CHAPTER

2.1

GEOMORPHOLOGY AND SEDIMENT REGIMES OF INTERMITTENT RIVERS AND EPHEMERAL STREAMS

Kristin L. Jaeger*, Nicholas A. Sutfin†, Stephen Tooth‡, Katerina Michaelides§,¶, Michael Singer¶,**

USGS Washington Water Science Center, Tacoma, WA, United States *Los Alamos National Laboratory, Los Alamos, NM, United States*† *Aberystwyth University, Aberystwyth, Wales, United Kingdom*‡ *University of Bristol, Bristol, United Kingdom*§ *Earth Research Institute, University of California Santa Barbara, Santa Barbara, CA, United States*¶ *Cardiff University, Cardiff, United Kingdom***

IN A NUTSHELL

- As intermittent rivers and ephemeral streams (IRES) occur in all climates and across a range of scales and tectonic, lithological, and physiographic settings, generalizing about their geomorphology is challenging
- Valley-floor (i.e., channel and floodplain) processes and forms in IRES are extremely diverse and span a spectrum from distinctly different to overlapping with perennial systems
- Hydrological and sediment regimes are the primary drivers of IRES valley-floor processes and forms
- Variations in valley-floor processes and forms can be analyzed by considering the position along the river network
- Valley-floor morphology in IRES may persist for years to decades or longer, but also can be highly transient, adjusting with every competent flow event

2.1.1 INTRODUCTION

The physical characteristics of a river or stream channel—its size, shape, and dominant substrate—provide the template for physiochemical and biological processes. These physical characteristics are strongly influenced by hydrological and sediment regimes, which collectively encompass the nature of water and sediment delivery to the channel, and the erosional and depositional patterns within and adjacent to the channel. The physical characteristics of intermittent rivers and ephemeral streams (hereafter, IRES) are extremely diverse and span a spectrum from those that resemble their perennial counterparts to those that are distinctly different. This diversity underpins and promotes diverse, and in some respects distinctive, ecologies.

This chapter describes the geomorphology and sediment regimes of IRES occurring across a broad range of climates over scales of space and time that extend from reach-scale, single floods to network-wide, centennial-scale flow sequences. We begin by outlining the main determinants of IRES catchment conditions and how IRES can be analyzed within a catchment-scale framework that identifies and delineates the dominant geomorphological processes driving valley-floor (i.e., channel and floodplain) development. We then describe IRES valley-floor characteristics in different parts of the catchment and

Intermittent Rivers and Ephemeral Streams. http://dx.doi.org/10.1016/B978-0-12-803835-2.00002-4

then consider distinct longitudinal trends, the influence of human activities on IRES geomorphology and sediment regimes, and the geomorphological diversity of IRES at the global scale. We conclude by highlighting knowledge gaps and possible future research directions.

DETERMINANTS OF IRES CATCHMENT CONDITIONS

At the broadest scale, climate, geology, and human activities are the fundamental determinants of catchment conditions, and their effect on IRES ecosystems is translated through the catchment by hydrological, sedimentary, and geomorphological processes (Fig. 2.1.1). Catchment conditions, including the topography, soils, vegetation, and river/stream network topology, influence water and sediment delivery to and along the channels, which influences valley-floor morphology and, in turn, ecosystem processes and patterns. These interactions are not unidirectional as ecological processes and patterns can feed back to influence valley-floor morphology, which consequently helps to regulate hydrological and sediment regimes and the longer-term development of catchment conditions.

Various combinations of climate, geology, and human activity (Fig. 2.1.1) contribute to considerable diversity in IRES catchment conditions, hydrological and sediment regimes, and valley-floor forms and processes. For instance, IRES occur across climates ranging from humid to hyperarid. However, the occurrence of IRES in humid regions is generally limited to the upper parts of the catchment

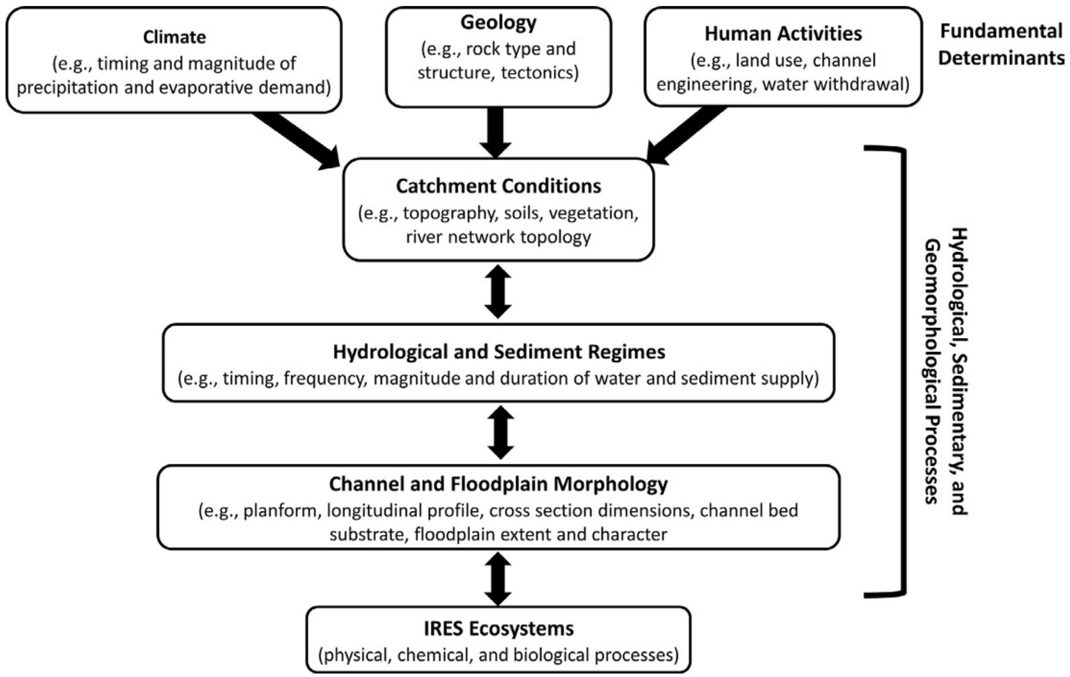

FIG. 2.1.1

Fundamental determinants of catchment conditions and their influence through hydrological, sedimentary, and geomorphological processes on IRES ecosystems. *Single-headed arrows* indicate predominantly unidirectional influences. *Double-headed arrows* indicate feedback interactions.

(e.g., Wohl, 2010) because wetter climates typically provide sufficient surface runoff and groundwater to support perennial systems throughout most of the channel network. In drier climates (e.g., drylands or the seasonal tropics), IRES are more widespread owing to less dependable, more variable surface runoff, and limited groundwater contributions.

Flow regimes of IRES are described in more detail in Chapters 2.2 and 2.3, but merit discussion here as they are a key driver of sediment transfers to and within valley floors, and therefore strongly control channel morphology and development (Fig. 2.1.1). Climates that support extensive IRES tend to be semi-arid and Mediterranean, and are characterized by precipitation or other sources of runoff that are highly variable in space and time (Nicholson, 2011), and by vegetation coverage that is sparse, unevenly distributed, or temporally variable (Tooth, 2013). Regardless of climatic setting, high-intensity convective storms can result in spatially discontinuous and localized flow responses within IRES catchments (Renard and Keppel, 1966; Goodrich et al., 1997; Nicholson, 2011; Chapters 2.2 and 2.3). Even when precipitation or other sources of runoff are more regular and widespread (e.g., climates characterized by seasonal snowmelt or monsoonal rains), the resulting flows can be highly variable and discontinuous as a consequence of transmission losses into unconsolidated alluvium (Graf, 1988; Tooth, 2013; Kampf et al., 2016). In addition, many climates may experience multiyear wet and dry cycles resulting from El Niño-Southern Oscillation (ENSO) phenomena and other global teleconnections. These diverse hydrological characteristics typically translate to long periods of zero flow, irregular floods, and high relative peak flow magnitudes compared to flow in perennial systems (Tooth, 2013).

GEOMORPHOLOGICAL ZONES IN IRES

Within a given climatic and geological setting, many fundamental geomorphological processes that operate in IRES and perennial systems (Box 2.1.1) tend to be influenced by longitudinal position in the catchment. General longitudinal (down-valley) trends in channel morphology and sediment regimes were outlined by Schumm (1977) who described three zones in relation to relative elevation and catchment position (Fig. 2.1.3A). The production zone is dominated by net erosion, which removes sediment from hillslopes and supplies it to the channels. The transfer zone is characterized by down-valley sediment transport; in a stable channel, there is an approximate balance between sediment input and output. The deposition zone is characterized by net sediment accumulation. The process domain concept (Montgomery, 1999) builds on Schumm's conceptual model by outlining how geomorphological processes can influence habitat conditions and ecosystem processes, and identifies regions of a channel network with distinct ecological characteristics that are directly associated with the dominant geomorphological processes. A benefit of Montgomery's (1999) concept is that it allows for longitudinal discontinuities and patch dynamics that occur in many IRES and perennial systems (e.g., Burchsted et al., 2014).

The model presented by Tooth and Nanson (2011), previously developed by Gordon et al. (1992), extends Schumm's (1977) and Montgomery's (1999) conceptual models to dryland river systems and designates four broad geomorphological zones: upland, piedmont, lowland, and floodout (Fig. 2.1.3). In this chapter, we adopt this model as a useful framework for describing IRES and it recurs in discussions of hydrological connectivity in Chapter 2.3. The relative importance, spatial extent, and even character of the four zones vary as a function of climatic, tectonic, and physiographic settings (Section 2.1.7). Therefore, we acknowledge that these zones serve as a very broad generalization and do not capture the full geomorphological diversity of IRES. Nonetheless, characterizing IRES within a context of zones provides a logical, physically meaningful framework for synthesizing information derived from highly variable natural phenomena. In addition, it provides a potential basis for coupling the dominant geomorphology and sediment regimes within each zone to down-valley changes in the characteristic ecological conditions.

BOX 2.1.1 QUANTITATIVE PARAMETERS TO EVALUATE CHANNEL MORPHOLOGY AND SEDIMENT TRANSPORT POTENTIAL

The shape (morphology) of rivers and streams is governed by physical forces studied within the fields of fluvial geomorphology and hydraulic engineering. The ability of flowing water to transport sediment is a function of flow depth (d), velocity (v), discharge (Q), and channel slope (S).

In ungauged rivers and streams, flow velocity (v, in $\mathrm{m\,s^{-1}}$) can be estimated indirectly, using equations such as the Manning formula:

$$v = \left(R^{2/3}S^{1/2}\right)/n \tag{2.1.1}$$

where R is hydraulic radius (channel cross-sectional area (A) divided by the wetted perimeter (P) of the stream bed and banks, but commonly substituted by d in wide, shallow channels) and n is a measure of the roughness of the bed and banks (lower values for smooth bed and banks, higher values for rough bed and banks).

The Manning formula can also be used to estimate discharge (Q, in $\mathrm{m^3\,s^{-1}}$) in ungauged streams by incorporating A into the formula:

$$Q = \left(AR^{2/3}S^{1/2}\right)/n \tag{2.1.2}$$

Many other hydraulic equations encompass these variables, such as those for bed shear stress (τ, in $\mathrm{N\,m^{-2}}$) and unit stream power (ω, in $\mathrm{W\,m^{-2}}$):

$$\tau = \gamma RS \tag{2.1.3}$$

$$\omega = \gamma QS/w \tag{2.1.4}$$

where γ is the specific weight of water and w is channel width. The significance of these equations is their strong association with the potential for geomorphic work (i.e., erosion and sediment transport), which influences many ecological processes and patterns.

Eqs. (2.1.3) and (2.1.4) show that for given values of γ, R, Q, and w, steeper channels (higher S) will be more powerful (higher τ and ω). Relatively steep channels, such as those in the upland and piedmont zones, may have τ and ω values sufficiently competent to erode bedrock and transport coarse-grained sediment, even during relatively moderate floods. Significant bed erosion and rapid sediment transport may lead to channel incision, thereby increasing R, d, and τ, thus creating a positive feedback that continues channel incision. Ultimately, this may lead to the formation of a relatively narrow and deep channel (Figs. 2.1.2A and 2.1.5A and B), depending on the controlling expression of regional climate (Slater and Singer, 2013).

By contrast, less steep channels, such as those in the lowland and floodout zones, may have τ and ω values that are incompetent to consistently transport large volumes even of finer-grained sediment, except perhaps during the largest floods. During low to moderate flood events, some sediment may be deposited within the channel, thereby reducing R, d, and τ. Over time, this may lead to channel aggradation and the formation of a relatively wide and shallow channel (Figs. 2.1.2 and 2.1.5). Arroyos of the American southwest cycle between these contrasting cross-section morphologies.

