10 points that everyone should know about

Flash Floods

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Flash Floods

produced by **Stephen Tooth, Hywel Meilyr Griffiths, Jonathan William Bridge, Esraa Tarawneh, Ibrahim Oroud** and **Osama Mohawesh**

adapted from **"10 reasons why Geomorphology is important",** produced by **Stephen Tooth** and **Heather Viles** for the **British Society for Geomorphology**

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In today's world, there is increasing concern about the global environment and how it operates. The threats of climate change are of particular concern, including the many potential changes to hydrological extremes such as storms, floods and droughts. What are the implications of these changes in hydrological extremes for physical landscapes, ecosystems, and human activities? River floods, for instance, can be beneficial – such as by recharging aquifers or supplying sediment and nutrients to floodplains – but floods are also one of the most significant and widespread natural hazards. Floods can lead to changes in the size, shape and even location of river channels, and can be associated with loss of life and severe economic impacts (INFORMATION BOX 1). Globally, large sums are invested annually in river flood defence and flood risk management schemes, particularly as urban and industrial developments continue to encroach on flood-prone terrain. But many questions remain to be answered:

- Will extreme rainfall, floods and droughts become more frequent and more powerful in a warming world?
- How rapidly will rivers change over the 21st century in response to changes in rainfall, floods and droughts?
- What dangers do hydrological extremes and river changes pose to human land use, settlements and infrastructure?
- How can we manage these dangers?
- How can we best communicate the science and uncertainties surrounding these questions to non-specialist audiences, including schoolchildren, members of the public, and environmental policymakers?

Such questions need to be tackled in an interdisciplinary manner, with different disciplinary specialists contributing complementary data, knowledge and perspectives (Figure 1). Alongside hydrologists, ecologists, environmental historians, environmental engineers and many other specialists, geomorphologists (INFORMATION BOX 2) provide contributions that are important – indeed essential – for enabling a comprehensive approach to investigations of hydrological extremes and river changes. Increasingly, disciplinary specialists are working with local communities, health professionals, and environmental managers and policymakers to integrate data, knowledge and perspectives for environmental management purposes. For instance, individual and community memories of hydrological extremes can complement historical records, river gauging and other scientific data to provide a more comprehensive analysis of flood and drought impacts, and this analysis can help underpin sustainable environmental management practices.

INFORMATION BOX 1

Floods as hazards

Floods are one of the most significant and widespread natural hazards, accounting for some of the greatest losses of life annually and some of the greatest economic losses. In the last decade of the 20th century, floods accounted for about 12% of all deaths from natural disasters, claiming about 93 000 fatalities. As this booklet will argue, there are reasons to believe that global climate change and human activities may be increasing rather than decreasing flood hazards, including those related to flash floods. [**Sources:** statistics derived from Centre for Research on the Epidemiology of Disasters (CRED) International Disaster Database, www.cred.be, Université Catholique de Louvain, Brussels, and cited in Jonkman, S.N. 2003. Loss of life caused by floods: an overview of mortality statistics for worldwide floods. Delft Cluster Publication no. DC1-233-6, 31 pp.]

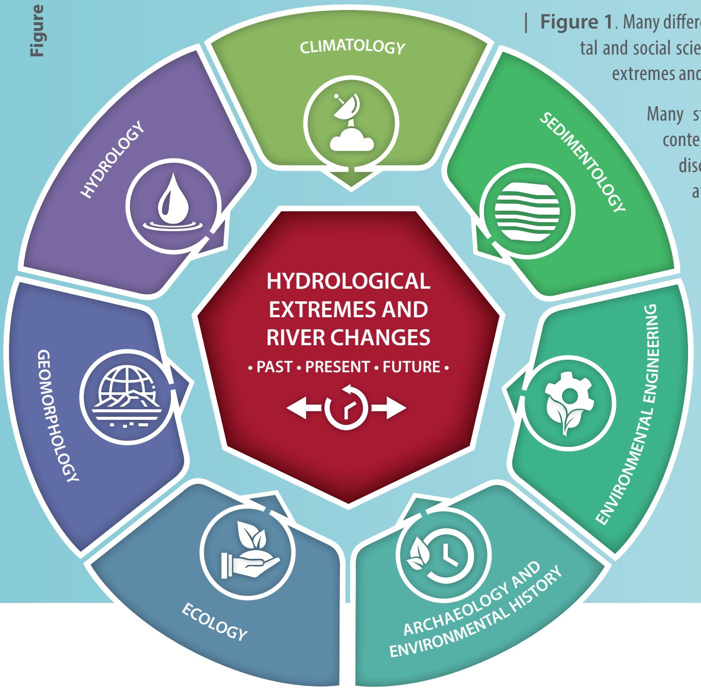
What is this booklet about?

