Fluvial processes and landforms

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Abstract: The period 1965–2000 saw a sustained increase in research and publications on fluvial processes and landforms. The trend towards generalization and/or mechanistic understanding, rather than site-specific history, continued. Research was multidisciplinary, with important contributions from hydraulic engineers, geologists and physical geographers and from experimental and theoretical approaches as well as geomorphological and sedimentological fieldwork. Rapidly increasing computer power underpinned new measurement methods, and greatly increased the scope of data analysis and numerical modelling. There were major advances in understanding the interaction of river process and form at reach scale, with growing recognition of differences between sand-bed and coarse-bed rivers. Field studies outside Europe and North America led to greater awareness of the diversity of river planforms and depositional landforms. Conceptual models of how rivers respond to natural or anthropogenic change in boundary conditions at different timescales were refined, taking advantage of studies of the response to land-use change, major floods and volcanic eruptions. The dating of sediments allowed greater appreciation of fluctuations in the incidence of extreme driving events over centuries and thousands of years. Towards the end of this period, research on bedrock rivers began to take off.

Rivers are key landscape components in most of Earth's continents. They convey erosion products as well as water from mountains and interiors to the oceans, and thereby create a diversity of rapidly changing channel landforms and longer-lasting alluvial deposits. River erosion and deposition are of interest to engineers and geologists, as well as to geomorphologists, so the literature on river form and process is extensive and multidisciplinary. It grew rapidly in the late twentieth century, doubling every decade or so to hundreds of new research papers annually by 2000. Specialist conference series were inaugurated, starting with *Fluvial Sedimentology* (Miall 1978) and *Gravel-Bed Rivers* (Hey *et al.* 1982), and the resultant proceedings series provided stimuli for new research. As in other areas of geomorphology, there was an increased emphasis on a generic understanding of process–form interrelations rather than the character and history of particular regions or landforms.

Our review is necessarily highly selective and cites only a tiny fraction of the work published in 1965–2000, focusing on the most influential new topics, concepts, methods and findings. We start by reviewing progress during this period in understanding the short- to medium-term interactions between form and process in short reaches of alluvial rivers. At these time and space scales, valley gradient, hydrological regime and sediment supply are externally imposed constraints on the interaction of form and process within the reach. In the first three sections of this chapter, we identify important new ideas and findings about how, under given external constraints: (1) flow characteristics depend on channel morphology and bed material; (2) the entrainment and transport of bed and bank material depend on flow and sediment characteristics; and (3) channel morphology is governed by slope, discharge and sediment supply through the spatially distributed addition and removal of sediment. The third section includes a summary of evolving ideas on how to classify and predict channel pattern.

River reaches exist within drainage networks, and natural environmental change or human activity anywhere upstream of the reach can alter the boundary conditions for within-reach processes. The next two sections of this chapter switch attention to these more extended time and space scales. They cover developments during the period in understanding: (4) the movement of sediment along river systems and the associated development of floodplains and distributary systems; and (5) the reach-scale consequences of natural and anthropogenic change within drainage basins. This fifth section also discusses work on inferring past sequences of morphogenetic systems from the fluvial deposits they have left behind. A final section reviews how the study of fluvial process and form evolved in the latter part of the twentieth century, and summarizes the existing and new directions in which it was heading at the end of this period.

Some of the developments we describe came about through conceptual insights and deductive arguments, but others depended on measurement, observation and data analysis. These more empirical contributions were facilitated by, or in some cases only made possible by, advances in technology. The two of us who were doing fluvial research in the 1970s remember monitoring channel change through repeated plane table mapping and cross-section levelling, and performing statistical analyses by submitting a program for overnight execution on a mainframe computer. Microprocessor power increased by three orders of magnitude over the next two decades, facilitating the use of numerical modelling and enabling the development of instrumentation such as total stations, GPS, digital photogrammetry and acoustic Doppler velocimetry. Aerial photographs were supplemented by satellite imagery from the late 1970s, and new radiometric, luminescence and other dating methods increased the opportunities for deciphering historical channel change.

Flow in river channels

In the 1960s, knowledge about flow in natural river channels (typically containing bars and pools) lagged well behind what hydraulic engineers and applied mathematicians had learned about simple geometries through laboratory measurements and fluid-mechanics theory. It had long been recognized that reach-average velocity increases with mean depth and water discharge, flow accelerates and decelerates along bar-pool-riffle channels, and flow in bends has a helical character, but quantitative models of these attributes of river flow were poorly developed. Engineers had started using one-dimensional (1D, cross-sectionally averaged) step-backwater

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calculations for design purposes, but this had not yet been extended to geomorphological applications. After the 1960s, there was a move towards a more mechanistic understanding of small-scale flow processes constrained by channel morphology. This was assisted by technical advances that allowed flow to be measured in progressively more detail. Cup- or impeller-type current meters that measured only the time-averaged water speed at one point were supplemented in the late 1970s by two-component electromagnetic current meters (ECMs) that measured two orthogonal components of velocity. A further advance in the 1990s was acoustic Doppler velocimetry (ADV), which measured all three components of velocity at sufficient frequency to study turbulence as well as mean flow (Lane *et al.* 1998). At the end of the period, the synergy between higher-resolution measurements and 3D computational fluid dynamics (CFD) modelling opened the way to a much more detailed understanding of flow in bends and confluences.

River discharge is the product of wetted width, mean depth and mean velocity. Leopold and Maddock's (1953) 'hydraulic geometry' paper had suggested that each of these variables increases as a power function of discharge at a given site. Field workers in several countries came up with a wide range of fitted power-law exponents, but a meta-analysis by Park (1977) failed to identify any climate zone or other pattern. It was later recognized that the exponents are constrained by hydraulics and geometry: cross-section shape determines how width varies with depth, and flow resistance controls how velocity varies with depth (Ferguson 1986). Leopold and his colleagues had also noted that pools and riffles differ in hydraulic geometry, and Keller (1971) proposed that the tendency for riffles to have coarser beds than pools is explained by higher near-bed velocity in pools than riffles during floods. A series of papers by Richards (e.g. Richards 1976)), based on fieldwork and 1D modelling, showed that pools tend to be narrower than riffles and drew attention to the hydraulic implications.