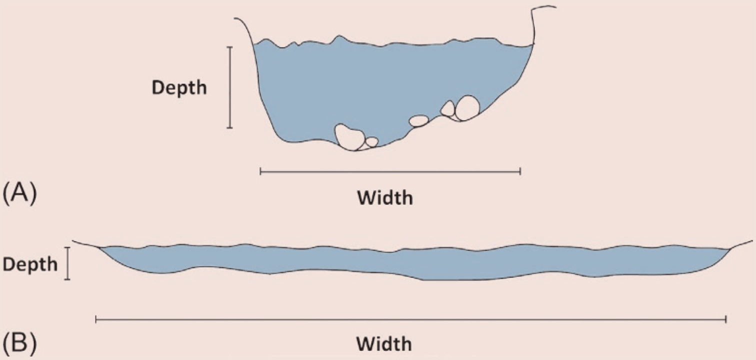

FIG. 2.1.2

Schematic diagram of channel cross-sections showing variability of width and depth. Narrow, deep channels possess a low width:depth ratio (A). Wide, shallow channels possess a larger width:depth ratio (B).

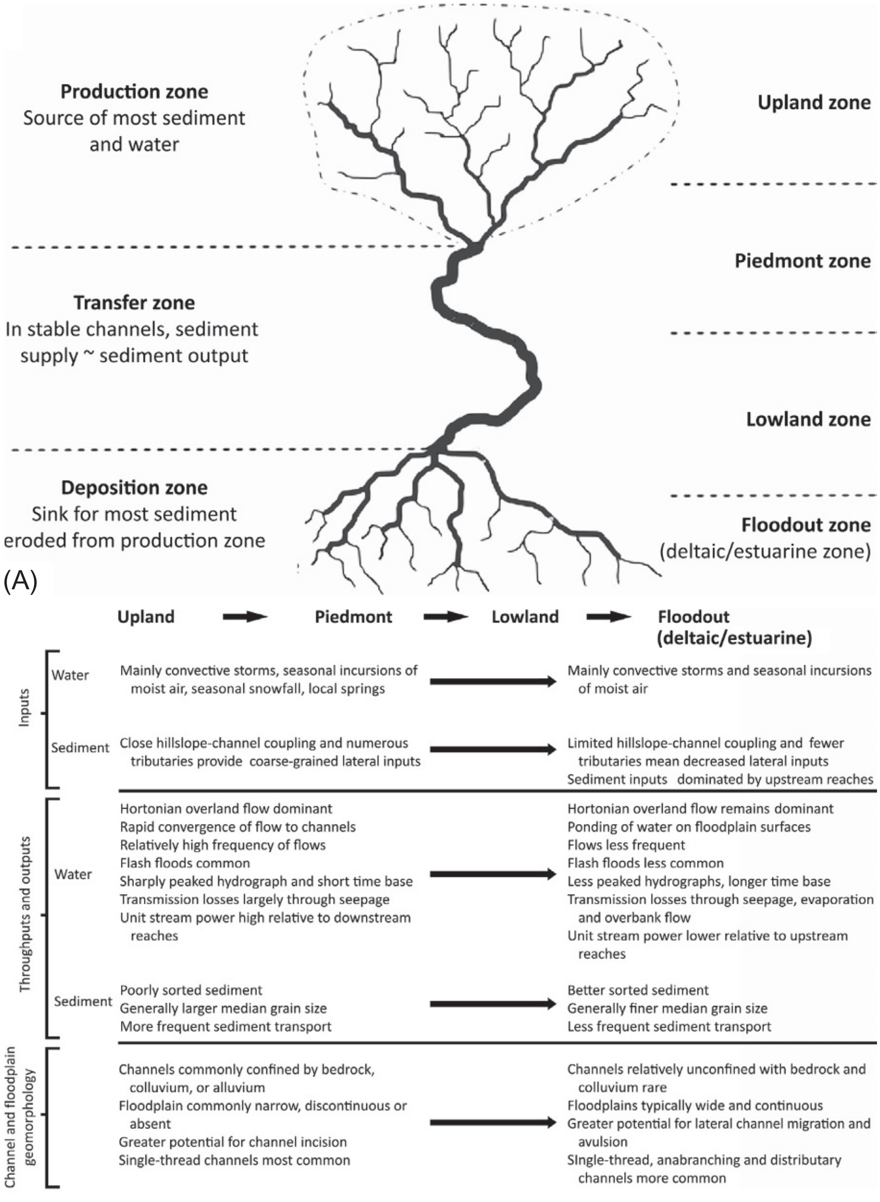

FIG. 2.1.3

Conceptual model showing the four geomorphological zones of an idealized IRES system (A) and the diverse hydrological, sediment regime and geomorphological characteristics across the four zones (B). The four geomorphological zones broadly correspond to the source, transport, and deposition zones of an idealized river, originally proposed by Schumm (1977). Down-valley changes through the zones highlight the tendencies for adjustment of the different characteristics along multiple continua. In any given catchment, down-valley hydrological, sediment regime and geomorphological changes are commonly irregular and nonlinear and may involve step changes or threshold crossings, as influenced by features such as local bedrock outcrop, the spacing of tributary junctions, dams, or artificial abstractions.

Conceptual model (A) is modified from Tooth, S., Nanson, G.C., 2011. Distinctiveness and diversity of arid zone river systems. In Thomas, D.S.G. (Ed.), Arid Zone Geomorphology: Process, Form and Change in Drylands, third ed. Wiley-Blackwell, Chichester, pp. 269–300, with permission.

2.1.2 UPLAND ZONE

In the upland zone, IRES channels are closely coupled with hillslopes, and lateral sediment inputs result from delivery by overland flow and more abrupt, mass failures that may develop into landslides and debris flows (Wohl and Pearthree, 1991). Periodic high-energy flood events may transport large volumes of sediment and erode bedrock. Hence, in the upland zone, IRES systems tend to be primarily erosive and serve as the dominant source of sediment to downstream reaches.

Channel substrate in the upland zone may consist of bedrock, alluvium, or some combination of the two. Bedrock reaches—characterized by a dominance of exposed bedrock in the bed and banks—may possess a relatively thin (typically <10–20 cm thick) veneer of alluvium (Jaeger et al., 2007; Sutfin et al., 2014). Bed sediments in the upland zone tend to be poorly sorted and include a range of grain sizes up to boulders (Fig. 2.1.4). Channels are typically small, steep, and single thread with low width-depth ratios (<20) (Figs. 2.1.2 and 2.1.5A). Floodplains are commonly absent or restricted in width

FIG. 2.1.4

Characteristics of IRES in the upland zone shown in (a) schematic form illustrating key landforms and sedimentary deposits. Examples include this bedrock-incised upland drainage network, Utah, USA (b, view looking up-valley) where the base of the channel is marked by vegetation to the right of the standing figure. Smooth, bare bedrock slopes shed large amounts of overland flow after rainstorms, leading to rapid stage rises in the channel. Other upland examples include this single-thread channel (c, view looking downstream) deeply incised into coarse-grained valley deposits and confined by bedrock outcrop, and this single-thread, step-pool channel (d, view looking downstream), both occurring in Arizona, USA.

Photos: Courtesy S. Tooth (b), N. Sutfin (c), K. Jaeger (d).

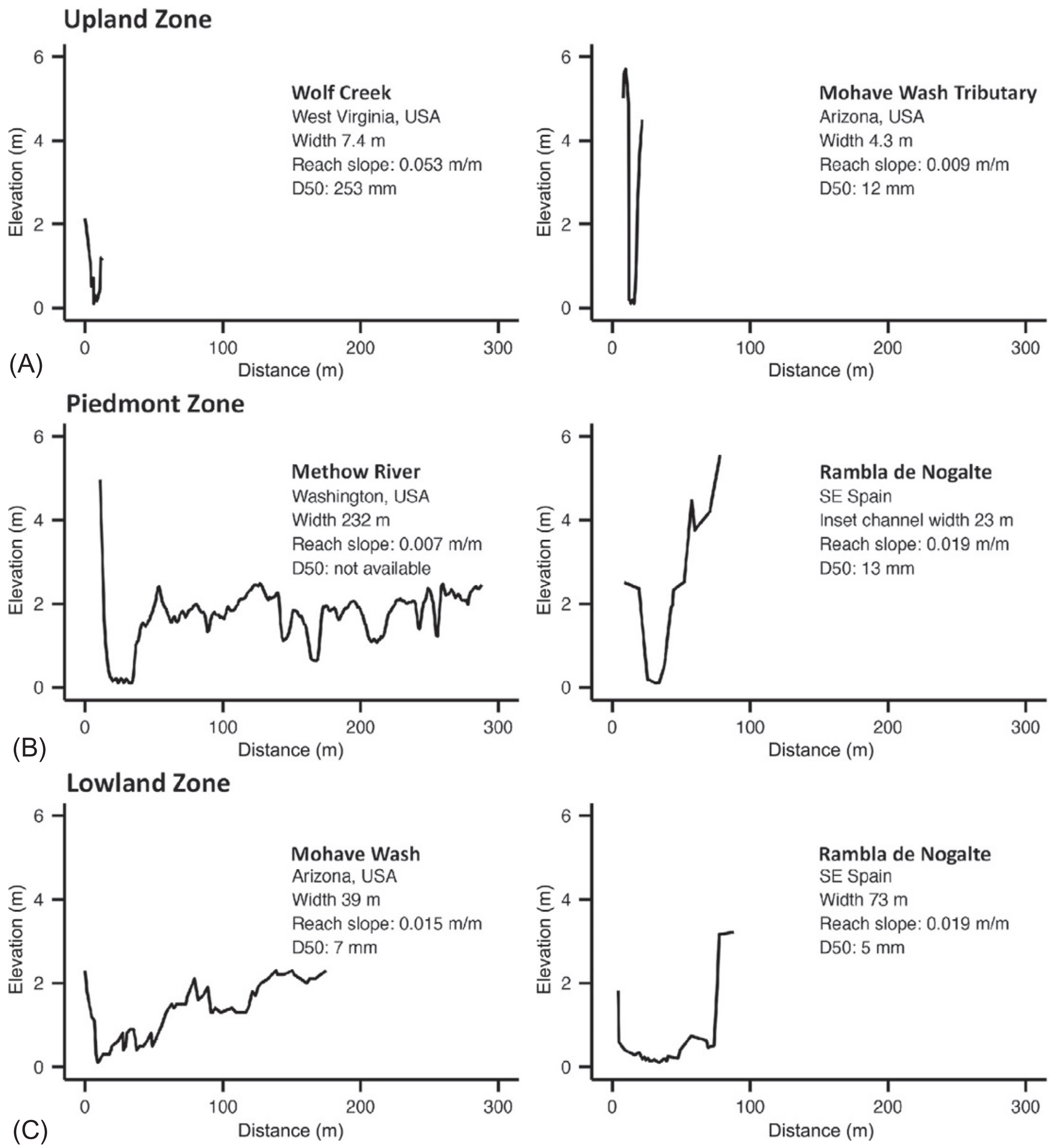

FIG. 2.1.5

Selected IRES cross-sections across the four geomorphological zones. Cross-sections in the (A) upland, (B) piedmont, (C) lowland, and (D) floodout zones are from different rivers. Inset text in (A), (B), and (C) indicates geographic location and cross-section characteristics including channel width, reach slope, and the median grain size (D50). Inset text in (D) indicates river kilometers (rkm), increasing in the downstream direction, and cross-section characteristics. The most upstream cross-section of the Tobiasspruit (D, *right panel*) is from the transition between the lowland and floodout zones, and the most downstream survey is on the floodout itself. Cross-sections are drafted from published (Tooth, 2000; Tooth et al., 2002) and unpublished data (Jaeger, unpublished; Michaelides, unpublished; Sutfin, unpublished), including publicly available LiDAR data (http://pugetsoundlidar.ess.washington.edu).

