade control problems and high bank erosion rates.

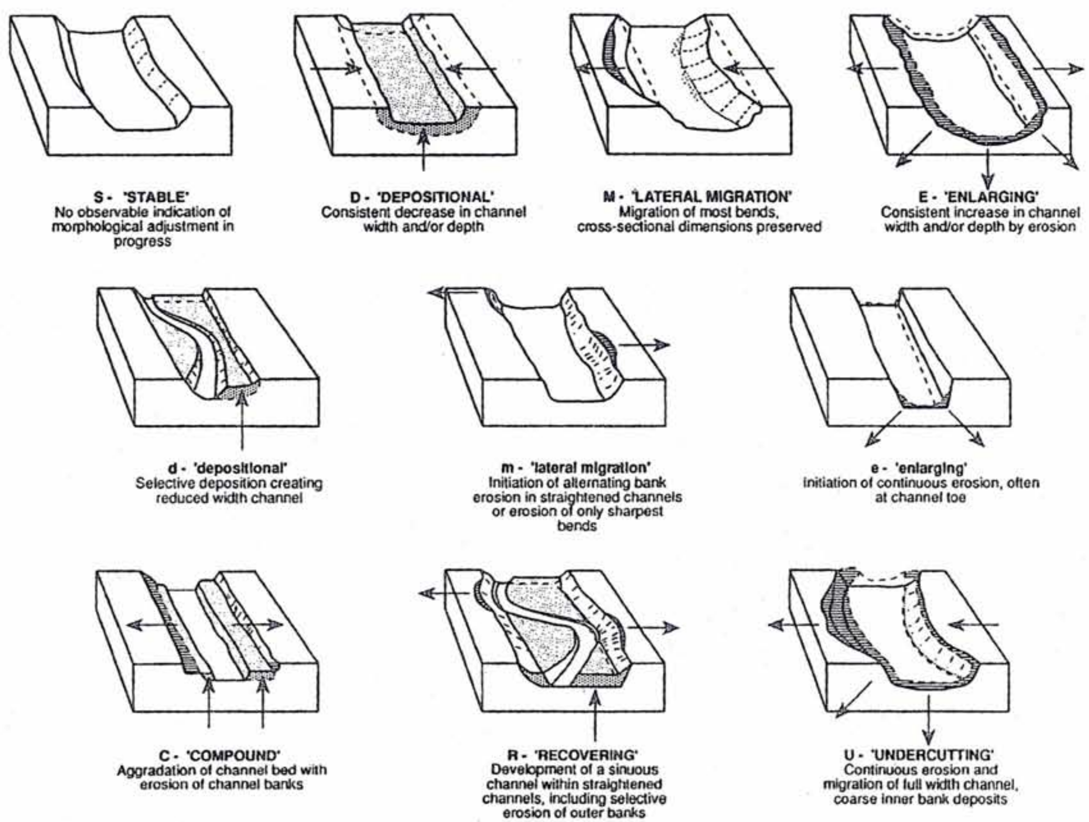


Figure 7.28 Downs' channel classification, based on trends and types of morphological change (modified from Downs, 1995)

Adjustment-based classifications differ fundamentally from morphology-based schemes in that they require the individual performing the classification to determine the current nature of channel adjustment processes. While historical records of types, trends and rates of channel change are very useful as the basis for determination of the current situation, such information is not always available and, even if it is, ongoing changes in catchment characteristics, alterations to channel management, or complexity in the response of the fluvial system often mean that past changes are not representative of current or future adjustments (Downs and Thorne, 1996). For these reasons, classification of channel adjustment requires judgement on the part of the engineer or scientist, who must infer adjustment processes from channel form. Evaluations of this demand careful observation coupled to insight into process–form linkages that support qualitative interpretation and evaluation. This places additional emphasis on the need for reliable and repeatable methods of stream reconnaissance to support rapid acquisition of the observational data necessary to support classification (Thorne, 1993; Simon and Downs, 1995). Also, training in applied fluvial geomorphology is essential to equip those responsible for stream classification with the skills necessary to allow sound interpretation of morphological data (Downs, 1995).

