RIVERS

FORM AND PROCESS IN ALLUVIAL CHANNELS

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Keith Richards
University of Cambridge
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Contents

1

Alluvial river channels: their nature and significance

Alluvial river channels are 'self-formed'. Their morphology results from the entrainment, transportation and deposition of the unconsolidated sedimentary materials of the valley fill and floodplain deposits across which they flow. Alluvial channel forms are dependent on the environmental controls of hydrology and sedimentology, and while these remain constant in a particular drainage basin, the river morphology remains stable even though the channel may not be static. This stability is reflected in numerous empirical generalizations which demonstrate both adjustment of river form

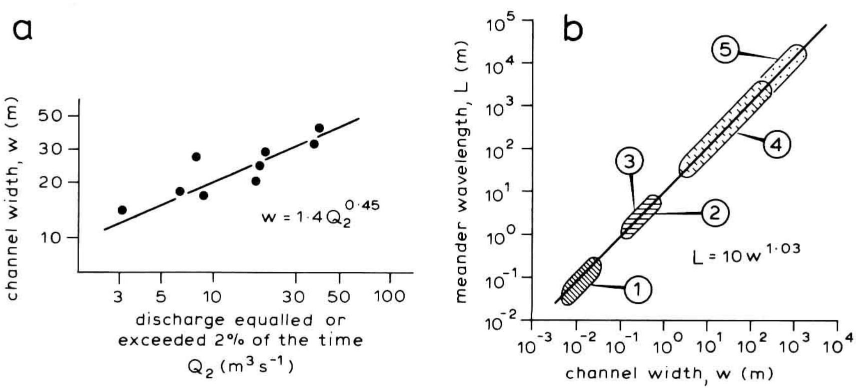

Figure 1.1 (a) Downstream adjustment of channel width to increasing discharge: principal gauging stations on the Brandywine Creek, Pennsylvania (after Wolman, 1955). (b) Relationship between meander wavelength and channel width (after Zeller, 1967). 1 = limestone furrow meanders; 2 = supraglacial stream meanders; 3 = laboratory channel meanders in sand; 4 = Swiss river meanders; 5 = alluvial river meanders (Leopold and Wolman, 1960).

to process (Figure 1.1a) and interrelationships between various aspects of channel form (Figure 1.1b). Equilibrium channel forms result from an interaction between the two sets of variables which measure the 'forces' applied by the flowing water and the 'resistance to erosion' of the sediments. All types of river channel can be referred to a continuum of force-resistance relationships, but those formed in unconsolidated alluvial sediments, with which the flow can readily interact, are distinguished by the adjustable nature of their morphology. Bedrock channels occasionally obey alluvial channel regularities (Figure 1.1b), but their forms are usually governed by lithological and structural influences. Even underfit alluvial streams (Dury, 1964a) with immobile residual bed material inherited from the coarse bedload of more powerful palaeochannels exhibit systematic adjustment of channel form to this sedimentological control (Wilcock, 1967).

The significance of alluvial river channels

In any catchment, areal slope erosion and linear river erosion yield sediment which the rivers transport from the various source areas to the ultimate sediment 'sinks' of the ocean basins. The products of catchment erosion are often only transported short distances to slope bases or floodplain surfaces, but rivers carry an average of 97 t km^{-2} yr^{-1} of suspended sediment and 37 t km^{-2} yr^{-1} of solutes to the sea (Holeman, 1968), much of which represents net denudation of the landscape. Chapter 2 briefly considers the enormous spatial variability of sediment yield, reflecting as it does the influences of climate, vegetation, relief, geology and man on the erosional processes which represent external controls of river channel behaviour. However, most of this book is concerned not with the denudational effect of river transport, but with the physical processes responsible for the observed regularity of alluvial channel behaviour. An understanding of these process–form relationships is of practical significance in watershed management, river management and design, and palaeohydraulic reconstruction. Although Chapters 9 and 10 consider these problems in detail, examples are given here to illustrate the importance of such understanding.

Watershed management

Optimal water resource development must often balance water and power supply with flood alleviation, navigation, recreation and conservation, which together necessitate planning at the catchment scale. Some objectives are met by controlling the river flow by physical structures (dams) which directly influence sediment transport processes. Alternatively, catchment land-use changes may alter hydrological response and sediment yield to affect river processes indirectly and possibly prejudice investment in capital projects.