INFORMATION BOX 2

What do geomorphologists study?

Geomorphologists are specialists that are typically found within larger disciplinary groupings such as physical geography or geoscience. Geomorphology (derived from Greek: ge, 'earth'; morfé, 'form'; logos, 'study') is the science that studies the origin and development of landforms (such as hills, valleys, sand dunes and caves), and how those landforms combine to form landscapes. Geomorphological studies include the quantitative analysis of landform shapes, the monitoring of surface and near-surface processes (e.g. running water, ice, wind) that shape landforms, and the characterisation of landform changes that occur in response to factors such as tectonic and volcanic activity, climate and sea level change, and human activities. Investigations may be directed principally towards reconstructing past processes and landform changes, towards understanding present-day processes and landform changes, or towards anticipating future processes and landform changes.

Figure 1



| **Figure 1**. Many different disciplines across the earth, environmental and social sciences contribute to the study of hydrological extremes and river changes.

Many studies are carried out in interdisciplinary contexts, with specialists from many different disciplines working alongside each other in an attempt to answer common questions.

Increasingly, disciplinary specialists are working in wider teams that include local communities, health professionals, and environmental managers and policymakers to develop sustainable management practices.

The aim of this booklet is to consider one type of hydrological extreme: the flash flood (INFORMATION BOX 3). Although flash floods can occur in many different climatic settings, particular emphasis is placed on flash floods that occur in drylands (INFORMATION BOX 4). A wide range of flood types can occur in drylands (INFORMATION BOX 5) but many are best described as flash floods. 'Flash flood' is a term widely used in many academic, environmental management, and environmental policy circles, and also commonly appears in the media and wider public discourses. In some cases, however, the accuracy and clarity of discussion could benefit from greater grounding in some of the key principles of flash flood science (INFORMATION BOX 6). Drawing inspiration from previous initiatives in science communication[1-2], particularly a brochure produced by the British Society for Geomorphology[3], we highlight ten key points that everyone should know about flash floods. These ten points are not exhaustive but are simply intended to highlight some of the key controls, characteristics, and significance of flash floods in a rapidly changing world. The document concludes by providing sources of additional information.

INFORMATION BOX 3

What is a flash flood?

Perhaps surprisingly, there is no universally accepted definition of a 'flash flood', with the term often being used quite loosely in scientific literature, policy documents, and media reports. Reports of flash floods have been provided from many different climatic and physiographic regions worldwide, including humid mountainous regions through to hyperarid lowland regions, and from rural through to more urban settings. Generally, however, the term is used to refer to floods that happen very quickly (floodwaters rise in minutes to hours) and that can be distinguished from types of flood that happen more slowly (e.g. other river flooding, coastal flooding, groundwater flooding). Reports refer to a wide range of natural factors (e.g. heavy rainfall) and human factors (e.g. dam failures) that can give rise to flash floods, with natural and human factors sometimes acting in combination, such as when heavy rainfall and debris transport leads to blocking of culverts. Compared to other floods, flash floods tend to have some of the highest fatalities, as these are generally unexpected and rapidly evolving events, which severely affect smaller areas. [**Source:** Jonkman, S.N. and Vrijling, J.K. 2008. Loss of life due to floods. Journal of Flood Risk Management, 1: 43-56.]

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[1] US-based Climate Literacy initiative (www.globalchange.gov/resources/educators/climate-literacy)

[2] Earth Science Literacy initiative (www.earthscienceliteracy.org)

[3] 10 reasons why geomorphology is important (www.geomorphology.org.uk/sites/default/files/10_reasons_geom/index.html)

INFORMATION BOX 4

What are drylands?

Drylands is a collective term for the world's extensive hyperarid, arid, semiarid and dry-subhumid regions. Essentially, drylands are regions where annual precipitation is exceeded by annual potential evapotranspiration, resulting in a net annual moisture deficit. These regions include many of the world's named deserts such as the Sinai, Sahara, Atacama, Simpson and Gobi, but drylands extend beyond the true deserts.

Collectively, warm drylands (i.e. excluding polar deserts) cover about 40% of the Earth's land surface and include around 20% of the global population, and thus span a vast range of climatic, tectonic, geological, soil and vegetation conditions while intersecting with diverse human societies.