Flow resistance in sand-bed rivers was already known to depend on bedform type, as well as on grain size. In gravel-bed rivers, Limerinos (1970) found that Manning's *n* could be predicted from bed-surface grain size via an underlying logarithmic relation. A decade later, field investigations by Bray (1979) in Alberta, Canada and Hey (1979) in Britain showed that the effective roughness height of a gravel bed was several times even the 84th percentile grain size, rather than equal to the mean diameter as suggested by laboratory work on rough turbulent boundary layers. Gravel-bed rivers are consequently deeper and slower than previous literature suggested. This finding was subsequently attributed to turbulent drag on protruding large clasts (e.g. Clifford *et al.* 1992). The distinctive nature of flow in steep shallow streams containing boulders was recognized and a search for appropriate flow-resistance equations began (e.g. Jarrett 1984). There was experimental research throughout the period on the ways in which vegetation in a channel increases flow resistance and thus reduces bankfull conveyance. It was established that resistance over submerged flexible 'plants' can be predicted from their effective height (e.g. Kouwen and Unny 1973). Later work focused on velocity profiles within and above the plant layer (e.g. Ikeda and Kanazawa 1996), and the interrelations between stem density, turbulence intensity and drag (e.g. Nepf 1999). The effects of vegetation on bank strength and reach morphology are considered later.

A major research interest throughout the period was the character of helical flow cells in river bends and the associated secondary circulation in the transverse plane, because of their relevance to meander development (which we discuss in a later section). The topic was approached both theoretically and in the field. Field investigations using ECMs revealed the presence of a small opposite-helicity cell at the outer bank of some bends (Bathurst *et al.* 1977), possibly analogous to cells that can form in straight channels through anisotropic turbulence. Hickin (1978) measured velocity profiles and flow directions in a long series of bends, confirming the theoretical prediction that secondary circulation is stronger in more highly curved bends. He also documented flow separation into a reverse eddy at the outer bank of a very sharp bend. The most influential theoretical contribution was by Engelund (1974), based on the idea that for morphological equilibrium the effects on sediment transport of secondary circulation and transverse bed slope must cancel out so that grains travel parallel to the banks. This assumed a channel-wide spiral flow, as found in the field by Bridge and Jarvis (1982), but Dietrich and Smith (1983, 1984) measured outwards-only flow over point bars with accompanying transverse sediment fluxes. A more sophisticated theoretical model (Smith and McLean 1984) gave a good match to Dietrich's measurements of water-surface elevation and velocity, and simplified versions of it were subsequently used in morphological models.

There was also sustained interest in flow patterns in tributary junctions and braid confluences, which were studied using laboratory experiments, field measurement campaigns and, latterly, also numerical modelling. The first major contribution (Mosley 1976) was experimental and examined how scour-hole depth in sand-bed confluences varies with junction angle, plan asymmetry and tributary discharge ratio. Using dye for flow visualization, Mosley (1976) observed back-to-back helical circulation cells with surface convergence causing downwards flow in the scour hole. This pattern was also found by Ashmore *et al.* (1992) in their analysis of ECM measurements in two braid confluences; in this setting, the divergent flow downstream from a confluence typically leads to bifurcation round the next medial bar**,** formed by sediment scoured from the confluence. Best and Reid (1984) investigated experimentally how the separation zone where a tributary enters a straight channel depends on the junction angle and the momentum ratio between the two tributary flows. Complex 3D flow structures were also found to be generated by bed discordance (one tributary deeper than the other), even in parallel-tributary experiments with no planform curvature (Best and Roy 1991). Bed discordance was also found to be the main topographical control in a field study by De Serres *et al.* (1999), who used an array of differently orientated ECMs to obtain the first 3D mean and turbulent flow measurements in a natural confluence (Fig. 1 shows an early trial of the ECM rig). In another field study of an asymmetrical junction, Rhoads and Kenworthy (1995) showed the importance of the momentum ratio between the two flows, with increased tributary discharge pushing the mixing interface across the combined channel so that back-to-back spirals are replaced by a single helical structure. These findings helped to explain the existence, location and size of junction bars. Finally, at the end of the period, British geomorphologists began exploring the application of 3D CFD modelling to river bends, braids and junctions. Several papers were published in a special issue of *Hydrological Processes* in 1998 (Bates and Lane 1998), and soon afterwards Bradbrook *et al.* (2000) successfully modelled Rhoads and Kenworthy's (1995) field measurements.

The ability to measure velocity at higher spatial and temporal resolution led to intensified investigations of shear flows in natural rivers, and the role of turbulence in driving sediment transport and developing bedforms. The theoretical model evolved from American experimental work led by Kline *et al.* (1967), who proposed an alternation of near-bed bursts (ejections of low-velocity water from the near-bed region) and sweeps (inrushes of higher-velocity water) in uniform channels. By the 1990s, technical developments in flume

Fig. 1. New technology for flow measurement. André Roy measuring flow structure in a braid confluence using electromagnetic current meters. Photograph: R.I. Ferguson.

instrumentation allowed the turbulence structure over fluvial bedforms to be investigated. Bennett and Best (1995) showed that local Reynolds (shear) stresses over fixed 2D dunes were dominated by ejections along the shear layer, while sweeps were significant in the separation zone, near the reattachment point, and close to the dune crest. The implications for sediment entrainment and deposition were confirmed by Nelson *et al.* (1995) using laser Doppler velocimetry and high-speed cinematography of mobile dunes. The burst–sweep cycle and larger-scale 'coherent flow structures' were the subject of a conference proceedings edited by Ashworth *et al.* (1996), and have featured in much subsequent work on river mechanics.

Sediment mobilization and transport

Fine wash load derived from hillslopes and channel margins is flushed more or less continuously down river systems at a supply-limited rate, but sand and coarser material reside in alluvial riverbeds and are transported only intermittently. Sediment is also added to rivers by bank erosion, and locally also by debris flows or detachment of exposed bedrock.

Flume experiments by G. K. Gilbert (1843–1918), A. Shields (1908–74) and others had established that a bed of nearly identical grains begins to be mobilized at a critical fluid shear stress that is proportional to grain diameter, and above which the transport rate increases rapidly. Most late-twentieth-century research on bed-material transport was concerned with extending these findings to natural rivers. One strand was about quantitative prediction of transport rates, whether for practical purposes or in theories of river regime. A second was about how the threshold concept applies to riverbeds that contain little sand but a wide range of coarser grain sizes. Related to both of these was the need to understand how changes in the composition or arrangement of a riverbed affect transport capacity. Work on fine- and coarse-bed rivers also diverged because of increased awareness of major differences in their sediment mechanics.

Only a few low-power rivers have muddy bed material, and in semi-arid environments the mud may form sand-sized pedogenic aggregates that are transported as bed load (Rust and Nanson 1989). In sand-bed rivers, the entrainment threshold is low and bed-material transport occurs more frequently than in coarse-bed rivers. In floods, it usually takes the form of migrating bedforms in combination with some suspension. Flume experiments conducted for the United States Geological Survey (USGS) by Simons, Richardson and others in the 1950s and 1960s had shown that bedform type depends on flow strength and, in turn, affects flow resistance, thus altering the effective stress available to entrain grains. Engelund and Hansen (1967) devised a way to allow for these interactions in a simple total load rate equation that became widely used in sand-bed rivers. More elaborate methods for predicting sand transport rate, treating bed load separately from suspended load and considering the physics of each mode, were subsequently developed by Engelund and Fredsoe (1976) and van Rijn (1984).