(Continued)

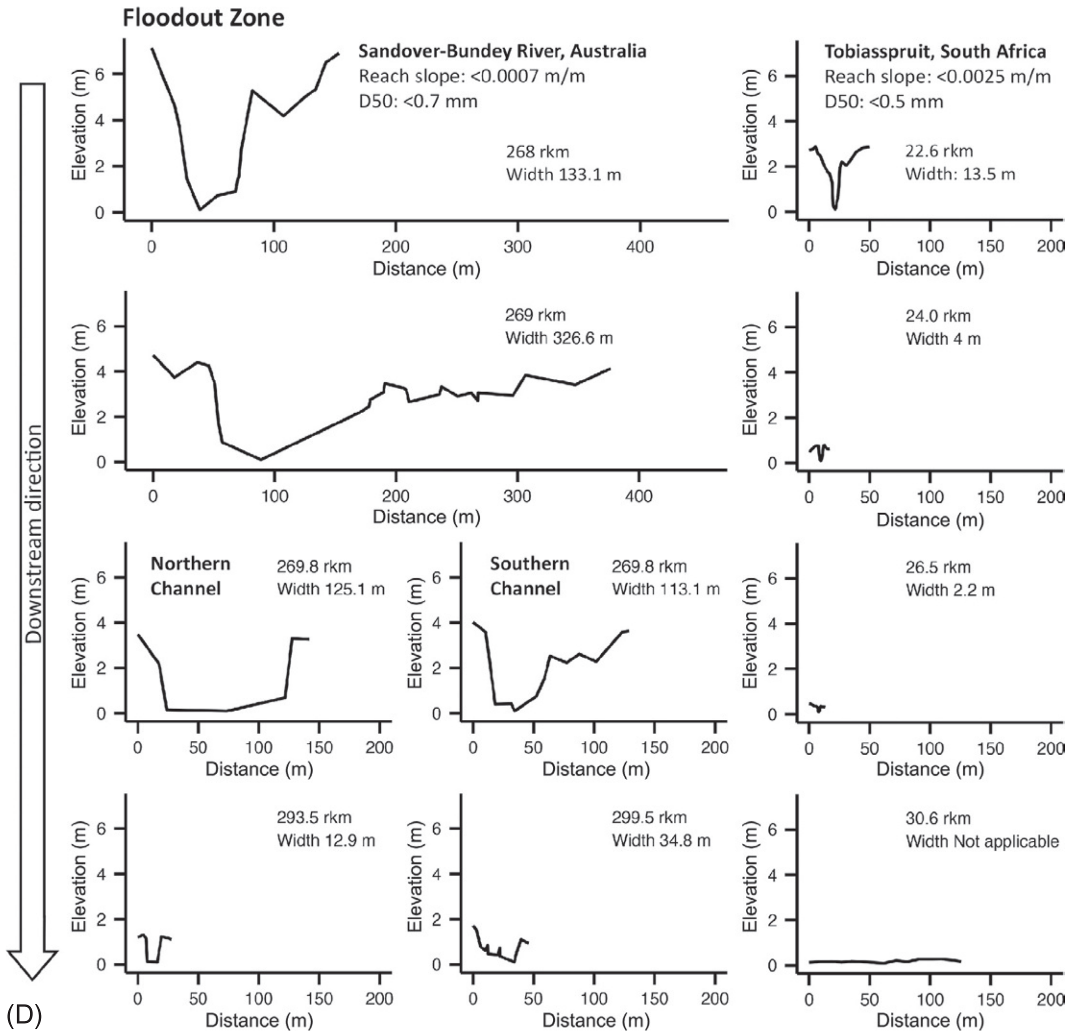

FIG. 2.1.5, cont'd

and longitudinal extent by outcropping bedrock, colluvium, or older indurated alluvium (Wohl and Pearthree, 1991; Larned et al., 2008; Fig. 2.1.3B).

High-intensity convective precipitation in combination with short overland flowpaths can generate flash floods capable of high rates of coarse-grained sediment transport (Michaelides and Martin, 2012; Lucía et al., 2013). However, very large clasts (>0.5 m diameter) derived from rockfalls, landslides, or debris flows may persist *in situ*, perhaps only slowly abrading while smaller clasts are winnowed from around them (Irwin et al., 2014).

Bedrock exposure and size-selective sediment transport processes may help form the cascade or step-pool morphologies that characterize some IRES in the upland zone (Wohl and Pearthree, 1991; Powell et al., 2012; Billi, 2015; Fig. 2.1.4). Other upland IRES with high sediment inputs, however, may develop comparatively simple, planar-bed channel geometries with only low-relief channel bars, thus facilitating efficient sediment transport (Powell et al., 2012). Where present on the bed, banks, and the floodplain, riparian vegetation can substantially influence in-channel and overbank flow and sediment transport processes (Sandercock et al., 2007; Sandercock and Hooke, 2011; Tooth, 2013). Overbank deposits can be extremely coarse, particularly where infrequent large floods rework debris flows or form levees and boulder berms along channel margins (Wohl and Pearthree, 1991; Macklin et al., 2010). Channel morphology in the upland zone of IRES may appear relatively stable in the short term (years to decades), but sequences of episodic high-energy floods can result in rapid sediment delivery and channel erosion and deposition over longer timescales.

Consistent with other zones in IRES systems, surface water-groundwater interactions are generally limited and highly spatially variable. Except where local springs occur, groundwater is commonly at great depths (>10 m) and disconnected from surface water. As a result, transmission losses can occur through alluvium and/or cracks and fractures in bedrock. Where relatively impermeable bedrock lies at shallow depths, this may promote shallow subsurface flow (Mansell and Hussey, 2005). The general absence of perennial flow and limited groundwater supplies means that aquatic habitats in upland IRES that can serve as important refugia are typically small and transient in time (Bogan and Lytle, 2011; Chapter 4.8) compared to larger features downstream (Bunn et al., 2006). However, localized parts of channel beds can support surface water for extended periods of time during otherwise dry channel conditions (Jaeger and Olden, 2012; Godsey and Kirchner, 2014). For example, stream potholes that are eroded into bedrock outcrops during successive large floods can retain water for several months, providing critical aquatic and terrestrial habitats (Bogan et al., 2014).

2.1.3 PIEDMONT ZONE

In the piedmont zone, valley floors typically are wider relative to the upland zone and channels are commonly flanked by older alluvium, colluvium, and/or bedrock. Hillslopes and channels remain closely coupled, and episodic lateral sediment inputs to steep or moderate-gradient channels are derived from diffusive processes and mass movements on adjacent hillslopes (Box 2.1.2) and from tributaries.

BOX 2.1.2 IMPLICATIONS OF CHANNEL-HILLSLOPE COUPLING FOR SEDIMENT DELIVERY

In many IRES, overland flow is a key contributor to sediment delivery in the piedmont zone. For a given rainstorm, the local sediment supply from hillslopes to channels depends on the characteristics of the adjacent hillslopes and their hydrological response to sequences of spatially variable rainstorms (Michaelides and Martin, 2012). Within a catchment and for a given rainstorm, not all hillslopes will be contributing sediment at the same time. However, over multiple rainfall events, channels will receive sediment intermittently throughout a reach at locations where hillslopes are directly coupled to the channel.

Fig. 2.1.6 demonstrates a plausible scenario of sediment supply in an IRES characterized by substantial fluctuation in valley and channel width but that maintains the typical overarching downstream trend of increasing valley and channel width (Fig. 2.1.6A). The first key aspect is that both mass and grain size of supplied sediment will vary between storms at different locations within a reach (Fig. 2.1.6B and C). A second key aspect is that the overall impact of hillslope sediment supply on the channel is a function of the interaction between channel width and supplied sediment mass and grain size. In particular, an increase in channel width reduces the impact of hillslope sediment supply to the channel because the same mass and size of sediment is spread out over a larger area. This relationship can be articulated for

(Continued)

BOX 2.1.2 IMPLICATIONS OF CHANNEL-HILLSLOPE COUPLING FOR SEDIMENT DELIVERY *(Cont'd)*

discrete locations within a reach by a "hillslope supply index" (HSI) (Michaelides and Singer, 2014), which represents the degree of hillslope impact on the channel as proportional to the mass and the grain size of sediment supplied and inversely proportional to the channel width (Fig. 2.1.6D). As the channel progressively widens downstream and floodplains become more common, the impact of hillslope sediment supply to the channel tends to decline, reflecting a progressive downstream decoupling between hillslope and channels.

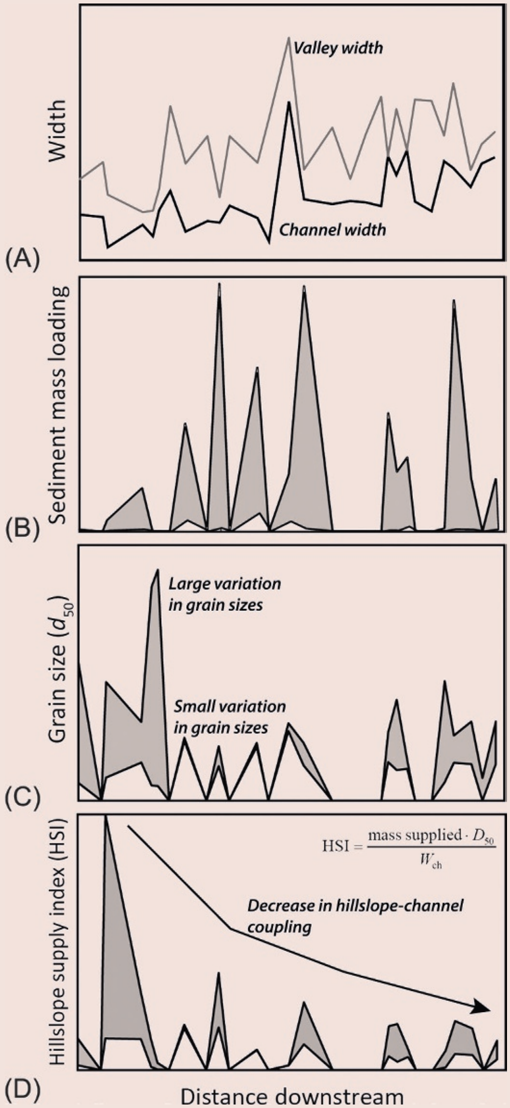

FIG. 2.1.6

Schematic of longitudinal trends in (A) channel and valley-floor width, (B) sediment mass loading from hillslopes to channel, (C) median grain size of sediment supplied from hillslopes to the channel, and (D) the hillslope supply index (HSI) illustrating the decrease in hillslope-channel coupling in the downstream direction as a result of increases in channel width. The gray shading in (B), (C), and (D) represents the range of values based on modeling a range of rainfall events bracketed by the minimum and maximum values. The calculation of the HSI is given within the panel (D).

Bedrock may crop out locally in channel beds, but commonly channel beds are fully alluvial, with a range of sediment sizes up to boulders. Flood events of differing magnitude and frequency sequentially deposit and erode sediment within channels and the wider valley floor, generating a wide variety of fluvial landforms, including floodplains and alluvial terraces (Figs. 2.1.5B and 2.1.7). In general, the characteristics of the geomorphology and sediment regimes of IRES in the piedmont zone reflect the intermediate position between the upland zone of net erosion and the lowland zone of transfer, with sediment being eroded, deposited, and reworked over various spatial and temporal scales (Fig. 2.1.3).

The interplay between episodic hillslope and tributary sediment supply and fluvial reworking in the trunk channel is a key characteristic of IRES in the piedmont zone (Michaelides and Wainwright, 2002; Wainwright et al., 2002; Michaelides and Singer, 2014) and contributes to a wide variety of channel patterns from wide and shallow, single thread, or braided channels (Graf, 1981; Singer and Michaelides, 2014) to narrower and deeper anabranching complexes (Graeme and Dunkerley, 1993; Jacobson et al., 1995; Fig. 2.1.7). The tendency for development of bar forms and bedforms varies

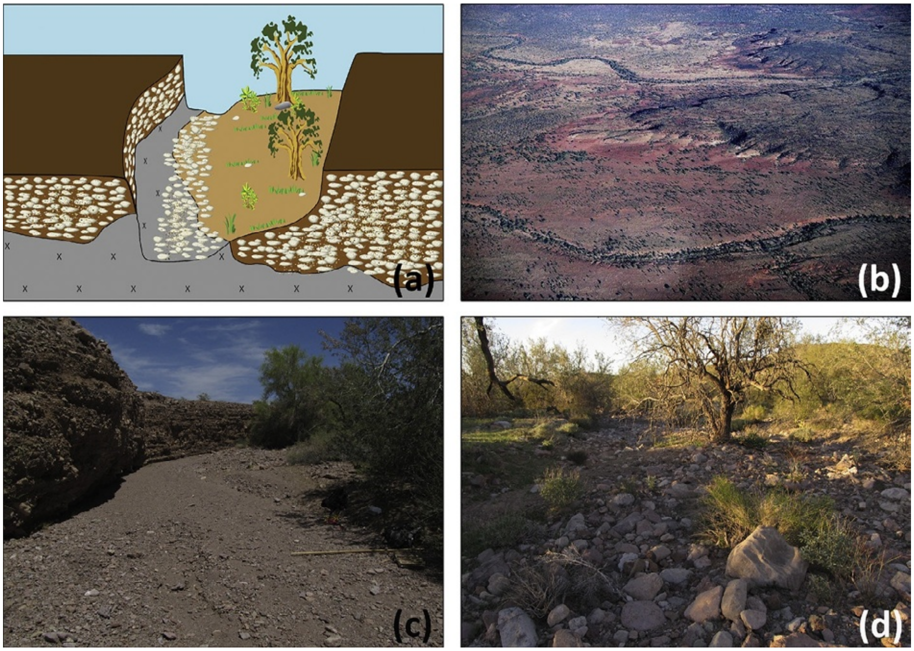

FIG. 2.1.7

Characteristics of IRES in the piedmont zone shown in (a) schematic form illustrating key landforms and sedimentary deposits. Examples include channels on the Northern Plains, central Australia (b, flow from right to left), illustrating confinement by bedrock and by sparsely vegetated older alluvium. Other examples from Arizona, USA, include this single-thread channel (c, view looking downstream), illustrating incision into coarse-grained, indurated Pleistocene alluvium and evidence for coarse-grained sediment transport during high- to moderate-energy floods, and this gravel-bed channel in the Sonoran Desert, Arizona (d, view looking downstream), with abundant boulders and small anabranching side channels.