Catchment management is particularly difficult in sensitive semi-arid environments. For example, gullying in the south-west USA in the early twentieth century reflected a web of causal influences including increased runoff caused by overgrazing and subtle climatic changes (Cooke, 1974). The Rio Puerco (Bryan, 1928) widened from 30 to 85 m and deepened from 1 to 8.5 m between 1845 and 1928, yielding 1200 $m^3 yr^{-1}$ of sediment which aggraded the Rio Grande main stream and caused a 16% loss of storage capacity in Elephant Butte reservoir from 1915 to 1940 (Happ, 1948). Reservoir sedimentation, accelerated by injudicious land-use changes upstream, reduces storage capacity and hence the safe water yield. It thus has a major economic effect on reservoir operation by reducing revenue, shortening the project lifespan, and necessitating expenditure on sediment clearance when traps are installed. For example, even a small Pennine reservoir in Britain entailed a budget of £800 per annum in the 1960s for clearance of 250 $m^3 yr^{-1}$ of bedload trapped on the main inflow stream (Morgan, 1980).

When the bedload is deposited in a reservoir, the clear released water may degrade the stream bed downstream until it is protected by coarse lag sediments. These represent that fraction of the bed material which is rendered immobile because of the reduction of peak discharges caused by the reservoir water storage. Average degradation below ten dams in the American Midwest over varying periods from 1910 to 1960 (Leopold *et al*, 1964, p. 454) was 0.4 m at an average rate of 0.04 $m yr^{-1}$. Figure 1.2(a) shows marked degradation closest to the dam site, possibly endangering the structure itself (Komura and Simons, 1967). Downstream channel instability may reflect reservoir management policy; deliberate flow regulation could increase the frequency of exceedance of the threshold stress for bed material transport while reducing the frequency of extreme events (Hey, 1976). However, this will depend on regional climatic conditions. In British Columbia increased winter flow in the regulated Peace River resulted in massive spring ice jams which caused flooding to unprecedented levels (Bray and Kellerhals, 1979).

River management and channel design

Widening, deepening or straightening of natural streams (channelization) have often been undertaken to improve navigability or accelerate the passage of flood peaks. Artificial channels are also constructed for irrigation and navigation. In both cases, channel width, depth and gradient are selected to pass the required discharge at a velocity sufficient to maintain transport of sediment without silting, but not so excessive that bed and banks are eroded. Channel design is most successful when it mimics nature because: (i) the resulting stability minimizes maintenance costs necessitated by silting or erosion; (ii) the aesthetics of the channel are enhanced (Leopold, 1969); and (iii) the aquatic ecology can be preserved by maintaining the range of