In rivers with beds consisting mainly of gravel or coarser sediment the threshold stress is much higher and significant transport occurs only during floods. The situation is complicated by the typically wide range of grain sizes – sometimes from sand to boulders. Understanding mixed-size entrainment and transport was a major research topic throughout the 1980s and 1990s. Coarse sediment transport is a stochastic process, as emphasized by H. A. Einstein (1904–73), and accurate rate measurements are notoriously difficult to make. Experiments in feed or recirculating flumes played a part, aided in one case by colour-coding different grain sizes (Wilcock and McArdell 1993). Ingenious new field measurement methods were devised to measure bed load at a point or to track it along a reach. Near-continuous measurement of width-averaged bed-load transport rate in small streams became possible using a vortex-tube extractor, as at Oak Creek, Oregon (Milhous 1973; see Fig. 2a) or pressure cells (the Birkbeck trap: first deployed by Reid *et al.* 1985 in England and subsequently by Reid and Laronne 1995 in Israel). The recovery rate of tracer pebbles was greatly improved by embedding magnets in them so that buried tracers could be located, as first done in Israel in the early 1980s by A. Schick (1931–2002) and associates.

As field studies accumulated it became apparent that the value of the threshold stress for a given median surface grain size (D_{50}) varied substantially (Buffington and Montgomery 1997). This was recognized as being due in part to different operational definitions, but also to how surface grains are packed. This was found to vary over time as near-threshold flows rearrange surface particles into more stable structures (Reid *et al.* 1985; Church *et al.* 1998), leading to great uncertainty in predictions of the total bed-load transport rate from the small excess of shear stress over a D_{50}-based threshold. This uncertainty remains if stream power is used as the predictor, as proposed by R.A. Bagnold (1896–1990) in a series of papers (e.g. Bagnold 1977).

There was much effort to establish whether, and if so to what extent, gravel entrainment and transport are size selective. Selectivity had tended to be assumed, not least to explain within-reach spatial variation in grain size; but if transport is selective what keeps a reach in equilibrium? Einstein (1950) and others had noted that coarser grains tend to protrude into the flow and shelter finer grains. Were these effects sufficient to cancel the intrinsic difference in mobility according to

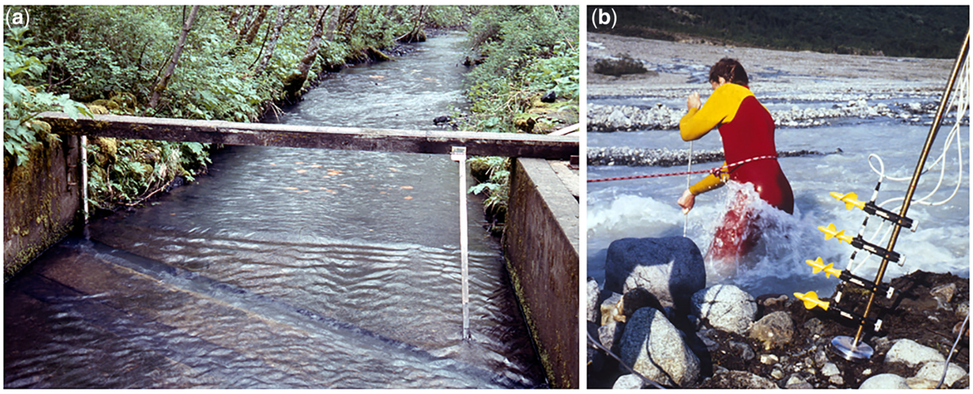

Fig. 2. Field measurements of gravel transport in the1980s. (**a**) The Oak Creek vortex-tube structure, Oregon, USA. Bedload was deflected into a pit off the right side of the image and sampled there. (**b**) Point sampling in a Norwegian braided river for comparison with shear stress estimated from velocity profiles. Photographs: R.I. Ferguson.

grain weight? Theoretical calculations taking protrusion and pivot angles into account suggested that some size selectivity remained (Wiberg and Smith 1987). The first thorough investigation of size-fraction transport in the field was by Parker *et al.* (1982), who reanalysed Milhous's Oak Creek measurements. At this site, as in most other gravel-bed channels, the surface is coarser than the underlying bed (a phenomenon called pavement or armour at the time) and the grain-size distribution of bed load was found to resemble the subsurface rather than the surface. Parker *et al.* (1982) found that different sizes had almost equal transport rates during floods when scaled by their abundance in the subsurface, and attributed this to hiding and protrusion effects once the surface pavement was disrupted. They also fitted a complicated set of equations for predicting size-fraction transport rates in streams of known subsurface size distribution. This was open to the criticism that what the flow acts on is the surface, not the subsurface. Parker (1990) recalibrated the equations in terms of surface size distribution and they became widely used.

In a companion paper, Parker and Klingeman (1982) argued that a coarser surface provides 'macro-hiding' of finer sediment to offset its slightly greater mobility when exposed on the surface. Flume experiments by Dietrich *et al.* (1989) confirmed Parker and Klingeman's (1982) speculation that the degree of surface coarsening is inversely related to sediment supply rate and acts to regulate transport capacity, with static armour below dams as the limit case. At the other extreme, Reid and Laronne (1995) recorded exceptionally high transport rates in flash floods in an ephemeral channel with no coarse surface layer. Surface coarsening was shown to be assisted in some reaches by spatial sorting, such that the bed is coarser where shear stress is higher (Dietrich and Smith 1984; Lisle 1995), and by the end of the period the first attempts were being made to relate patchiness to modelled flow patterns (Lisle *et al.* 2000).

Other researchers found clear evidence of size-selective entrainment and transport in field measurement campaigns using hand-held bedload samplers (Fig. 2b) or tracer pebbles. Andrews (1983) and Ashworth and Ferguson (1989) found that the maximum grain size in bedload samples increased with shear stress. Ashworth and Ferguson (1989) also analysed size-fraction transport rates, which indicated selective transport in most conditions at several sites but not in a major flood at one site. Magnetic tracer pebbles were deployed in Israel, Canada and Scotland by Schick, Church and Ferguson, respectively, and their students. Each found that dispersal was size selective over one or more complete flood hydrographs, and Church and Hassan (1992) showed that tracer travel distances in single floods at several sites collapse onto a consistent function of size relative to surface D_{50}.