Photos: Courtesy S. Tooth (b), N. Sutfin (c and d).

widely within and between different channel patterns. Examples include: sand-bed single-thread channels with low-relief channel beds and limited bedforms and bars (Powell et al., 2012); stone-pavement channels created by periglacial freeze-thaw cycles that rotate large clasts to create a relatively flat surface (McKnight et al., 1999); gravel-bed braided channels characterized by development of bars, dunes, and gravel aggregates (Hassan, 2005); and sand- and gravel-bed anabranching channels that display varying bed topographies including dunes and "flow chutes," the latter being influenced by riparian vegetation assemblages (Dunkerley, 2008).

Vegetation dynamics exert strong influences on the morphology and sediment regimes of IRES in the piedmont zone. Vegetation dieback during disturbance (drought or anthropogenic influences) can enhance sediment delivery to the channel (Collins and Bras, 2008), which can lead to partial obstruction of the trunk channel by tributary-junction fans (Larsen et al., 2004) but also to aggradation and alterations to trunk channel morphology. Vegetation recovery may reduce sediment delivery, with subsequent channel incision and terrace formation on the valley margins (Shakesby and Doerr, 2006). Terrace formation may topographically decouple hillslopes from the channels, resulting in locally buffered, heterogeneous patterns of sediment supply (Michaelides and Singer, 2014). Variable patterns of channel, floodplain, and valley-floor vegetation growth mean that overbank flow and sediment transport dynamics can be highly complex (Sandercock et al., 2007; Sandercock and Hooke, 2011). However, as in the upland zone, periodic high-energy floods and relatively short overland and overbank flow paths tend to result in steep lateral hydrological gradients and maintain channel-floodplain hydrological connectivity (Amoros and Burnette, 2002; Michaelides and Chappell, 2009; Trigg et al., 2013; Chapter 2.3).

As in the upland zone, channels in the piedmont zone may be characterized by relative stability over years to decades but then undergo short intervals of abrupt change, depending on the sequence of channel-changing flood events. Runoff and sediment dynamics drive the redistribution of nutrients (Michaelides et al., 2012), which in turn affects primary productivity (Chapter 3.1), plant distribution (Chapter 4.2), and broader ecosystem functioning. Discharges during small to moderate floods may initially increase downstream through the piedmont zone but as a result of limited or no groundwater input, discharge tends to decrease owing to flow transmission losses through the channel bed and banks (Dunkerley and Brown, 1999). Following floods, the retention and persistence of surface water depends largely on local bed topography. Alluvial channels with low-relief channel beds tend to remain largely dry, but where bedrock crops out locally or flow chute morphology has developed, temporary or permanent surface water may be present in topographic lows (Dunkerley and Brown, 1999; Dunkerley, 2008).

2.1.4 LOWLAND ZONE

In the lowland zone, alluvial valleys tend to become wider, thus hillslopes and channels tend to be less closely coupled compared to upland and piedmont zones. This contributes to a wide range of channel-floodplain morphologies, many of which strongly contrast with perennial systems (Fig. 2.1.8). Many IRES in the lowland zone are primarily transfer systems that maintain an approximate balance between sediment input and output, although some systems may be characterized by long-term net deposition.

A key characteristic of IRES in the lowland zone is the typical downstream decreases in flood flow volumes that result from transmission losses into unconsolidated alluvium, losses to overbank flow, and evapotranspiration (Tooth, 2013; Chapter 2.3). In many catchments, tributary inputs are also limited in the lowland zone. These downstream flow decreases are in stark contrast to the downstream flow

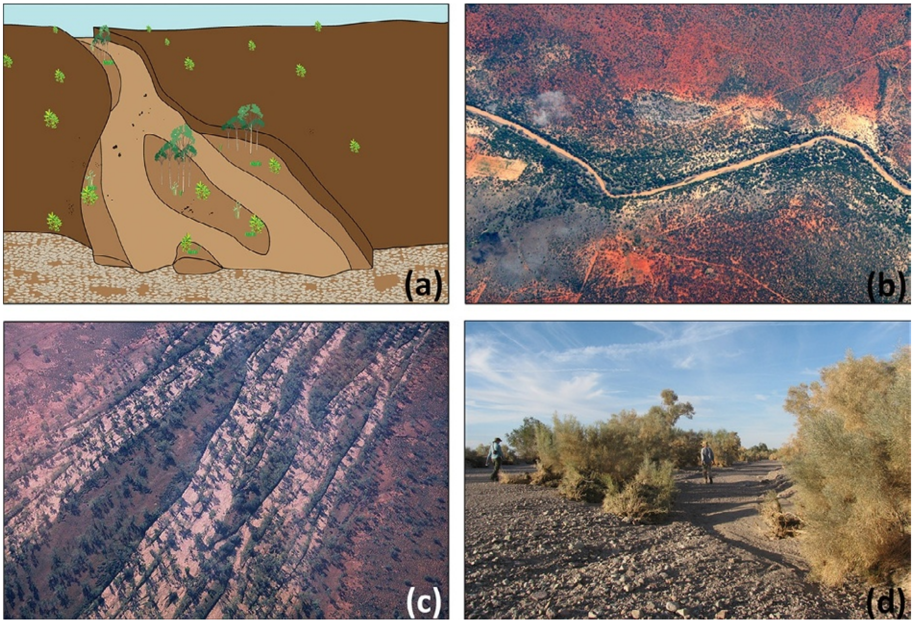

FIG. 2.1.8

Characteristics of IRES in the lowland zone shown in (a) schematic form illustrating key landforms and sedimentary deposits. Examples include a low-sinuosity, single-thread channel in northern South Africa (b, flow from *left to right*), showing a largely vegetation-free channel bed but dense vegetation on the adjacent floodplains. Other examples include anabranching channels in central Australia (c, flow from *upper right to lower left*) showing division and rejoining around vegetated, narrow ridges and wider islands. Vegetated bars along a mixed sand-gravel bed, braided channel in the Sonoran Desert of southwestern Arizona (d) illustrate complex interactions between vegetation and sediment transport processes.

Photos: Courtesy S. Tooth (b and c), N. Sutfin (d).

increases typical of perennial systems and have implications for channel-bed substrate, sediment sorting and transport, and channel and floodplain morphologies. Channel-bed substrates in the lowland zone are strongly influenced by catchment lithology and sediment supply, and so can vary widely, ranging from variable mixtures of alluvium and bedrock (Heritage et al., 1999), through sand and gravel (Reid and Frostick, 1997) to silt and clay (e.g., Knighton and Nanson, 1997).

Some lowland-zone IRES are characterized by low sinuosity, relatively wide and shallow rectangular cross-sections (Leopold et al., 1966; Reid and Frostick, 1997; Singer and Michaelides, 2014; Figs. 2.1.5C and 2.1.8). In these channels, bed and bar forms tend to be poorly developed and seldom persist over decadal to centennial timescales (Hassan, 2005), in part because fluxes of water and sediment can be considered to occur primarily in one dimension (downstream) with negligible cross-stream components (Leopold et al., 1966; Singer and Michaelides, 2014). Other IRES are characterized by more complex channel-floodplain morphologies, such as the extensive anastomosing and anabranching channel systems that occur across wide areas of inland Australia and parts of southern Africa (Heritage et al., 1999; Tooth and McCarthy, 2004; Tooth et al., 2008) or the alluvial gravel-bed rivers in wetter regions in Europe, the US, and New Zealand (Doering et al., 2007; Larned et al., 2008, 2011). In systems with complex channel-floodplain morphologies, various bed and bar forms can develop and persist over centennial to millennial timescales, commonly in association with riparian vegetation patterns (Heritage et al., 1999; Tooth and Nanson, 2000; Tooth et al., 2008). Compared to lowland IRES with rectangular cross-sections, fluxes of water and sediment are influenced by a variety of poorly documented channel-floodplain exchanges. For instance, during extensive flooding in the Channel Country of eastern central Australia, flow in interconnecting anastomosing channels is accompanied by low-energy overbank flows that disperse through networks of extensive floodplain "braid" channels (Knighton and Nanson, 1997), with floodwaters then evaporating or draining back to the anastomosing channels as stage falls.

Studies in central Australia have shown how highly contrasting channel-floodplain morphologies can be found even on closely adjacent IRES, with transitions from wide, shallow single-thread channels to anabranching channels commonly being associated with limited tributary inputs of water and sediment (Tooth and Nanson, 2004). In particular, periodic flows from tributaries into a normally dry trunk channel promote in-channel growth of trees through positive feedbacks between sediment deposition, moisture retention, and vegetation establishment (Tooth and Nanson, 2004). Over time, initially wide, shallow single channels can subdivide into complexes of narrow anabranches divided by tree-lined narrow ridges or wider islands (Fig. 2.1.8). In other settings, marked shifts between complex multi-channel reaches and single-channel reaches also have been associated with local changes in gradient, sediment supply, and influence of riparian vegetation (Larned et al., 2008). Despite these strong contrasts in channel-floodplain morphologies, work in central Australia, Spain, and elsewhere has shown that longitudinal profiles in many lowland-zone IRES are straight (Vogel, 1989; Powell et al., 2012; Singer and Michaelides, 2014), contrasting with the characteristic concave-up profiles of lowland-zone perennial systems (Fig. 2.1.9). The straight longitudinal profile may reflect an oversupply of alluvium that covers the bed surface and is smoothed by incomplete lateral and longitudinal sorting (Singer and Michaelides, 2014). Where bedrock crops out more extensively, however, longitudinal profiles in the lowland zone can be far more irregular, sometimes alternating between moderate-gradient, dominantly bedrock reaches atop resistant outcrop and lower-gradient, mixed bedrock-alluvial or alluvial reaches atop weaker outcrop (Heritage et al., 1999; Tooth and McCarthy, 2004).

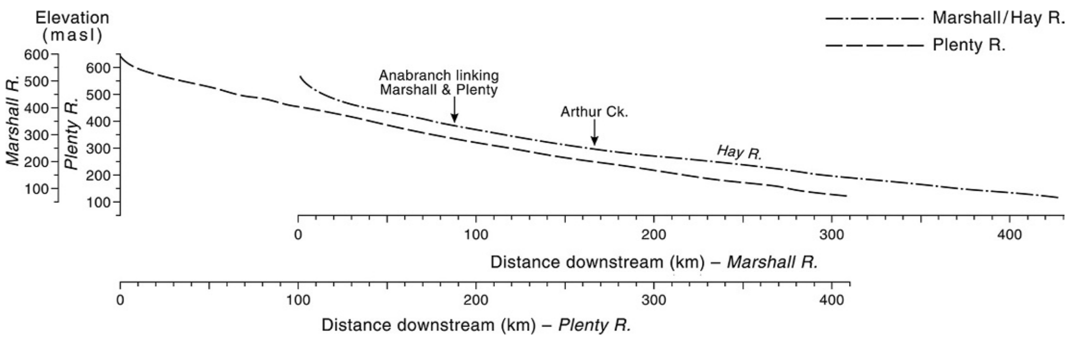

FIG. 2.1.9

Straight longitudinal profiles in the lowland zones of the Plenty and Marshall Rivers, Australia, illustrating the contrast with the concave-up longitudinal profiles typical of many lowland perennial systems.

Reproduced with permission from Tooth, S., Nanson, G.C., 2004. Forms and processes of two highly contrasting rivers in arid central Australia, and the implications for channel-pattern discrimination and prediction. Geol. Soc. Am. Bull. 116, 802–816.

In the lowland zones of IRES, channel-floodplain stability can vary widely. In some IRES, lowland channel-floodplain morphologies can remain relatively stable over centuries or millennia, particularly where the potential for erosion during low-energy floods is restricted by well-developed riparian vegetation (Tooth and Nanson, 2000; Sandercock et al., 2007; Larned et al., 2008). In other settings, sediment aggradation occurs during decadal-scale sequences of small to moderate floods, with extensive channel and floodplain erosion (stripping) and vegetation removal occurring during occasional large floods (Heritage et al., 1999).

Flow transmission losses can be extremely high (e.g., $2.5\,m^3\,s^{-1}\,km^{-1}$, Doering et al., 2007) and contribute to groundwater recharge and in-channel sediment deposition in lowland-zone IRES (Keppel and Renard, 1962; Renard and Keppel, 1966). In many lowland channels, retention of surface water after floods is limited, although exceptions may occur in reaches where bedrock outcrop has resulted in local development of pools (Heritage et al., 1999) or where the confluence of anastomosing channels on extensive muddy floodplains leads to scour and the formation of permanent waterholes (e.g., Knighton and Nanson, 1994, 2000). Although transmission losses are a typical characteristic, groundwater input can contribute to discharge that supports local perennial reaches in the lowland zone (Doering et al., 2007; Larned et al., 2008; Chapter 2.3). Shallow groundwater recharge from channels can sustain water availability to riparian trees that otherwise have limited access to soil moisture (Singer et al., 2014).

2.1.5 FLOODOUT ZONE

For IRES flowing to the coast, there tends to be a gradual transition from the lowland zone to an estuarine or deltaic zone. Across the globe, however, many IRES fail to reach a coastline, instead undergoing various forms of "breakdown" or "failure," and ultimately terminating in inland topographic basins on alluvial plains (Mabbutt, 1977; Tooth, 1999a,b; Billi, 2007) or on the margins of pans or playas (Fisher et al., 2008; Donselaar et al., 2013; Fig. 2.1.10). All these environments are characterized by net deposition, as reflected in a diverse—and, in some instances, distinctive—range of geomorphological features and sedimentary deposits. This section focuses mainly on the geomorphology and sediment regimes of IRES terminating in inland basins (collectively termed the floodout zone), although some characteristics are shared with IRES that end at a coastline.