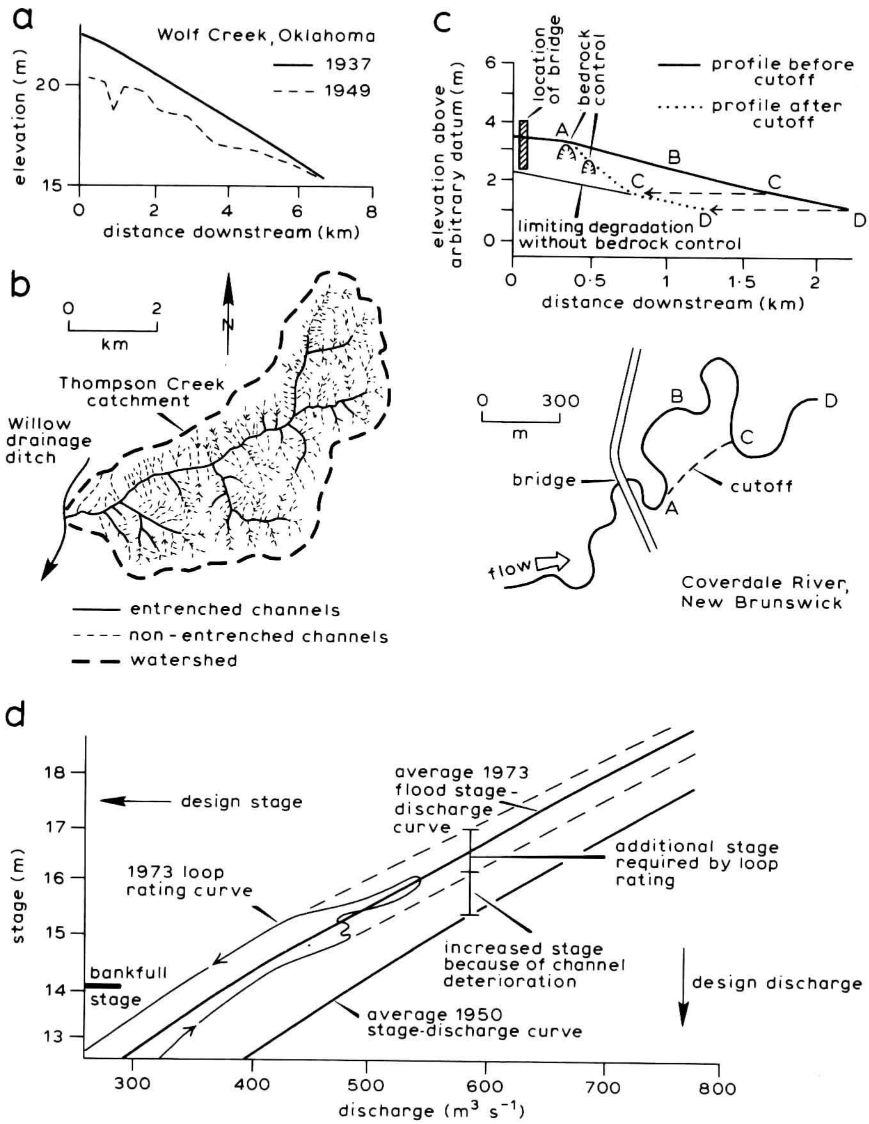

Figure 1.2 (a) River bed degradation downstream from Fort Supply Dam, Wolf Creek, Oklahoma (after Leopold *et al*, 1964). (b) Gullying and network expansion triggered by channelization, Willow Drainage Ditch, Iowa (after Ruhe, 1971). (c) An example of meander bend cut-off which could have endangered bridge foundations had there not been a bedrock control at the upstream end (after Bray and Kellerhalls, 1979). (d) Mississippi River stage–discharge curve showing channel deterioration and 'loop' effects on projected stage at design discharge for levee height (after Noble, 1976).

ecological niches found in natural streams with spatially varying depth, velocity and bed material (Keller, 1976).

Local channelization often ignores the upstream and downstream links of a reach which is part of a wider system. Straightening the Willow drainage ditch (Daniels, 1960) increased the rates of stream energy expenditure because the gradient was steepened, and incision of the channel bed rejuvenated tributaries and initiated gully extension of the drainage network (Figure 1.2b). When the Blackwater River, Missouri, was locally steepened from a gradient of 0.0017 to 0.0031 by straightening (Emerson, 1971), increased flooding occurred downstream, where aggradation of 2 m in 50–60 years resulted from erosion in the channelized reach. In addition, increased turbidity and loss of habitat caused a decline from 600 to 100 kg ha^{-1} in the fish population. The consequences of channelization for existing engineering structures are equally serious (Figure 1.2c). A cut-off on the East Prairie River, Alberta (Parker and Andres, 1976) locally doubled the gradient, and a 3 m high nickpoint created inadvertently at the upstream end receded at 1.6 km yr^{-1} to undermine a bridge pier. Consequently construction of a replacement and of protective stonework on the banks ('rip-rap') was required. Natural readjustment of the channel after 'improvement' also causes engineering problems, such as those of levée design highlighted by the 1973 Mississippi floods (Noble, 1976). A 1950 stage–discharge curve predicted a stage of 17.5 m at the design flood, and levée heights were designed accordingly. However, channel capacity in 1950 had been enlarged by channelization, and by 1973 deterioration resulted in 1–1.5 m higher stages at given discharges. In addition, the looped stage–discharge relation for the 1973 flood indicates a higher water surface elevation as the bed filled on the falling stage than during the rising stage scour. Thus a range of projected stages occurs at the design flood which exceeds the freeboard on the levées (Figure 1.2d).

Palaeohydraulic and palaeohydrological reconstruction

Actively migrating rivers create sedimentary structures which, when preserved in the sedimentary record by burial during aggradation, allow an identification to be made of the type of channel which created the deposits. Meandering streams have a wide range of particle sizes organized in fining-upwards cycles, from basal cobbles through sands to silts (pp. 206–11). Braided streams have coarse sediments (gravels) and structures dominated by lens-shaped channel fills caused by abandonment of braid distributaries (Allen, 1965). Recognition of these structures permits qualitative reconstruction of hydraulic and hydrological conditions; braided streams, for example, are associated with high stream power and unstable sediments, often unvegetated. Smaller-scale sedimentary structures allow more quantitative reconstruction; Figure 1.3(a) illustrates the bedforms associated with different stream power conditions. For a known sand size, this enables an estimation to be made of the range of stream power expenditure in a river characterized by certain bedform structures, with dune cross-bedding implying greater power than the smaller-scale cross-laminae formed by ripple migration.