A far more detailed understanding of the interaction between shear stress, surface size distribution and size-fraction transport rates emerged from a sustained experimental programme by P. Wilcock, initially in doctoral research at MIT and then with his own 'bed of many colours' flume in Johns Hopkins. A key paper by Wilcock and McArdell (1993) showed that in near-threshold conditions coarser fractions are immobile and fine fractions experience only 'partial' transport, meaning only some grains of each size class move. As shear stress increases, progressively coarser fractions experience partial transport and the finest fractions become fully mobile. Size selectivity is therefore present until all sizes became fully mobile, which was found to occur at about twice the threshold stress for D_{50}.

Separately from all this work on bed-material transport, other researchers made advances in understanding the recruitment of sediment by bank erosion or bedrock incision. Bank erosion was investigated both empirically by physical geographers and in a much more deductive way by researchers with an engineering background. River banks retreat partly through fluvial entrainment during floods but also by mass instability, and the former can promote the latter through undercutting of the base of the bank. Channel curvature is an important control of bank erosion rate, as discussed in the next section, but it is not the only factor. Monitoring of field sites revealed how rates of retreat correlated with flood magnitude, antecedent precipitation and size of river (Hooke 1979, 1980). Other researchers adapted standard soil-mechanics failure models to the special circumstances of cohesive or layered river banks: cantilever failure following undercutting (Thorne and Tovey 1981), the effects of bed degradation (Osman and Thorne 1988) and the role of hydrostatic confining pressure (Darby and Thorne 1996). The collapse of trees into channel margins was shown to have major effects in smaller rivers, particularly by creating log-jam steps in steep torrents (Keller and Swanson 1979). Conversely, in low-energy sand/mud river floodplains, riparian trees have a strong stabilizing effect; the implications for channel pattern are discussed in the next section.

Very little research on bedrock erosion took place until the late 1990s, but the topic then took off as Earth scientists interested in tectonics recognized that river incision controls the evolution of mountain landscapes and began to devise numerical models using slope and catchment area as proxies for stream power and shear stress (Howard *et al.* 1994). An edited collection (Tinkler and Wohl 1998) was a sign of the increased interest in bedrock rivers, and the first thorough work on the mechanics of bedrock erosion was published at the end of the period (Whipple *et al.* 2000). This became a major branch of fluvial geomorphology in the next decade.

Channel morphology

It is natural to ask how rivers form and maintain their channels, and an understanding of what controls channel size and planform is essential for predicting the direction and magnitude of river response to environmental change or human intervention. The work of Luna Leopold and his USGS colleagues in the 1950s and early 1960s provided a major stimulus to this field. In the next three decades there was increased attention to process-based explanations and quantitative models, and planform typologies were refined.

River channels exist within drainage networks and generally increase in size downstream in order to drain ever more runoff, although the opposite applies in deltas, alluvial fans and interior-basin distributary systems. The 'regime theory' of hydraulic engineers like G. Lacey stemmed from experience with irrigation canals and involved simple power-law relations between channel dimensions and water discharge. Leopold and Maddock's 'downstream hydraulic geometry' in 1953 had the same character (Leopold and Maddock 1953). Attempts from the late 1970s onwards to refine and explain these empirical relations took several directions. Some researchers retained the empirical approach but used non-dimensional variables or stratified their analysis according to bank vegetation density (Hey and Thorne 1986). Others proposed 'rational' regime theories that incorporated equations representing physical processes. The only existing mechanistic theory, developed in the 1950s by E. Lane and other American hydraulic engineers, was for canals whose non-cohesive bed and bank sediment was at the threshold of movement. This threshold approach was not directly transferrable to natural alluvial rivers, which do transport their bed material while maintaining a fairly constant width. Parker (1978*a*, *b*) reconciled stable banks with a mobile bed by showing theoretically that lateral redistribution of turbulent momentum could cause sufficient near-bank deposition to balance erosion in silt/sand rivers, or reduce near-bank shear stress to its threshold value in coarse-bed rivers. Other researchers approached the problem by combining a flow-resistance equation, a bed-load transport rate equation and an extremal assumption such as maximum transport efficiency. For example, White *et al.* (1982) showed that an optimum width/depth ratio could be calculated for any given combination of discharge, slope and bed grain size, and derived regime relations from the results. The maximum-capacity model was subsequently refined to allow for vegetated or cohesive banks through the device of an effective friction angle (Millar and Quick 1993).

Much research on channel planform in the 1970s and 1980s was inspired by Leopold and Wolman's classic 1957 United States Geological Survey Professional Paper, which proposed a straight–meandering–braided typology and offered some evidence that braided reaches were steeper than meandering ones with similar discharge (Leopold and Wolman 1957). Schumm and Khan (1972) confirmed this slope dependence experimentally, but noted that the controlling factor could be seen as sediment load rather than slope per se. Schumm (1985) subsequently speculated that the progression from straight to meandering to braiding involves not just higher sediment load but also a higher proportion of bed load in the total load. Mathematically trained theorists confirmed the controlling influence of slope and the width/depth ratio by analysing whether multi-talweg or single-talweg perturbations of a straight plane-bed channel would grow faster (e.g. Parker 1976). Much later, Millar (2000) combined his own regime equations with Parker's (1976) result to show that the threshold slope for braiding depends on both bed grain size and bank strength, as well as discharge. This had already been proposed on conceptual grounds by Carson (1984) and Ferguson (1987), who interpreted the slope threshold as one of shear stress or stream power, and argued that the erodibility of the bed and banks had to be relevant. They also noted that valley slope, not channel gradient, is the independent control. These ideas were subsequently adopted by van den Berg (1995), who discriminated meandering and braided reaches in terms of stream power and median grain size, and Nanson and Croke (1992), who proposed a floodplain typology based on stream power.

Other work on channel planform focused on how meandering and braiding develop, and on the nature of bar sedimentation in rivers of different pattern and bed material. Lewin (1976) documented how a straightened gravel-bed river formed alternate bars that deflected flow towards one bank then the other, and Ashmore (1982, 1991) used time-lapse photography of stream-table experiments to investigate how an initial alternate-bar pattern becomes braided through widening, chute cut-offs and avulsion from choked talwegs. His experiments were generic scale models of gravel-bed prototypes. Different mechanisms may be involved in braided sand-bed rivers: for example, Ashworth *et al.* (2000) documented the development of a 1.5 km-long mid-channel bar in the Jamuna by the amalgamation of stalled dunes in a flow expansion zone. Sedimentologists provided complementary insights from detailed investigations of bar structures, as in Bridge's (1993) keynote and several other chapters in the same collection (Best and Bristow 1993). Hickin and Nanson (1975) reconstructed bend growth rates in a Canadian meandering river by tree-ring dating of scroll bars, and discovered that migration rate increases with curvature until bends become so tight that flow recirculation develops at the outer bank and the fastest current switches to the inner bank. The morphological consequences of neck or chute cut-off were documented in detail by Lewis and Lewin (1983) and Hooke (1995) using map and air photograph evidence. Quantitative models of long-term meander development through the interaction of bar growth and outer-bank erosion were also developed, with key contributions by Ikeda *et al.* (1981) and Blondeaux and Seminara (1985). These models used the depth-averaged mass and momentum equations to estimate near-bank velocity, but Murray and Paola (1994) showed that braiding could be simulated fairly realistically by a much simpler cellular model that routes water according to bed slope and sediment according to discharge and slope. This inspired a whole strand of subsequent 'reduced complexity' modelling of river systems, mostly post-2000.