In most floodout zones, limited or absent hillslope-channel coupling means that flow and substrate characteristics are largely determined by the distance from the upland and piedmont sources of runoff and sediment. In some small IRES, the floodout zone may be within a few tens of kilometers of the uplands, so flow events may occur semiregularly (e.g., after every local convective thunderstorm) and channel-bed sediment may include local cobbles and boulders (Billi, 2007; Craddock et al., 2012). In larger IRES, however, the floodout zone may be located many tens or even hundreds of kilometers from the uplands and the characteristic downstream decreases in discharge described earlier mean that flow events may be very infrequent (perhaps only once every few years or decades), while bed sediment typically is no coarser than granules (Dubief, 1953; Mabbutt, 1977; Tooth, 2000).

Downstream decreases in the magnitude and frequency of discharge can occur in association with downstream gradient decreases caused by changes in lateral confinement and subsequent channel-bed aggradation (Tooth, 1999a) or by lithological/structural factors, such as a change from a harder to a weaker lithology underlying the channel bed (Donselaar et al., 2013; Grenfell et al., 2014). These decreases in discharge and/or gradient mean that unit stream power and sediment transport capacity also decrease. These, in turn, lead to a downstream reduction in the channel size, diversion of an increasing proportion of floodwaters overbank, and sediment deposition (Fig. 2.1.5D). These processes are

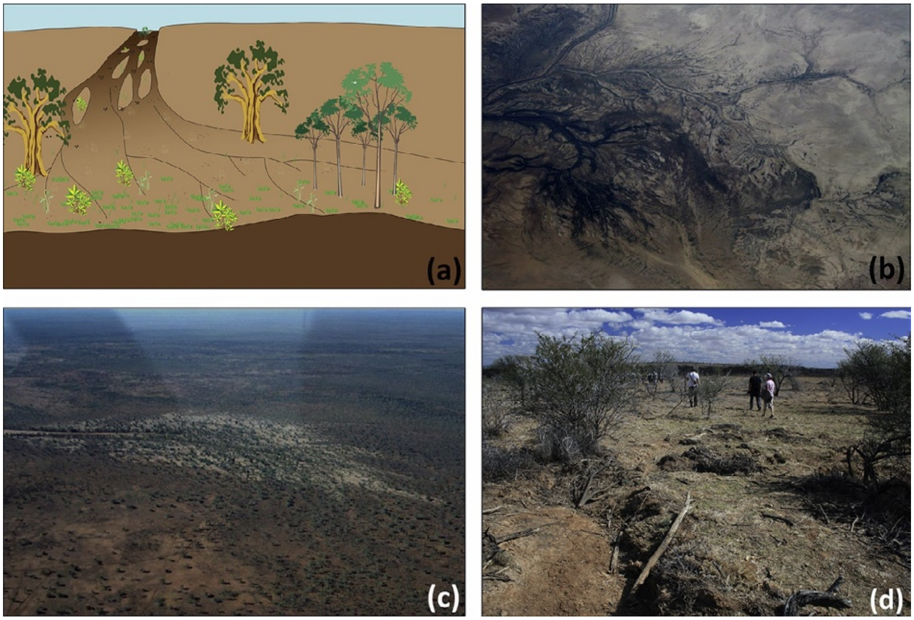

FIG. 2.1.10

Characteristics of IRES in the floodout zone shown in (a) schematic form illustrating key landforms and sedimentary deposits. Examples include the lower reaches of channels on the margins of a playa in northwest Iran (b, flow from *left to right*), showing how channel breakdown and the transition to floodouts is accompanied by widespread development of splays and distributary channels. Other examples include this channel terminus on the Northern Plains, central Australia (c, flow *left to right*), showing widespread deposition of sandy sediment in the transition to the floodout, and floodout channels in southern South Africa (d, view looking down-valley) showing evidence for transport of organic material during the occasional floods.

Photos: Courtey S. Tooth (b, c and d).

commonly promoted by the presence of aeolian or bedrock barriers, such as where linear dune formation or fault uplift has occurred across a channel (Bourke and Pickup, 1999; Tooth, 1999a). In floodout zones, channel cross-section morphology can vary widely, from relatively wide and shallow in gravel- and sand-bed channels to narrow and deep in mud-rich channels (Sullivan, 1976; Mabbutt, 1977; Tooth, 1999b; Fig. 2.1.5D). However, channel beds tend to have low relief with limited bed or bar form development owing to the limited sediment transport during the short-lived flow events (e.g., Craddock et al., 2012). Even along channels with well-developed riparian vegetation, channels may be laterally active and subject to bank-line erosion, levee breaching, and periodic avulsion (Tooth, 2005; Billi, 2007). Depending on flood sequencing, channels and floodplains may remain stable for many years or decades and then undergo significant change during short-lived events, resulting in a range of morphological and sedimentary features that include active and inactive distributary channels, paleochannels, splays, waterholes, and various aeolian-fluvial interactions (Tooth, 1999a,b; Billi, 2007).

In some settings, the channel may lose definition and disappear entirely to form a floodout *sensu stricto* (Tooth, 1999a), defined as a site where channelized flow ceases and floodwaters spill across adjacent alluvial surfaces. Floodouts can range widely in scale, reaching up to approximately 1000 km^2 on some larger IRES. The size and shape of floodouts are often strongly influenced by local physiography. In central Australia, floodouts are <500 m wide where rivers terminate between the longitudinal dunes and local bedrock outcrops of the northern Simpson Desert but can reach up to several kilometers wide on the relatively unconfined Northern Plains (Bourke and Pickup, 1999; Tooth, 1999a,b). At the channel terminus, the coarser bedload sediment tends to be deposited in a splay-like form, but low-energy flows and finer suspended sediments may spill across the unchanneled surfaces (Fig. 2.1.10). On terminal floodouts, floodwaters spill across the unchanneled surfaces and eventually dissipate through infiltration or evaporation but on intermediate floodouts at least some floodwaters persist across the unchanneled surfaces and ultimately concentrate into small "reforming channels". Reforming channels commonly develop where the unchanneled floodwaters become constricted by aeolian deposits or bedrock outcrops, or where small tributaries provide additional inflow. These reforming channels either join a larger river or decrease in size downstream before disappearing in another floodout (Tooth, 1999a).

As in the lowland zone, floodwater infiltration in the floodout zone contributes to groundwater recharge (e.g., Morin et al., 2009). Toward the center of some deeper topographic basins, such as those occupied by large playas, groundwater exfiltration may contribute to saturation of near-surface sediments and periodic shallow flooding (Shaw and Bryant, 2011). Overall, the strongly pulsed hydrological and sediment regimes in floodout zones, and the varied morphology of the channels, floodplains, and floodouts result in pronounced down-valley and cross-valley hydrological gradients and a mosaic of ecological patches at various scales. Case studies show that vegetation and other biota commonly respond rapidly to the irregular flood events and the associated material supply (Box 2.1.3).

BOX 2.1.3 MATERIAL TRANSPORT IN IRES SYSTEMS

Most previous investigations of material transport in IRES systems have focused on relatively coarse-grained clastic sediments moving in continuous or near-continuous contact with the channel bed (bedload and saltation load) or finer-grained sediment moving in suspension within the water column (suspended load) although these data sets remain sparse. Less attention has been directed toward other components of material transport, such as the dissolved sediment load and the particulate organic load. In many IRES, concentrations of sediment and certain ions may increase downstream as peak discharges and total flow volumes decrease. Chemical analyses have largely been restricted to inorganic constituents, although some studies have also investigated the nature of organic loads. For example, Jacobson et al. (2000) investigated floodwater chemistry in the ephemeral Kuiseb River, Namibia, by tracking floodwaters along some 200 km of the river's lower reaches. Data from below the confluence of the upper Kuiseb and Gaub rivers (Table 2.1) reveal very high levels of dissolved organic matter but even higher levels of particulate organic matter, derived principally from the riparian vegetation. Some of the dissolved organic matter was derived from leaching of the transported particulate organic matter. In the 2-day January 1994 flood, dissolved inorganic, dissolved organic, and particulate organic matter tended to show an overall downstream increase in response to waning flood volumes (Table 2.1), with all the transported material being deposited in the lower reaches (floodout zone) and no water or matter reaching the Atlantic Ocean.

In a related study focusing on downstream transport of large woody debris (achieved by painting and tracking representative pieces), Jacobson et al. (1999) found that 65% of the painted wood exported from marking sites during the 1994 flood was retained within debris piles associated with in-channel growth of large ana trees (*Faidherbia albida*), and wood retention also peaked in the lower reaches. Debris piles induced deposition of clastic sediment and fine particulate organic matter, and promoted the formation of in-channel islands. Following flood recession, these debris piles and the associated sediments provided moist, organic-rich microhabitats, and these became focal points for decomposition and secondary production. Jacobson et al. (2000) concluded that the lower Kuiseb is a sink for materials transported from upstream, and that the large amounts of labile organic matter provide an important carbon supplement to flood-activated heterotrophic communities among these lower reaches (Chapters 3.2 and 4.7).

(Continued)

Table 2.1 Characteristics of floodwaters along the Kuiseb River during a 2-day flood in January 1994

Station	Catchment area (km^2)	Distance (km)	Elevation (m)	Gradient ($m\,m^{-1}$)	Discharge ($m^3\,s^{-1}$)	Total flood volume ($10^6\,m^3$)	Total susp. solids ($g\,L^{-1}$)	Conductivity ($\mu S\,cm^{-1}$)	Dissolved organic matter ($g\,L^{-1}$)	Particulate organic matter ($g\,L^{-1}$)
Schlesien (upper Kuiseb R)	6520	n/a	760	0.0040	~20	~2	–	–	–	–
Greylingshof (Gaup R tributary)	2490	0	720	0.0055	159	2.75	11.8	302	0.0390	0.78
Confluence (upper Kuiseb and Gaup R)	9500	–	620	0.0035	–	4.75	–	–	–	–
Homeb	–	105	–	–	–	–	30.3	627	0.0557	1.90
Gobabeb	11,700	140	360	0.0030	51	2.3	48.0	703	0.0492	3.24
Rooibank	14,700	197	120	0.0039	<1	0.05	19.7	1035	0.0831	2.36

– indicates data not provided or not available. Distance downstream is the distance downstream from Greylingshof; Rooibank is approximately 18 km from the Atlantic Ocean. Discharge, total suspended solids, conductivity, dissolved organic matter, and particulate organic matter measured during peak discharge at each site. Total suspended solids (Total susp. solids) include organic matter.

Based on data presented in Jacobson, P.J., Jacobson, K.M., Angermeier, P.L., Cherry, D.S., 2000. Variation in material transport and water chemistry along a large ephemeral river in the Namib Desert. Freshw. Biol. 44, 481–491.

2.1.6 DISTINCTIONS IN IRES LONGITUDINAL TRENDS

Considering all four geomorphological zones in down-valley sequence, many IRES appear to possess some distinctive longitudinal trends when compared to perennial systems. These trends are largely related to the distinctive hydrology of IRES, especially the limited and spatially heterogeneous runoff generation, and the tendency for flow transmission losses that leads to downstream decreases in flow volumes and flood peaks.