7.6 CONCLUSIONS

Scientists, engineers and water resource managers in the mid-1990s are expected to take a broad, environmentally oriented view of the river that recognises the need to work with, rather than against, nature. Environmental considerations do not, however, absolve the engineer of the obligation to account for flood defence, land drainage, channel stability and navigation interests. The need to balance the needs of different interests, sometimes with conflicting aims, makes it essential to take a multifunctional approach. Engineers seek to solve river-related problems while retaining those natural forms and features that allow the river to transmit the inputs of water and sediment, support diverse habitats and provide a pleasing landscape for river-centred recreation. A comprehensive and reliable morphological analysis and classification system forms the essential basis to sound engineering geomorphology.

The identification of channel type and the classification of channel morphology are fairly new additions to the methodologies routinely used by river engineers and managers. While care must be exercised by users unfamiliar with the limitations of geomorphic parameters and discriminants, even a rudimentary classification of channel morphology puts significant flesh on the bones provided by a standard channel survey consisting of cross-sections, plan maps and a long profile.

The ambitious method recently developed by Rosgen (1994) attempts to produce a comprehensive, semi-quantitative, holistic morphological classification system that incorporates all three dimensions of channel form while also accounting for differences in channel-forming materials. This approach, combining qualitative description and quantitative parameters in the definition of channel type, no doubt represents the way forward, although Rosgen's method does not represent the final product in terms of classification systems.

This chapter has shown that at present the key to identifying and classifying channels correctly lies in selecting techniques appropriate to the fluvial system in question and in using a variety of approaches in order to increase confidence in decision-making.

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APPENDIX: NOTATION

a	a constant in threshold equation of Chang (1985)
B	channel width or meander belt width (m)
BD_b	mean scour depth in bend (m)
BD_m	maximum scour depth in bendway pool (m)
d	channel depth (m) or bed material size
d_m	channel bankfull maximum depth (m)
D	average channel depth
D_{50}	bed material median size (mm or m)
D_{84}	bed material size for which 84% of the sediment is finer (mm or m)
F	width/depth ratio
Fr	Froude number
L	meander wavelength measured along the axis of the channel (m)
M	weighted silt-clay index
p	planform sinuosity = channel length/valley length
Q_a	mean annual discharge (m^3/s)
Q_b	bankfull discharge (m^3/s)
Q_m	mean annual discharge (m^3/s)
Q_{ma}	mean annual flood (m^3/s)
Q_{2f}	two year flood (m^3/s)
R_c	bend radius of curvature (m)
R_d	riffle bankfull mean depth (m)

R_{dm}	riffle bankfull maximum depth (m)
R_v	riffle bankfull mean velocity (m/s)
R_w	riffle bankfull width (m)
RD_{50}	riffle bed material median size (mm)
s	specific gravity of sediment (usually 2.65)
S	channel slope
S_v	valley slope
T	meander wavelength multiplied by sinuosity (m)
v	channel bankfull mean velocity (m/s)
w	bankfull width (m)
$\omega_{v,bf}$	specific stream power at bankfull discharge (W/m^2)
ω_v	specific stream power (W/m^2)
ω_{vt}	specific stream power at the braiding/meandering transition (W/m^2)
x	distance along channel centreline
XD_b	mean depth at crossing (m)
z	riffle spacing (m)
θ	meander arc angle and parameter in Fredsoe's method (Fig. 7.22)
Σp	total sinuosity
τ	boundary shear stress (N/m^2)
τ_{ave}	cross-section average boundary shear stress (N/m^2)
ω	stream power (W/m)
ϕ	local angle of channel planform curvature
ϕ_{max}	maximum angle of channel planfrom curvature