Many of the authors already mentioned regarded 'meandering' and 'braiding' as parts of a planform continuum rather than entirely separate types. Some channels have hard-to-classify transitional patterns, and some gravel-bed rivers flip between meandering and braiding according to recent flood history. It became recognized that there are different types of multichannel planform (Fig. 3): highly active 'bar braiding' of channels around sand or gravel bars that are submerged in floods; 'island braiding' or 'wandering' of gravel-bed rivers around stable vegetated islands; and stable but branching 'anastomosing' of narrow channels, usually but not always sinuous, that are separated by fragments of aggrading floodplain. The last type is associated with low flow energy, a predominantly suspended-load transport regime and strong vegetated banks, with channel change largely restricted to local avulsion (Smith and Smith 1980; Schumm 1985; Knighton and Nanson 1993; Tooth 2000). Avulsion was also recognized to be a key process in alluvial fans, in which it is precipitated by aggradation of the existing main channel (Hooke 1967). It is also the main type of channel change within deltas, but the early literature on deltas was much more concerned with the coastal processes at the outer margin (e.g. Wright 1977).

Almost all steep headwater channels are 'straight' in Leopold and Wolman's terms, but distinct morphological subtypes came to be recognized by fieldworkers in the western USA (Grant *et al.* 1990; Montgomery and Buffington 1997). The typology that emerged is based on the coarseness of the

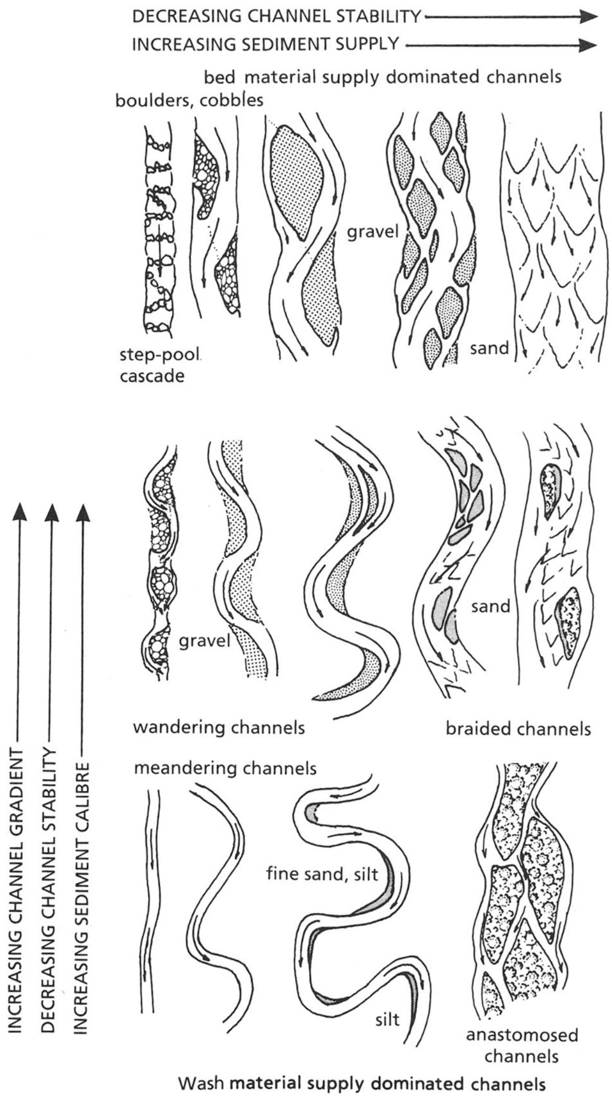

Fig. 3. Channel pattern typology proposed by Church (1992), extending the scheme of Schumm (1985). Republished with permission of John Wiley & Sons from Calow and Petts (1992); permission conveyed through Copyright Clearance Center, Inc.

bed and the presence or absence of pool–riffle or step–pool sequences. It also correlates with gradient: cascading flow over randomly distributed boulders at slopes typically above 5%, boulder step–pool sequences at around 3–6%, plane cobble beds at 2–3% and gravel pool–riffle sequences at 1–2%.

The fluvial cascade

Inspired perhaps by Leopold, Wolman and Miller's book *Fluvial Processes in Geomorphology* (Leopold *et al.* 1964), geomorphologists began to delve more deeply into the complexities of entire fluvial process systems, especially as component parts of so-called 'cascades'. Such research involved exploring drainage network geometry, river long profiles, and catchment-wide systems of erosion, sediment transport and deposition from sediment sources to depositional 'sinks'. Themes in this period at first followed systems theory in recognizing connections, structures and equilibrium states, largely for form geometries with statistical testing for correlation, trends and probability. The 'laws' of stream order and stream length that had been proposed by R.E. Horton in 1945 were shown by Shreve (1966) to be expectable if drainage networks were topologically random. Attention then turned to field, hardware or numerical model catchment investigations. Some were deterministic and linked to hydraulic processes, while others relied on statistical correlation. Field catchment research set out to quantify sediment sources, and then transport and depositional zones. Experimental research quantifying processes at different scales, ranging from plot experiments to small catchments, extended ecological studies undertaken by the United States Forest Service at its H.J. Andrews facility in Oregon since 1948, and these helped to establish sediment sources on-site and delivery to channel systems. Such research also came from decade-long field monitoring by individual geomorphologists (e.g. Harvey 1992). Others scaled up to process controls operating across subcontinental landscapes: for example, relating drainage density to different climatic and lithological settings (e.g. Douglas 1967), or exploring responses of large catchments to sea-level changes (Blum and Törnqvist 2000). The first steps were taken in the numerical modelling of fluvial landscape evolution during uplift, using drainage area and local slope to predict channel-incision rate and hillslope transport rates (Howard *et al.* 1994).

For catchment processes more extensive than the reach scale, S.A. Schumm (1927–2011) introduced a set of qualitative concepts that later gave some structure to empirical work: types of equilibrium, process timescales (cyclic, graded and steady, and the state of system variables within them), thresholds, metamorphosis and complex response within catchment systems (Schumm and Lichty 1965; Schumm 1977). Schumm's further interests included the analogue potential of experimental physical modelling, measurements undertaken in badland landscapes where morphological development was rapid enough to document catchment evolution in miniature and palaeohydrological controls visible in older fluvial forms. Process research relevant to natural fluvial landform generation expanded in multidisciplinary 'river science' research in engineering, hydrology and freshwater ecology.