As in perennial systems, IRES channels initially tend to widen downstream through the upland, piedmont, and lowland zones as catchment area increases. However, two distinctions become evident in some IRES. First, channel width initially may be higher for a given catchment area than it is for perennial streams (Fig. 2.1.11A), at least partly owing to the geomorphological effectiveness of rare extreme

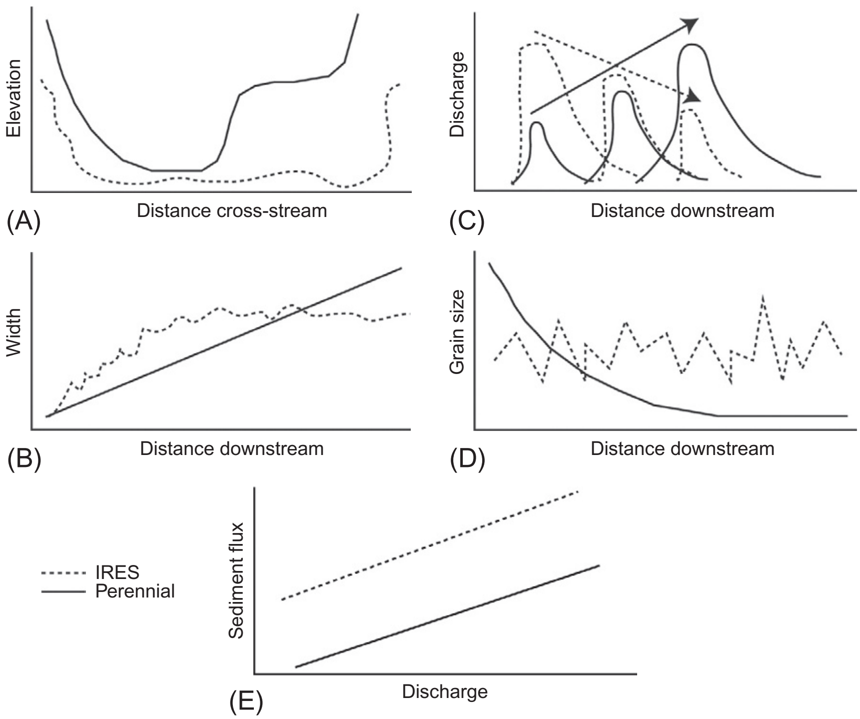

FIG. 2.1.11

Distinctions in IRES longitudinal trends. Channels tend to be wider in IRES (A) compared to perennial systems at a cross-section for a given drainage area. Channel width can be asymptotic to a value of 100–200 m in IRES (B), whereas perennial channel widths continue to increase with increasing drainage area. Discharge magnitudes decrease in the downstream direction in IRES (C) and peak flows are short lived compared to perennial systems. Channel-bed grain size in IRES alternates between coarse- and fine-grained reaches (D) compared to characteristic downstream fining in perennial systems. For a given discharge, sediment flux can be much greater in IRES (E) compared to perennial systems.

events compared to perennial systems (Baker, 1977; Wolman and Gerson, 1978). Second, width has been shown to be asymptotic to a value of 100–200 m for drainage areas ranging from 100 to 1000 km^2 (Fig. 2.1.11B). Wolman and Gerson (1978) attribute this pattern to several possible interrelated factors, notably the widening of channels by extreme flows until they accommodate the largest available discharges, themselves constrained by the higher transmission losses that occur in widened channel beds. In other words, channel widths may be limited by diminishing discharges or muted discharge increases downstream (Fig. 2.1.11C). These trends are not universal, however, and other IRES display different downstream width changes. For example, in some IRES in central Australia, southern Africa, and the Mediterranean, channel widths in the middle to lower reaches alternate downstream between relatively narrow and wide reaches, or are characterized by relatively regular decreases associated with declining discharges (Tooth, 2000, 2013; Fig. 2.1.5).

Downstream decreases in flow volumes and flood peaks also influence sediment transport processes. Some IRES are characterized by fluctuating reaches of coarse and fine sediment with no clear downstream decrease in grain size or any obvious longitudinal transition from gravel to sand, the latter being more typical of perennial streams (Fig. 2.1.11D; Thornes, 1977; Frostick and Reid, 1980; Singer, 2010; Michaelides and Singer, 2014; Singer and Michaelides, 2014). Sediment flux in some IRES channels can be very high compared with their perennial counterparts (Fig. 2.1.11E), a difference attributed to the commonly nonexistent or poor armor-layer development in IRES (Laronne and Reid, 1993). In ephemeral gravel-bed rivers, poor armor-layer development has been attributed to various interrelated factors including abundant sediment supply from sparsely vegetated hillslopes, the substantial particle mixing resulting from scour and fill processes, and the infrequent short-lived floods that minimize the potential for winnowing finer particles from the bed surface (Laronne and Reid, 1993; Laronne et al., 1994; Reid and Laronne, 1995; Reid and Frostick, 1997). Sediment transport data tend to confirm the high rates of bedload or suspended load transport, including evidence for hyperconcentrated washloads in IRES. For instance, measurements from the ephemeral Rio Puerco, a tributary to the Rio Grande River, indicate that it has the fourth highest average annual suspended-sediment concentration for all rivers globally, with the exception of the Yellow River, Asia (Gellis et al., 2004). In addition, bedload transport has been observed to exceed suspended transport in several IRES in Spain (Castillo and Marin, 2011).

2.1.7 INFLUENCE OF HUMAN ACTIVITIES ON IRES MORPHOLOGY AND SEDIMENT REGIMES

In recent decades, there has been increasing awareness of the extent to which a wide range of human activities are affecting IRES (Kingsford et al., 2006; Chapter 5.1). Some regions (e.g., the Mediterranean) have a long history of human activities in and near the riparian zone (Poesen and Hooke, 1997), while in other regions (e.g., the American southwest, Australia, southern Africa), significant human impacts have only occurred during the last few centuries following European exploration and colonization (Graf, 1988; Thoms and Sheldon, 2000; Tooth, 2016). Human activities can affect IRES both indirectly (e.g., through land-use changes that influence hillslope runoff and sediment supply) and directly (e.g., through flow abstraction or various forms of channel and floodplain engineering). Activities may be widespread throughout a catchment, such as grazing which in part has been linked to the extensive incision/depositional behavior of the arroyo cycle in the American southwest (e.g., Cooke and Reeves, 1976).

Other activities may occur in a specific geomorphological zone but nonetheless affect other zones both upstream and downstream. Examples include where dam construction, sediment mining, or vegetation planting in the upland zone alters downstream flow and sediment supply (e.g., Boix-Fayos et al., 2007; Kamp et al., 2013; Chapter 5.1).

Many human-induced changes to the hydrological and sediment regimes of IRES have been associated with profound changes to channel-floodplain geomorphology and ecological processes and patterns. The most visible changes are commonly associated with changes to riparian vegetation assemblages. In many regions drained by IRES, flow regulation through damming and abstraction has fundamentally altered flow regimes, either by reducing hydrological variability (e.g., suppressing peak flows and increasing base flows) or by increasing periods of low and no flow. In many locations, such flow regime alterations have changed the recruitment and survival of many native tree species (e.g., Johnson, 1994, 1997), while commonly promoting colonization by exotic invasive tree species (e.g., Graf, 1978; Everitt, 1979, 1995; Chapter 5.4). In some locations, widespread establishment of vegetation on formerly exposed and transient bars as a consequence of flow regulation has dramatically reduced the cross-sectional area of river channels, with repercussions for other aspects of ecosystem dynamics.

On a smaller scale, some contrasting examples can be found where flow magnitude and frequency have actually increased in IRES owing to agricultural and urban runoff, including wastewater disposal. In Israel and the Palestinian Territories, nutrient-rich wastewater flow from developing urban areas caused rapid shifts from dry ephemeral channels with intermittent floods to vegetated channels with continuous flow (Hassan and Egozi, 2001). In other settings, urban runoff and reclaimed water discharges can contribute to enhanced flow volumes and severe erosion (Chin and Gregory, 2001). For instance, along Las Vegas Wash, Nevada, which drains past one of the United States's fastest growing cities, flash floods in the 1980s and 1990s caused severe erosion along the wash and its associated wetlands, damaging wildlife habitat and threatening homes (Kingsford, 2006).

In many IRES catchments, human impacts have been most widespread and severe in the upland and piedmont zones, but the changes to flow and sediment supply have deprived lower reaches of water, sediment, and nutrient supplies, leading to a variety of changes to channel-floodplain morphology, substrate composition, and ecological habitat (e.g., Casado et al., 2016). These changes can be complex, commonly including channel contraction and stabilization, secondary salinization, widespread vegetation dieback, and ecosystem collapse (Thoms, 1995; Micklin, 2007; Mac Nally et al., 2011; Box 2.1.4). In an era of rapid environmental change and population growth, human pressure on water supplies can only increase, and in coming decades it may be that increasing numbers of perennial river systems start to behave more like IRES. Therefore, study of the geomorphology and sediment regimes of current IRES may provide insights that can help guide management practices in rivers that start to undergo this type of transition (Kingsford, 2006).

2.1.8 DIVERSITY OF IRES AT A GLOBAL SCALE

Although necessarily selective, the coverage of IRES geomorphology and sediment regimes in the previous sections of this chapter illustrates how valley-floor morphology and substrate characteristics vary widely across different climatic and geological settings. A comprehensive assessment of the geomorphological diversity of IRES at a global scale has yet to be attempted (e.g., Tooth and Nanson, 2011),

BOX 2.1.4 DEWATERING THE LOWER COLORADO RIVER AND DELTA

The lower Colorado River and Delta in the United States and Mexico provide good examples of the deleterious effect of human activities on flow and sediment regimes (Mueller and Marsh, 2002). The Colorado River, once the fifth largest river (by discharge) and carrying the largest sediment load in the United States (McDonald and Loeltz, 1976), used to flow onto a vast delta in the Gulf of California. Dams, large-scale diversions, and abstractions over the last 95 years (Carriquiry and Sánchez, 1999) now make the Colorado River one of the most regulated rivers globally (Andrews, 1991).

Historically, the lower Colorado River was a wide (hundreds of meters), braided and shallow (mean depth < 3 m) river. The system supported a highly transient channel, perennial wet meadows, and expansive floodplain forests (reviewed in Mueller and Marsh, 2002). The Delta extended over more than 15,500 km^2 and was characterized by a complex maze of sloughs, wetlands, and oxbows (Mueller and Marsh, 2002).

Today, most flow from the upper and middle reaches of the river only reaches the Delta during major flow events and only about 0.5% of the original sediment load is delivered to the Delta (Carriquiry et al., 2001). As a result, approximately 100 km of the river downstream of the lowermost dam is usually dry, with less than 8% of the wetlands remaining in the Delta (Mueller and Marsh, 2002). In the absence of a significant upstream sediment supply, the Delta is experiencing widespread erosion, with associated habitat loss affecting endemic fish (Carriquiry and Sánchez, 1999). For example, seven of the nine endemic fish in the lower Colorado River are endangered, with several living in small refugial populations (e.g., desert pupfish). Despite active restoration efforts, the losses of water, sediment, and nutrient supplies from the river are difficult to mitigate and the lower Colorado River and Delta are likely to persist in an extremely diminished ecological state.

partly because there is relatively little published, accessible information on the IRES in many regions of Africa, Asia, and South America (notable exceptions include Billi, 2007; Yang and Scuderi, 2010; Irwin et al., 2014). Nonetheless, the conceptual approach adopted in this chapter—namely, characterizing IRES in the context of four geomorphological zones (Fig. 2.1.3)—provides a framework for integrating and synthesizing additional information as it becomes available, as well as a basis for more rigorously comparing the characteristics of IRES within and between different regions (Tooth and Nanson, 2011). As an illustration, a comparison can be made between IRES in the Mediterranean, southern Africa, and Australia. These regions have different physiographies, largely as a function of their contrasting geological setting, especially the degree of tectonic activity. Consequently, the spatial extent and relative proportions of the upland, piedmont, lowland, and floodout zones vary dramatically.

In many Mediterranean catchments, upland and piedmont zones are characterized by high elevation, rugged and tectonically active topography, and are relatively extensive. In comparison, the lowland zone is more restricted in extent and the floodout zone is typically nonexistent, with most deposition instead occurring in deltas, estuaries, or offshore. Consequently, their IRES characteristics are dominated by those commonly associated with relatively high-energy upland and piedmont settings (e.g., bedrock rivers, coarse-grained braided rivers—Fig. 2.1.4, 2.1.5, and 2.1.7).

By contrast, in many Australian catchments, the upland and piedmont zones tend to have lower elevation, and more subdued, tectonically stable topography, and are relatively restricted in spatial extent compared with the extensive lowland and floodout zones. For instance, on the basis of 1:250,000 mapping and an elevation-based definition, more than 90% of the total length of all Australian watercourses can be classified as "lowland rivers," with the majority distributed across the dryland continental interior (Thoms and Sheldon, 2000; Sheldon and Thoms, 2006). Although this broad categorization includes rivers in both the lowland and floodout (deltaic/estuarine) zones, the characteristics associated with lower energy settings are more widespread (e.g., single- and multiple-thread channels, distributary channels, and floodouts—Fig. 2.1.10).

In southern Africa, there is more of a balance between the spatial extent of tectonically quiescent, upland, piedmont, lowland, and floodout (deltaic/estuarine) zones. Consequently, IRES characteristics tend to be associated with a wide variety of energy settings, including various bedrock, alluvial, and mixed bedrock-alluvial styles (e.g., braided, single-thread straight, meandering, anabranching/anastomosing and distributary rivers, and floodouts—Figs. 2.1.4, 2.1.5, 2.1.7, 2.1.8, and 2.1.10).

In these three regions, therefore, the different ecological conditions associated with the channels and floodplains in each of the zones will also vary in spatial extent. However, the precise composition of the biological communities will be a function of regional evolutionary history (Chapter 4.10) and the nature of ecosystem modification by human activities (Chapter 5.1).

2.1.9 SYNTHESIS AND NEW RESEARCH DIRECTIONS

Research on IRES has generally lagged behind that devoted to perennial rivers (Kingsford, 2006), and there are various challenges to improving understanding of the links between hydrology, sediment dynamics, geomorphology, and ecology in IRES. New lines of research are required to extend beyond individual IRES to develop knowledge that will lead to more widely generalizable concepts and theories. Key questions can be posed at a range of temporal and spatial scales, and include: How do flood sequences over years to centuries shape aquatic and riparian community structure, and what are the key feedbacks influencing channel and floodplain development in IRES? How do hillslope vegetation dynamics acting over decades to millennia influence hydrological and sediment fluxes and thus longer term topographic development? Over multimillennial and longer timescales, how does IRES catchment topography develop and what are the dominant drivers?