Schumm's (1968a) study of palaeochannels on the Murrumbidgee riverine plain is a classic illustration of hydraulic and hydrological reconstruction. The two palaeochannels (Figure 1.3b) exhibit different forms and sediments. The older channel is wide, and sections show it to have been shallow; the channel fill is sand and gravel. Application of the Manning

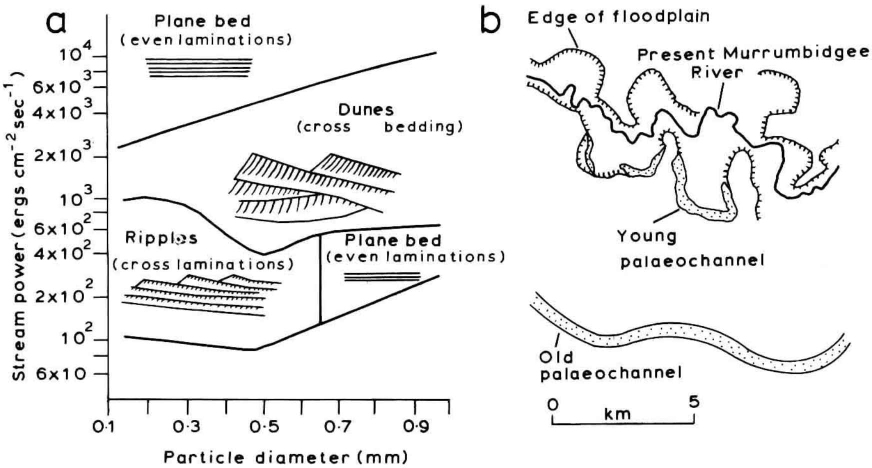

Figure 1.3 (a) The relationship between bedforms, associated bedding characteristics, and stream power and particle size (after Allen, 1970a). 10^7 erg = 1 joule (see Appendix). (b) Part of the riverine plain of the Murrumbidgee River, NSW, sketched from an air photograph (after Schumm, 1969a).

equation (p. 63) allows the velocity of flow to be estimated from the depth, slope and roughness, and multiplication of the velocity by the cross-section area yields an estimated bankfull discharge of 650 m^3 s^{-1}. The fluvial sediments correlate with saline palaeosols, and the channel is interpreted as a bedload-dominated stream of a drier Quaternary climate characterized by rapid runoff and sediment yield. The younger palaeochannel has a smaller width:depth ratio and channel fill deposits of silt and clay; in this case the estimated bankfull discharge is 1450 m^3 s^{-1}. The implied palaeohydrology involves a wetter climate than at present, but comparable vegetation and weathering regime (and alluvium). These palaeochannels preserved on alluvial surfaces are easy to investigate because of their observable continuity; in older, buried sediments and sedimentary rocks, there may only be isolated, discontinuous exposures. Nevertheless, Ferguson (1977a) has shown that the variance of the direction of a river channel is directly related to sinuosity, so that sinuosity can be estimated from the directions of a set of random channel exposures. In conclusion, we may note that the practical importance of palaeohydraulic reconstruction is exemplified by Schumm's (1977) predictions of the locations of heavy mineral placer deposits in floodplain and valley fill sediments.

The alluvial system

'Functional' and 'realist' theory dominate contemporary fluvial geomorphology. The former views reality as 'instances of repeatable and predictable regularities in which form and function can be assumed to be related' (Chorley, 1978, p. 2). Thus Figure 1.1(a) is considered an acceptable basis for estimating peak discharge from measured widths in ungauged catchments (Dunne and Leopold, 1978, p.643). 'Realist' theory eschews this black-box approach, and attempts 'the identification of detailed causal mechanisms and the underlying structures of which the external forms are the artefacts' (Chorley, 1978, p. 2). It is more concerned with explanation than with mere identification of relationships. Functionalism tends to be empirical and inductive in scientific method, whereas realism is theoretical and deductive, and is often focused at the smaller scale of specific processes (Chorley, 1978). Theoretical considerations of sediment transport and flow processes in hydraulics and fluid mechanics (Chapter 3) strengthen a largely empirical fluvial geomorphology by explaining some functional relationships identified empirically. However, realist models of the behaviour of the alluvial channel in its entirety are hampered by the multiplicity of variables, the complexity of feedback between them, and the indeterminacy of process–form relationships at this scale (pp. 24–8).

The predominance of functionalism has encouraged the use of systems analysis. Chorley and Kennedy (1971) define a system as a structured set of objects and/or attributes, which in the present case is the variable set defining alluvial channel form and process. Although criticized for adding nothing fundamentally new to our understanding (Smalley and Vita-Finzi, 1969), systems analysis has two important advantages. First, it emphasizes the measurement process, in which qualitative concepts are translated into quantitative variables, with clear operational definitions which minimize operator variance (Chorley, 1958). Second, it encourages systematic identification of all relevant variables in a given system, as well as their status as dependent or independent variables, and the hypothesized direction of causal links between them. Two types of particularly important systems are the 'morphological' and 'process-response' systems. In a morphological system, variables describing equilibrium channel form and associated sediment size and structure properties are interrelated, and perhaps correlated with the morphological properties of the catchment. The process–response