Sediment transit through catchment systems became a particular research focus. This made use of measured or estimated site erosion losses and compared them with river sediment loads measured downstream. 'Sediment delivery ratios' were estimates of dispersal loss between contributing sources and downstream outputs (Walling 1983), whilst global patterns in sediment yields reaching the oceans made use of internationally available data, despite its limited availability for some continents such as Africa. At this scale, the importance of active tectonics and mountain sources, together with human impacts, became clear (Milliman and Meade 1983; Milliman and Syvitski 1992; Summerfield and Hulton 1994). However, there were also within-catchment processing and storages being worked out. Where was sediment coming from to be deposited *within* catchments? Greater understanding came from sediment budgeting quantitatively identifying inputs, storages and outputs (Dietrich and Dunne 1978), including the identification of sediment sources from their chemical or other 'fingerprints' (Walling and Woodward 1995). Complex outcomes of historical land-cover change were documented in research by S.W. Trimble in Wisconsin, showing the changing balances between erosion and storage over some 100 years (Trimble 1983). In a similar manner, formerly glaciated parts of catchments could naturally provide large amounts of 'paraglacial' sediment, as outlined by Church and Ryder (1972).

Moving on from earlier Davisian and other qualitative 'stages', down-channel morphological and sedimentological process types and transitions emerged as strong individual target areas for research: processes of headwater extension, bedrock and boulder-bed channels, active channel migration zones, and the domains of particular channel types in nominal process terms (Nanson and Croke 1992; Montgomery and Buffington 1997). Figure 4 shows some typical trends schematically. The link between longitudinal profile and downstream fining received new attention, with the recognition that both could be disrupted by coarse tributary inputs (Rice and Church 1998) and that strong downstream fining could be generated by size-selective transport on an aggrading profile (Paola *et al.* 1992; Ferguson *et al.* 1996), rather than by abrasion as generally assumed.

Complementing research on sediment sources and flux, fluvial depositional environments became a major research focus supported especially by funding for hydrocarbon exploitation. Continental sedimentary rocks are rich in the terrestrial deposits of alluvial fans and basins, and what was termed 'alluvial architecture' emerged in active sedimentological research across this time period (reviews by Allen 1965; Paola 2000). Sedimentary hierarchies from ripples to larger composite assemblages were established (Miall 1977, 1996). Research also involved flume modelling and computer-based numerical simulation (Bridge and Leeder 1979). M.G. Wolman and L.B. Leopold had earlier underlined the distinction between lateral accretion and overbank deposits, and this led on to quantifying sediment diffusion volumes with distance from channels and to establishing rates of lateral accretion. This then expanded to field case studies of depositional processes for levees, crevasse splays, avulsions, palaeochannel fills and floodplain lakes (Miall 1996). Vertical aggradation, or incision producing terraces, was studied in different topographical, tectonic and climatic contexts. Fan sedimentation by different combinations of channel flow, sheetwash and sediment gravity flow was investigated in case studies that led to a major synthesis (Blair and McPherson 1994). This involved upscale moves from reach-scale deposition to the composite sediment bodies of alluvial fans in arid and active tectonic areas, and to alluvial basin fills more generally. The first geomorphological studies were made of large alluvial rivers such as the Amazon, Nile and Brahmaputra, extending earlier work on the Mississippi (Coleman 1969; Mertes *et al.* 1996). At such scales, fluvial systems demonstrated considerable channel and depositional complexity, but also down-channel form sequences. Other research focused on lacustrine and larger marine deltas (Spencer and French 2022, this volume), allowing depositional processes and contributing catchment histories for distributional systems to be further unravelled. Research on dryland rivers and inland deltas expanded, particularly in Australia (Nanson *et al.* 1986; Tooth 2000) and Africa (Stanistreet and McCarthy 1993). This was symptomatic of research developing in the southern hemisphere and reporting on forms and processes previously unidentified by geomorphologists who were largely researching in the northern hemisphere.

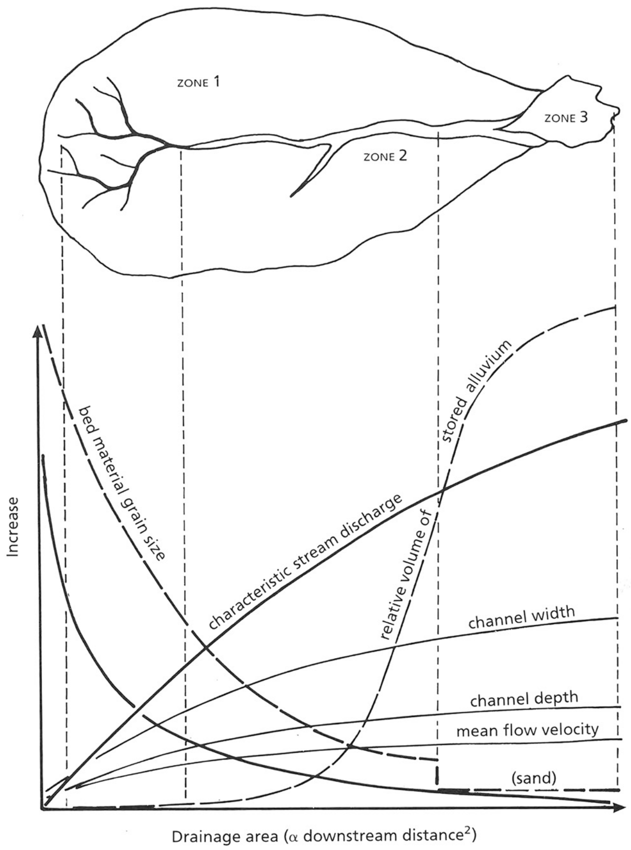

Fig. 4. The sediment cascade and river character in a typical drainage basin according to Church (1992). Upper part is based on the scheme of Schumm (1977). Republished with permission of John Wiley & Sons from Calow and Petts (1992); permission conveyed through Copyright Clearance Center, Inc.

To summarize, in this time period various disciplinary motivations led to an enlarging body of fundamental and applied fluvial research. Geologists particularly sought modern analogues for interpreting ancient environments. An important consideration was which of the observable sedimentary units actually got preserved in ancient deposits; some that formed initially were reworked and later destroyed, such as from channel migration. Geomorphologists and engineers were motivated to study process environments to understand their surface forms and for channel engineering design (Anderson *et al.* 1996). Riverine depositional environments include the floodplains where many of the world's population live, and there was a perceived need to understand how such floodplains formed and how stability and community protection could best be achieved. This came to involve flood flow hydraulics, sediment systems and dynamics, and land and river management for different alluvial environments (Thorne *et al.* 1997). Whilst morphological understanding for its own sake persisted as 'blue skies' research, both research funding and ethical concerns for environmental hazards and natural system conservation also increased the volume of applied studies involving whole-catchment process systems generating sediment movement, and ones associated with floods in particular.