To address these and related questions, a range of approaches will be required that include a combination of field, flume, and computational model-based enquiry to integrate findings obtained at different spatial and temporal scales. For example, the interlinked hillslope, channel, and floodplain processes must be incorporated in field or flume study designs or in computational model structures. Field and flume studies should extend beyond point and plot scales to help generalize over larger scales, including longer channel reaches or entire catchments. Event-based process models can investigate a particular geomorphological process in isolation within a specific part of a catchment, while landscape evolution models (LEMs) can explore the impacts of external forcing (e.g., climate variability, tectonic activity, human disturbances) on IRES catchment development. Associated vegetation dynamics could be addressed by combining existing ecohydrology models (e.g., Rodriguez-Iturbe et al., 2001; Collins and Bras, 2008) with process models and LEMs.

Finally, recent decades have seen increasing use of a wide range of geochronological techniques (e.g., radiocarbon, luminescence, and cosmogenic radionuclide dating) to investigate geomorphological processes in IRES systems, including the timing and rates of sediment transport and storage, channel and floodplain development, and related vegetation dynamics (e.g., Tooth, 2012). In some cases, geochronology can generate knowledge about IRES dynamics at spatial and temporal scales that is intermediate between short-term field and flume studies and modeling studies of longer-term changes. Given the critical influences of geomorphological processes on ecology, a more comprehensive understanding of IRES dynamics will provide information that can be applied by managers and policy makers.

ACKNOWLEDGMENTS

We thank three reviewers (Allen Gellis and two anonymous referees) and the Handling Editor (Thibault Datry) for valuable comments on an earlier draft.

REFERENCES

Amoros, C., Burnette, G., 2002. Connectivity and biocomplexity in waterbodies of riverine floodplains. Freshw. Biol. 47, 761–776.

Andrews, E.D., 1991. Sediment transport in the Colorado River basin. In: Committee to Review the Glen Canyon Environmental Studies (Ed.), Colorado River Ecology and Dam Management: Proceedings of a Symposium, May 24–25, 1990. National Academy Press, Washington, DC, pp. 54–74.

Baker, V., 1977. Stream-channel response to floods, with examples from central Texas. Geol. Soc. Am. Bull. 88, 1057–1071.

Billi, P., 2007. Morphology and sediment dynamics of ephemeral stream terminal distributary systems in the Kobo Basin (northern Welo, Ethiopia). Geomorphology 85, 98–113.

Billi, P., 2015. Sediment dynamics and morphology of a boulder-bed ephemeral stream. In: Lollino, G., Arattano, M., Rinaldi, M., Giustolisi, O., Marechal, J.-C., Grant, G.E. (Eds.), Engineering Geology for Society and Territory. River Basins, Reservoir Sedimentation and Water Resources, 3. Springer, Dordrecht, pp. 371–375.

Bogan, M.T., Lytle, D.A., 2011. Severe drought drives novel community trajectories in desert stream pools. Freshw. Biol. 56, 2070–2081.

Bogan, M.T., Noriega-Felix, N., Vidal-Aguilar, S.L., Findley, L.T., Lytle, D.A., Gutiérrez-Ruacho, O.G., et al., 2014. Biogeography and conservation of aquatic fauna in spring-fed tropical canyons of the southern Sonoran Desert, Mexico. Biodivers. Conserv. 23, 2705–2748.

Boix-Fayos, C., Barberá, G., López-Bermúdez, F., Castillo, V., 2007. Effects of check dams, reforestation and land-use changes on river channel morphology: case study of the Rogativa catchment (Murcia, Spain). Geomorphology 91, 103–123.

Bourke, M., Pickup, G., 1999. Fluvial form variability in arid central Australia. In: Miller, A.J., Gupta, A. (Eds.), Varieties of Fluvial Form. Wiley, Chichester, pp. 249–271.

Bunn, S.E., Thoms, M.C., Hamilton, S.K., Capon, S.J., 2006. Flow variability in dryland rivers: boom, bust and the bits in between. River Res. Appl. 22, 179–186.

Burchsted, D., Daniels, M., Wohl, E.E., 2014. Introduction to the special issue on discontinuity of fluvial systems. Geomorphology 205, 1–4.

Carriquiry, J., Sánchez, A., 1999. Sedimentation in the Colorado River delta and upper Gulf of California after nearly a century of discharge loss. Mar. Geol. 158, 125–145.

Carriquiry, J.D., Sánchez, A., Camacho-Ibar, V.F., 2001. Sedimentation in the northern Gulf of California after cessation of the Colorado River discharge. Sediment. Geol. 144, 37–62.

Casado, A., Peiry, J.-L., Campo, A.M., 2016. Geomorphic and vegetation changes in a meandering dryland river regulated by a large dam, Sauce Grande River, Argentina. Geomorphology 268, 21–34.

Castillo, L., Marin, M., 2011. Hydrologic properties and sediment transport in ephemeral streams. WIT Trans. Ecol. Environ. 146, 313–324.

Chin, A., Gregory, K.J., 2001. Urbanization and adjustment of ephemeral stream channels. Ann. Assoc. Am. Geogr. 91, 595–608.

Collins, D., Bras, R., 2008. Climatic control of sediment yield in dry lands following climate and land cover change. Water Resour. Res. 44, W10405.

Cooke, R.U., Reeves, R.W., 1976. Arroyos and Environmental Change in the American South-West. Clarendon Press, Oxford.

Craddock, R.A., Howard, A.D., Irwin III, R.P., Tooth, S., Williams, R.M., Chu, P.S., 2012. Drainage network development in the Keanakākoʻi tephra, Kīlauea Volcano, Hawaiʻi: implications for fluvial erosion and valley network formation on early Mars. J. Geophys. Res. Planets 117, E8.

Doering, M., Uehlinger, U., Rotach, A., Schlaepfer, D., Tockner, K., 2007. Ecosystem expansion and contraction dynamics along a large Alpine alluvial corridor (Tagliamento River, Northeast Italy). Earth Surf. Process. Landf. 32, 1693–1704.

Donselaar, M., Gozalo, M.C., Moyano, S., 2013. Avulsion processes at the terminus of low-gradient semi-arid fluvial systems: lessons from the Río Colorado, Altiplano endorheic basin, Bolivia. Sediment. Geol. 283, 1–14.

Dubief, J., 1953. Report on the Superficial Hydrology of the Sahara. General Government of Algeria, Service of Scientific Studies, Birmandreis.

Dunkerley, D., 2008. Flow chutes in Fowlers Creek, arid western New South Wales, Australia: evidence for diversity in the influence of trees on ephemeral channel form and process. Geomorphology 102, 232–241.

Dunkerley, D., Brown, K., 1999. Flow behaviour, suspended sediment transport and transmission losses in a small (sub-bank-full) flow event in an Australian desert stream. Hydrol. Process. 13, 1577–1588.

Everitt, B.L., 1979. Fluvial adjustments to the spread of tamarisk in the Colorado Plateau region: discussion and reply. Geol. Soc. Am. Bull. 90, 1183.

Everitt, B.L., 1995. Hydrologic factors in regeneration of Fremont cottonwood along the Fremont River, Utah. In: Costa, J.E., Miller, A.J., Potter, K.W., Wilcock, P.R. (Eds.), Natural and Anthropogenic Influences in Fluvial Geomorphology, Geophysical Monograph 89. American Geophysical Union, Washington, DC, pp. 197–208.

Fisher, J.A., Krapf, C.B., Lang, S.C., Nichols, G.J., Payenberg, T.H., 2008. Sedimentology and architecture of the Douglas Creek terminal splay, Lake Eyre, central Australia. Sedimentology 55, 1915–1930.

Frostick, L., Reid, I., 1980. Sorting mechanisms in coarse-grained alluvial sediments: fresh evidence from a basalt plateau gravel, Kenya. J. Geol. Soc. London 137, 431–441.

Gellis, A.C., Pavich, M.J., Bierman, P.R., Clapp, E.M., Ellevein, A., Aby, S., 2004. Modern sediment yield compared to geologic rates of sediment production in a semi-arid basin, New Mexico: assessing the human impact. Earth Surf. Process. Landf. 29, 1359–1372.

Godsey, S., Kirchner, J., 2014. Dynamic, discontinuous stream networks: hydrologically driven variations in active drainage density, flowing channels and stream order. Hydrol. Process. 28, 5791–5803.

Goodrich, D.C., Lane, L.J., Shillito, R.M., Milier, S.N., Syed, K.H., Woolhiser, D.A., 1997. Linearity of basin response as a function of scale in a semiarid watershed. Water Resour. Res. 33, 2951–2965.

Gordon, N.D., McMahon, T.A., Finlayson, B.L., 1992. Stream Hydrology: An Introduction for Ecologists. John Wiley and Sons, Chichester.

Graeme, D., Dunkerley, D., 1993. Hydraulic resistance by the river red gum, *Eucalyptus camaldulensis*, in ephemeral desert streams. Aust. Geogr. Stud. 31, 141–154.

Graf, W.L., 1978. Fluvial adjustments to the spread of tamarisk in the Colorado Plateau region. Geol. Soc. Am. Bull. 89, 1491–1501.

Graf, W.L., 1981. Channel instability in a braided, sand bed river. Water Resour. Res. 17, 1087–1094.

Graf, W.L., 1988. Fluvial Processes in Dryland Rivers. Springer-Verlag, New York.

Grenfell, S., Grenfell, M., Rowntree, K., Ellery, W., 2014. Fluvial connectivity and climate: a comparison of channel pattern and process in two climatically contrasting fluvial sedimentary systems in South Africa. Geomorphology 205, 142–154.

Hassan, M.A., 2005. Characteristics of gravel bars in ephemeral streams. J. Sediment. Res. 75, 29–42.

Hassan, M.A., Egozi, R., 2001. Impact of wastewater discharge on the channel morphology of ephemeral streams. Earth Surf. Process. Landf. 26, 1285–1302.

Heritage, G., Van Niekerk, A., Moon, B., 1999. Geomorphology of the Sabie River, South Africa: an incised bedrock-influenced channel. In: Miller, A.J., Gupta, A. (Eds.), Varieties of Fluvial Form. Wiley, Chichester, pp. 53–79.

Irwin III, R.P., Tooth, S., Craddock, R.A., Howard, A.D., de Latour, A.B., 2014. Origin and development of theater-headed valleys in the Atacama Desert, northern Chile: morphological analogs to martian valley networks. Icarus 243, 296–310.

Jacobson, P.J., Jacobson, K.N., Seely, M.K., 1995. Ephemeral Rivers and Their Catchments: Sustaining People and Development in Western Namibia. Desert Research Foundation of Namibia, Windhoek.

Jacobson, P.J., Jacobson, K.M., Angermeier, P.L., Cherry, D.S., 1999. Transport, retention, and ecological significance of woody debris within a large ephemeral river. J. North Am. Benthol. Soc. 18, 429–444.

Jacobson, P.J., Jacobson, K.M., Angermeier, P.L., Cherry, D.S., 2000. Variation in material transport and water chemistry along a large ephemeral river in the Namib Desert. Freshw. Biol. 44, 481–491.

Jaeger, K.L., Olden, J., 2012. Electrical resistance sensor arrays as a means to quantify longitudinal connectivity of rivers. River Res. Appl. 28, 1843–1852.

Jaeger, K.L., Montgomery, D.R., Bolton, S.M., 2007. Channel and perennial flow initiation in headwater streams: management implications of variability in source-area size. Environ. Manag. 40, 775–786.

Johnson, W.C., 1994. Woodland expansions in the Platte River, Nebraska: patterns and causes. Ecol. Monogr. 64, 45–84.

Johnson, W.C., 1997. Equilibrium response of riparian vegetation to flow regulation in the Platte River, Nebraska. Regul. Rivers Res. Manage. 13, 403–415.

Kamp, K.V., Rigge, M., Troelstrup Jr., N.H., Smart, A.J., Wylie, B., 2013. Detecting channel riparian vegetation response to best-management-practices implementation in ephemeral streams with the use of spot high-resolution visible imagery. Rangeland Ecol. Manage. 66, 63–70.

Kampf, S.K., Faulconer, J., Shaw, J.R., Sutfin, N.A., Cooper, D.J., 2016. Rain and channel flow supplements to subsurface water beneath hyper-arid ephemeral stream channels. J. Hydrol. 536, 524–533.

Keppel, R.V., Renard, K., 1962. Transmission losses in ephemeral stream beds. J. Hydraul. Div. ASCE 8, 59–68.

Kingsford, R.T., 2006. Changing desert rivers. In: Kingsford, R.T. (Ed.), Ecology of Desert Rivers. Cambridge University Press, Melbourne, pp. 336–345.

Kingsford, R.T., Lemly, A.D., Thompson, J.R., 2006. Impacts of dams, river management and diversions on desert rivers. In: Kingsford, R.T. (Ed.), Ecology of Desert Rivers. Cambridge University Press, Melbourne, pp. 203–247.

Knighton, A.D., Nanson, G.C., 1994. Waterholes and their significance in the anastomosing channel system of Cooper Creek, Australia. Geomorphology 9, 311–324.