Changeable rivers

River systems are liable to change in two ways: *autogenically* as active processes such as rivers meandering and working their way across landscapes; and *allogenically* as external controls such as tectonics, climate and human activities vary and affect river processes. Hydroclimates can also change during the 'lifetimes' of landforms, including variations within the Holocene, but also Quaternary sequences of glacial and interglacial conditions. Linkages to fluvial process changes and transformations were also demonstrated as arising from human activities such as river flow regulation and mining activity (Lewin *et al.* 1977; Petts 1984; James 1989) (Fig. 5). Human impacts in general are discussed more fully in Goudie (2021, this volume).

Channel dimensions may also change incrementally and autogenically over a matter of years, whole channel patterns switching over decades, with entire alluvial systems being transformed in the long term. These timescales are not intrinsically absolute (many may be reproduced rapidly in laboratory flumes or modelled numerically, as discussed in Church (2021, this volume) and Martin (2022, this volume)), but their actualities became established in the later twentieth

Fig. 5. The human impact: legacy sediment inherited from the California Gold Rush *c.* 1850s, Greenhorn Creek, California. L. Allan James, who has studied such deposits extensively, is the left-hand foreground figure. Photograph: J. Lewin.

century through numerous case studies involving field study and monitoring. These were published in journals in large numbers, in symposia volumes such as the series on *Fluvial Sedimentology* (Miall 1978) and *Gravel-Bed Rivers* (Hey *et al.* 1982), and in other edited volumes (e.g. Carling and Petts 1992; Best and Bristow 1993; Anderson *et al.* 1996). Evidence was derived from direct observation, historical documents, and the dating and interpretation of the sedimentary record.

Studies of fluvial change made use of such evidence to reconstruct autogenic channel planform change: for example, determining empirically how meanders evolve by lateral expansion or down-valley translation, or change from one pattern style to another over appropriate decadal and centennial timescales (Gregory 1977, 1983). Other studies demonstrated both climate shifts and human activity over millennia, such as the study across the Mediterranean by Vita-Finzi (1969). As more studies unfolded, human and episodic climatic influences became more and more apparent, with timed occurrences in human activities such as deforestation and agricultural intensification producing one set of effects, but with climatic episodes such as the Little Ice Age also leading to changes in the frequency of sedimentation events. It was often not clear which allogenic drivers dominated, climatic or anthropogenic (Macklin and Lewin 1993). Assumptions of Holocene environmental equilibrium for formative periods lasting for decades to centuries began to appear increasingly untenable (Newson and Lewin 1991), with increasing recognition of transient behaviour, step or ramped changes and recovery from one state to another. This included fluvial response and recovery from volcanic eruptions as from Mount St Helens in 1980 (Simon 1992). This eruption also prompted research on flows with very high sediment concentrations, and on the preservation, or not, of lahar and mudflow deposits within alluvial systems.

The second half of the twentieth century saw increasing numbers of case studies on the effects of human activity in particular: deforestation, land drainage and agriculture, urbanization, channel ‘training’, reservoir control, and mining (Wolman 1967; Gregory 1977; Knox 1977; Trimble 1983; Petts 1984; Williams and Wolman 1984; Brookes 1988; Petts *et al.* 1989; Kondolf 1994). Some studies involved paired catchments: for example, one transformed by river regulation or afforestation, and the other an otherwise similar unaffected ‘control’ for comparison. Following Wolman (1967), other urban studies were ‘before and after’ investigations that tracked and measured the effects of building activity and subsequent drainage transformations on sediment delivery. Collectively, all of these had effects on the nature and rate of sediments supplied to rivers, river flow regimes, the ways that channel patterns were constrained, and the rates of erosion, sediment transport and sedimentation (see also Goudie 2021, this volume).

Even in the short term, over decades, relationships between processing events and morphologies began to seem more complex. M.G. Wolman and J.P. Miller’s 1960 magnitude–frequency paper had recognized a dominant role for bankfull discharges (Wolman and Miller 1960: based on gauged river data available for a relatively short period), but a series of extreme events in subsequent decades both from storms in Europe and hurricanes in North America also drew attention to extreme floods (Costa 1974), and to their contrasting forms of activation in different environments (Wolman and Gerson 1978; Lewin 1989). The response to large floods could be rapid and catastrophic, but recovery periods might then last for many years (Burkham 1972); in the meantime, slugs of material were shown to move down-channel event by event for extended periods, and responding to human sediment inputs and to flood surges in sediment supply (Nicholas *et al.* 1995).

Much longer-term environmental fluctuations leading to morphogenetic changes over geological time periods became widely studied, interpreted and dated during this period (Gregory 1983; Brown and Quine 1999; Summerfield 2000). For the mid-latitudes, this included the river aggradation and incision responses to alternating interglacial, periglacial and glacial conditions during the Quaternary, together with environmental interpretation of even older alluvial deposits. These showed interacting effects from base-level, tectonic and climatic change (Gibbard 1988; Blum and Törnqvist 2000; Bridgland 2000). The range of geomorphological processing timescales, and the roles of inheritance and historical contingency, also means that these continue to influence present-day fluvial processes including, for example, the sediments produced under former morphogenetic systems available to rivers, and including those circumscribed by the history of human activity.

Research by G.H. Dury (1916–96) on the quantitative analysis of misfit channels (those smaller than the valleys that their antecedents had produced), using dimension/discharge relationships and investigation of valley fills, was subsequently followed up by work on the nature and role of very large palaeofloods. This later research was partly inspired by field studies of the Lake Missoula Pleistocene megafloods and the resultant Channelled Scablands of North America, notably by V.R. Baker and co-workers (Baker 1973). Similar studies followed in global environments across the world where rock gorges allowed flood peak depths to be reconstructed and transported sediment sizes to be observed.

In general, palaeodischarge reconstructions relied on established process relationships between channel dimensions and bankfull discharges, and on hydraulic relationships between velocities or stream power and the size of transportable material (e.g. see Church 1978; and chapters by J.C. Knox, K. Rotnicki and J. Maizels in Gregory 1983). The increasing availability of radiometric and other dating tools (Anderson 2021, this volume), and palaeoenvironmental reconstruction methods, allowed change sequences and different formative conditions to be widely assessed in Quaternary terrace deposits and alluvial fills. For example, research by Leszek Starkel and co-researchers in Poland (summarized in Gregory 1983) made extensive use of such methods for the Holocene, whilst Pleistocene fluvial deposits in England, France and The Netherlands that had long attracted attention were more precisely dated and interpreted on a more secure (although sometimes still controversial) footing (Gregory 1983; Branson *et al.* 1996).

Three broad research styles linked to the timescales of catchment-scale fluvial research came to dominate in the late twentieth century:

1. Long-term activity, with terrace formation and valley fills related to alternating Quaternary climates, tectonics and base-level changes were recognized, dated and also related to the marine oxygen isotope record (see also Anderson (2021) and Bridgland (2021), this volume). Many of these studies were taxonomic, with 'processes' being viewed as changing in time linked to known climatic episodes, incident biological indicators and, to an extent, to hydroclimates during the units recognized.
2. Holocene river changes, incision and alluviation were related to both climate and human activity phases. This included relationships with structures such as river regulation, mining and accelerated sediment inputs from land-cover changes.
3. Short-term dynamics that directly affected current catchment management were identified, using historical evidence to extend what could only be short periods of direct observation.

Altogether, there was growing emphasis on identifying formative episodes, their characteristics and timescales. Quantitative prediction in space and time relied equally on both numerical and physical process modelling, and mainly on flume experiments and reach-scale studies distributed within catchments in the field, as described earlier in this chapter. However, empirical evidence increasingly suggested that the anthropogenic present added extra dimensions to 'natural' process research, such that the past was a less reliable guide to the present and the future. Conceptual and hypothetical models – for example, involving lagged responses to catchment disturbance or base-level change – also remained to be tested further empirically at the turn of the century.

Appraisal: fluvial geomorphology at the turn of the century

The huge expansion of the fluvial geomorphology literature in the last part of the twentieth century was notably multidisciplinary. Understanding how river channels and river systems function, and how they alter over different time spans, attracted interest with a variety of motivations. The advances made over the period were predominantly the work of individual geomorphologists, sedimentologists and engineers, together with their graduate students, but scientists with different backgrounds, nationalities and motivations learned from each other. Hydraulic engineers concerned primarily with design and management became more aware of the contribution that geomorphologists could make, geomorphologists became more aware of the existing engineering literature, and there was synergy between sedimentologists interested in hydrocarbon reservoirs and geomorphologists interested in river patterns. Hydrocarbon exploration was only one of several new ways in which geomorphology became 'relevant'; others include river management, freshwater ecology and impact assessment of human interference with rivers or their catchments.

It is tempting to see a turn from studying form to studying process, but how geomorphologists interpreted 'process' varied. In the 1970s, inspired by developments in systems analysis, many pointed to links and correlations between identified forms and controls. Studies purely of reach geometry and network topology were briefly in vogue in the 1970s but attention dwindled later in the period. At reach scale, the period saw increased emphasis on flow and sediment-transport processes within a Newtonian mechanics paradigm that harked back to G.K. Gilbert and European and American hydraulic engineering. The 'process' orientation took several forms: empirical in attempts to measure and interpret within-reach flow structures or to observe the development of meandering and braiding, conceptual in the case of early rational explanations for hydraulic geometry and pattern thresholds, but theoretical in the case of mechanistic models of flow structures, transport thresholds and bank stability.

At larger time and space scales, 'process' was often interpreted as temporal evolution to be revealed by identifying and dating formative episodes and their morphogenetic conditions, especially as revealed through use of global palaeoclimate templates. Form designation and interpretation also became more complex, with hierarchies of newly assessed morphological and sedimentary assemblages, and new global variety found in channel patterns and alluvial architecture at different scales. This burgeoning complexity was, to some extent, inevitable as case studies accumulated from a wider range of environments than the pioneers had worked in. Mounting evidence of longer-term environmental fluctuations and the shorter-term impact of discharge extremes and human activity led to increased recognition that rivers and drainage basins are not always in equilibrium.

Has work that was influential in this period stood the test of time? On the whole, we think it has. Little of it has been rejected as incorrect or superseded by very different approaches or interpretations. The use of Newtonian mechanics continues to be part of what is considered to validate new reach-scale process research, although now with a greater emphasis on the role of turbulence, which was only just starting to be measurable in the field by 2000. Some longstanding findings and models (e.g. Shields' entrainment threshold) are now regarded as limited in their applicability, but they continue to be widely used for practical purposes. Likewise, some early experimental work lacked consideration of dynamical scaling, but properly scaled laboratory experimentation continues to be seen as a valuable approach. Research on the history of fluvial landscapes has a different character: inference to the most plausible explanation for fragmentary evidence, validated by consistency with what else is accepted about global or regional climate and tectonics. It can, in principle, be falsified by new types of evidence (e.g. cosmogenic isotope dating) but, on the whole, new evidence has added detail rather than questioning the story. What has emerged is a considerably more nuanced account.

Where was fluvial geomorphology heading at the end of the period? At the start of this chapter we emphasized the importance of new technology as a factor in facilitating or enabling new research between 1965 and 2000. It is probably fair to say that in the 1960s and 1970s there were more ideas about fluvial forms and processes than data with which to test them. That became less and less so, and the situation at the time of writing has arguably reversed: it is easier to acquire terabytes of digital data relating to a river reach than to know what to do with it all. Continued technical development is therefore the first point to make about the direction of fluvial research as of the year 2000. The advent of GPS, terrestrial LiDAR and global digital terrain models derived from satellite radar were starting to revolutionize the characterization of land form at all scales. Cosmogenic isotope assay had recently been added to the dating toolkit and was starting to be used to estimate long-term denudation rates. Continued growth in computer power was enabling numerical models to include more detail or to be extended in space and time, and the development of software packages for satellite image analysis and GIS greatly extended awareness of the variety of fluvial landscapes, as well as providing new measurement tools.

However, as well as these technical and information developments, there was the human factor: what were fluvial scientists choosing to study at the turn of the century? Research continued after 2000 on all the topics featured in this chapter, taking advantage of the opportunities opened up by technical advances, but several previously neglected topics were beginning to attract attention. Reach-scale research, which had mostly been conducted in quite small rivers with gravel or sand beds, was extended to bedrock rivers, to headwater streams containing boulders and large woody debris, and to boat-borne or satellite measurements in very large lowland rivers. Alongside this extension of work to previously neglected types of river, there was ever-mounting interest in ecological and environmental aspects of river systems: the interactions between riparian vegetation and fluvial processes, the ways in which invertebrate and fish habitat depend on fluvial processes, and the ecological classification of rivers. Moreover, after a century of engineering interest in how to design stable artificial channels, interest turned to the principles that should underpin the restoration of previously channelized rivers. The study of rivers was becoming even more multidisciplinary, with ecologists and tectonic geologists joining in, and the literature continued to grow exponentially.

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