Knighton, A.D., Nanson, G.C., 1997. Distinctiveness, diversity and uniqueness in arid zone river systems. In: Thomas, D.S.G. (Ed.), Arid Zone Geomorphology: Process, Form and Change in Drylands, second ed. John Wiley and Sons, Chichester, pp. 185–203.

Knighton, A.D., Nanson, G.C., 2000. Waterhole form and process in the anastomosing channel system of Cooper Creek, Australia. Geomorphology 35, 101–117.

Larned, S., Hicks, D., Schmidt, J., Davey, A., Dey, K., Scarsbrook, M., et al., 2008. The Selwyn River of New Zealand: a benchmark system for alluvial plain rivers. River Res. Appl. 24, 1–21.

Larned, S.T., Schmidt, J., Datry, T., Konrad, C.P., Dumas, J.K., Diettrich, J.C., 2011. Longitudinal river ecohydrology: flow variation down the lengths of alluvial rivers. Ecohydrology 4, 532–548.

Laronne, J.B., Reid, I., 1993. Very high rates of bedload sediment transport by ephemeral desert rivers. Nature 366, 148–150.

Laronne, J.B., Reid, I., Yitshak, Y., Frostick, L.E., 1994. The non-layering of gravel streambeds under ephemeral flood regimes. J. Hydrol. 159, 353–363.

Larsen, I.J., Schmidt, J.C., Martin, J.A., 2004. Debris-fan reworking during low-magnitude floods in the Green River canyons of the eastern Uinta Mountains, Colorado and Utah. Geology 32, 309–312.

Leopold, L.B., Emmett, W.W., Myrick, R.M., 1966. Channel and hillslope processes in a semiarid area, New Mexico. In: U.S. Geological Survey Professional Paper, 352-G, pp. 193–253.

Lucía, A., Recking, A., Martín-Duque, J.F., Storz-Peretz, Y., Laronne, J.B., 2013. Continuous monitoring of bedload discharge in a small, steep sandy channel. J. Hydrol. 497, 37–50.

Mabbutt, J., 1977. Desert Landforms: An Introduction to Systematic Geomorphology. MIT Press, Massachusetts.

Mac Nally, R., Cunningham, S.C., Baker, P.J., Horner, G.J., Thomson, J.R., 2011. Dynamics of Murray-Darling floodplain forests under multiple stressors: the past, present, and future of an Australian icon. Water Resour. Res. 47, W00G05.

Macklin, M., Tooth, S., Brewer, P., Noble, P., Duller, G., 2010. Holocene flooding and river development in a Mediterranean steepland catchment: the Anapodaris Gorge, south central Crete, Greece. Global Planet. Change 70, 35–52.

Mansell, M., Hussey, S., 2005. An investigation of flows and losses within the alluvial sands of ephemeral rivers in Zimbabwe. J. Hydrol. 314, 192–203.

McDonald, C.C., Loeltz, O.J., 1976. Water resources of lower Colorado River-Salton Sea area as of 1971, summary report. In: U.S. Geological Survey Professional Paper, 486-A, pp. 1–34.

McKnight, D.M., Niyogi, D.K., Alger, A.S., Bomblies, A., Conovitz, P.A., Tate, C.M., 1999. Dry valley streams in Antarctica: ecosystems waiting for water. BioScience 49, 985–995.

Michaelides, K., Chappell, A., 2009. Connectivity as a concept for characterising hydrological behaviour. Hydrol. Process. 23, 517–522.

Michaelides, K., Martin, G.J., 2012. Sediment transport by runoff on debris-mantled dryland hillslopes. J. Geophys. Res. 117, F03014.

Michaelides, K., Singer, M.B., 2014. Impact of coarse sediment supply from hillslopes to the channel in runoff-dominated, dryland fluvial systems. J. Geophys. Res. 119, 1205–1221.

Michaelides, K., Wainwright, J., 2002. Modelling the effects of hillslope–channel coupling on catchment hydrological response. Earth Surf. Process. Landf. 27, 1441–1457.

Michaelides, K., Lister, D., Wainwright, J., Parsons, A.J., 2012. Linking runoff and erosion dynamics to nutrient fluxes in a degrading dryland landscape. J. Geophys. Res. 117, G00N15.

Micklin, P., 2007. The Aral Sea disaster. Annu. Rev. Earth Planet. Sci. 35, 47–72.

Montgomery, D.R., 1999. Process domains and the river continuum. J. Am. Water Resour. Assoc. 35, 397–410.

Morin, E., Grodek, T., Dahan, O., Benito, G., Kulls, C., Jacoby, Y., et al., 2009. Flood routing and alluvial aquifer recharge along the ephemeral arid Kuiseb River, Namibia. J. Hydrol. 368, 262–275.

Mueller, G.A., Marsh, P.C., 2002. Lost, a desert river and its native fishes: a historical perspective of the lower Colorado River: U.S. geological survey information technology report, 2002-0010. U.S. Fish and Wildlife Service, Fort Collins.

Nicholson, S.E., 2011. Dryland Climatology. Cambridge University Press, Cambridge.

Poesen, J., Hooke, J., 1997. Erosion, flooding and channel management in Mediterranean environments of southern Europe. Progr. Phys. Geogr. 21, 157–199.

Powell, D.M., Laronne, J.B., Reid, I., Barzilai, R., 2012. The bed morphology of upland single-thread channels in semi-arid environments: evidence of repeating bedforms and their wider implications for gravel-bed rivers. Earth Surf. Process. Landf. 37, 741–753.

Reid, I., Frostick, L.E., 1997. Channel form, flows and sediments in deserts. In: Thomas, D.S.G. (Ed.), Arid Zone Geomorphology: Processes, Form and Change in Drylands, second ed. Wiley, Chichester, pp. 205–229.

Reid, I., Laronne, J.B., 1995. Bed load sediment transport in an ephemeral stream and comparison with seasonal and perennial counterparts. Water Resour. Res. 31, 773–781.

Renard, K.G., Keppel, R.V., 1966. Hydrographs of ephemeral streams in the Southwest. J. Hydraul. Div. ASCE 92, 33–52.

Rodriguez-Iturbe, I., Porporato, A., Laio, F., Ridolfi, L., 2001. Plants in water-controlled ecosystems: active role in hydrologic processes and response to water stress: I. Scope and general outline. Adv. Water Resour. 24, 695–705.

Sandercock, P., Hooke, J., 2011. Vegetation effects on sediment connectivity and processes in an ephemeral channel in SE Spain. J. Arid Environ. 75, 239–254.

Sandercock, P., Hooke, J., Mant, J., 2007. Vegetation in dryland river channels and its interaction with fluvial processes. Progr. Phys. Geogr. 31, 107–129.

Schumm, S.A., 1977. The Fluvial System. John Wiley and Sons, New York.

Shakesby, R., Doerr, S., 2006. Wildfire as a hydrological and geomorphological agent. Earth Sci. Rev. 74, 269–307.

Shaw, P.A., Bryant, R.G., 2011. Pans, playas and salt lakes. In: Thomas, D.S.G. (Ed.), Arid Zone Geomorphology: Process, Form and Change in Drylands, third ed. Wiley-Blackwell, Chichester, pp. 373–401.

Sheldon, F., Thoms, M., 2006. In-channel geomorphic complexity: the key to the dynamics of organic matter in large dryland rivers? Geomorphology 77, 270–285.

Singer, M.B., 2010. Transient response in longitudinal grain size to reduced gravel supply in a large river. Geophys. Res. Lett. 37, L18403.

Singer, M.B., Michaelides, K., 2014. How is topographic simplicity maintained in ephemeral dryland channels? Geology 42, 1091–1094.

Singer, M.B., Sargeant, C.I., Piégay, H., Riquier, J., Wilson, R.J.S., Evans, C.M., 2014. Floodplain ecohydrology: Climatic, anthropogenic, and local physical controls on partitioning of water sources to riparian trees. Water Resour. Res. 50, 4490–4513.

Slater, L.J., Singer, M.B., 2013. Imprint of climate and climate change in alluvial riverbeds: Continental United States, 1950-2011. Geology 41, 595–598.

Sullivan, M.E., 1976. Drainage Disorganisation in Arid Australia and Its Measurement. Masters in Science Dissertation, University of New South Wales, Sydney.

Sutfin, N.A., Shaw, J.R., Wohl, E.E., Cooper, D.J., 2014. A geomorphic classification of ephemeral channels in a mountainous, arid region, southwestern Arizona, USA. Geomorphology 221, 164–175.

Thoms, M., 1995. The impact of catchment development on a semiarid wetland complex: the Barmah Forest, Australia. IAHS Publications-Series of Proceedings and Reports-Intern Assoc. Hydrol. Sci. 230, 121–130.

Thoms, M., Sheldon, F., 2000. Lowland rivers: an Australian introduction. Regul. Rivers Res. Manage. 16, 375–383.

Thornes, J.B., 1977. Channel changes in ephemeral streams: observations, problems and models. In: Gregory, K.J. (Ed.), River Channel Changes. Wiley, Chichester, pp. 317–335.

Tooth, S., 1999a. Floodouts in central Australia. In: Miller, A.J., Gupta, A. (Eds.), Varieties of Fluvial Form. Wiley, Chichester, pp. 219–247.

Tooth, S., 1999b. Downstream changes in floodplain character on the Northern Plains of arid central Australia. In: Smith, N.D., Rogers, J. (Eds.), Fluvial Sedimentology VI, International Association of Sedimentologists, Special Publication 28. Blackwell, Oxford, pp. 93–112.

Tooth, S., 2000. Downstream changes in dryland river channels: the Northern Plains of arid central Australia. Geomorphology 34, 33–54.

Tooth, S., 2005. Splay formation along the lower reaches of ephemeral rivers on the Northern Plains of arid central Australia. J. Sediment. Res. 75, 636–649.

Tooth, S., 2012. Arid geomorphology: changing perspectives on timescales of change. Progr. Phys. Geogr. 36, 262–284.

Tooth, S., 2013. Dryland fluvial environments: assessing distinctiveness and diversity from a global perspective. In: Shroder, J., Wohl, E.E. (Eds.), Treatise on Geomorphology, Vol. 9, Fluvial Geomorphology. Academic Press, San Diego, pp. 612–644.

Tooth, S., 2016. Changes in fluvial systems during the quaternary. In: Knight, J., Grab, S. (Eds.), Quaternary Environmental Change in Southern Africa: Physical and Human Dimensions. Cambridge University Press, Cambridge, pp. 170–187.

Tooth, S., McCarthy, T., 2004. Anabranching in mixed bedrock-alluvial rivers: the example of the Orange River above Augrabies Falls, Northern Cape Province, South Africa. Geomorphology 57, 235–262.

Tooth, S., Nanson, G.C., 2000. The role of vegetation in the formation of anabranching channels in an ephemeral river, Northern plains, arid central Australia. Hydrol. Process. 14, 3099–3117.

Tooth, S., Nanson, G.C., 2004. Forms and processes of two highly contrasting rivers in arid central Australia, and the implications for channel-pattern discrimination and prediction. Geol. Soc. Am. Bull. 116, 802–816.

Tooth, S., Nanson, G.C., 2011. Distinctiveness and diversity of arid zone river systems. In: Thomas, D.S.G. (Ed.), Arid Zone Geomorphology: Process, Form and Change in Drylands, third ed. Wiley-Blackwell, Chichester, pp. 269–300.

Tooth, S., McCarthy, T.S., Hancox, P.J., Brandt, D., Buckley, K., Nortje, E., et al., 2002. The geomorphology of the Nyl River and floodplain in the semi-arid Northern Province, South Africa. S. Afr. Geogr. J. 84, 226–237.

Tooth, S., Jansen, J.D., Nanson, G.C., Coulthard, T.J., Pietsch, T., 2008. Riparian vegetation and the late Holocene development of an anabranching river: Magela Creek, northern Australia. Geol. Soc. Am. Bull. 120, 1021–1035.

Trigg, M.A., Michaelides, K., Neal, J.C., Bates, P.D., 2013. Surface water connectivity dynamics of a large scale extreme flood. J. Hydrol. 505, 138–149.

Vogel, J.C., 1989. Evidence of past climatic change in the Namib Desert. Palaeogeogr. Palaeoclimatol. Palaeoecol. 70, 355–366.

Wainwright, J., Calvo Cases, A., Puigdefabregas, J., Michaelides, K., 2002. Linking sediment delivery from hillslope to catchment scale. Earth Surf. Process. Landf. 27, 1363–1489.

Wohl, E., 2010. A brief review of the process domain concept and its application to quantifying sediment dynamics in bedrock canyons. Terra Nova 22, 411–416.

Wohl, E., Pearthree, P.P., 1991. Debris flows as geomorphic agents in the Huachuca Mountains of southeastern Arizona. Geomorphology 4, 273–292.

Wolman, M.G., Gerson, R., 1978. Relative scales of time and effectiveness of climate in watershed geomorphology. Earth Surf. Process. 3, 189–208.

Yang, X., Scuderi, L.A., 2010. Hydrological and climatic changes in deserts of China since the late Pleistocene. Quatern. Res. 73, 1–9.