Given the moisture deficits typical of drylands, permanently-flowing rivers (perennial rivers) are relatively rare, and generally are the larger rivers sourced in better watered regions. In these rivers, the term 'flood' tends to refer to flow volumes that approach or exceed the tops of the banks to inundate surrounding land. Most dryland rivers, however, remain dry for long periods, and only flow for short periods each year (intermittent or seasonal rivers) or only occasionally (ephemeral rivers). In some scientific literature (e.g. ecology), these types of rivers are referred to as 'temporary rivers'. In these normally dry channels, 'flood' tends to be used to refer any flow event, regardless of the volume. Many – but certainly not all of these floods – are flash floods (INFORMATION BOX 5).

INFORMATION BOX 5

Flash floods in dryland rivers

In perennial, intermittent and ephemeral dryland rivers, natural flow can be derived from different sources (rainfall, snowmelt, groundwater) leading to a range of flood types (INFORMATION BOX 4). Flash floods are one of the most common types, however, owing to specific combinations of atmospheric and land surface conditions. Conditions that tend to promote flash floods include:

- intense rainfall events (e.g. convective thunderstorms);
- large areas of rock outcrop and/or thin soils;
- crusted soil surfaces and/or sparsely-vegetated land surfaces.

Collectively, these conditions mean that large volumes of water can be delivered rapidly to land surfaces with a limited infiltration capacity (i.e. the rate at which water can soak into the ground). Consequently, a large percentage of the rainfall is converted to overland flow (i.e. surface runoff), and rapidly runs down the hillslopes towards the river channels. Flow concentration in the channels leads to a rapid rise in water levels and a flash flood may be generated (Figures 2 and 3).

Figure 2

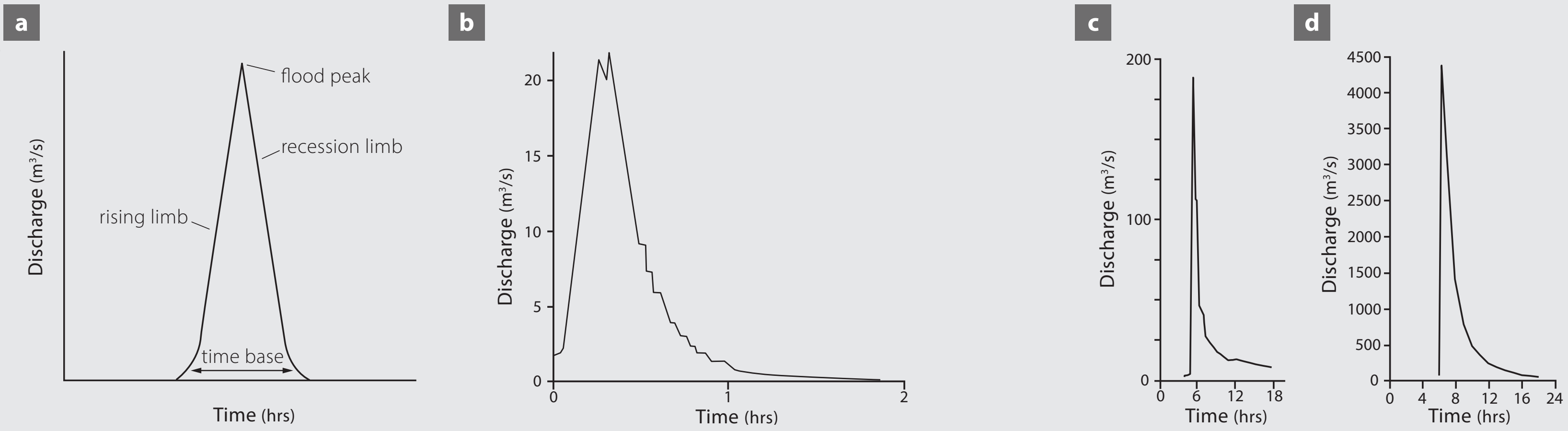


Figure 2. Examples of flash flood hydrographs, illustrating similarities in shape despite wide variations in flood size: **a**) schematic example, with labels to illustrate the key hydrograph elements; **b**) Il Kimere, Kenya; **c**) Tanque Verde Creek, Arizona, USA; **d**) Plum Creek, Colorado, USA. [**Sources:** compiled from Hjalmarson, H.W. 1984. Flash flood in Tanque Verde Creek, Tucson, Arizona. Journal of Hydraulic Engineering, American Society of Civil Engineers, 110: 1841-1852; Osterkamp, W.R. and Costa, J.E. 1987. Changes accompanying an extraordinary flood on a sand-bed stream. In: Mayer, L. and Nash, D. (Eds), Catastrophic Flooding. Binghamton Symposium in Geomorphology, Vol. 18. London: Allen and Unwin, pp. 201-224; Reid, I. and Frostick, L.E. 1987. Flow dynamics and suspended sediment properties in arid zone flash floods. Hydrological Processes, 1: 239–253.]

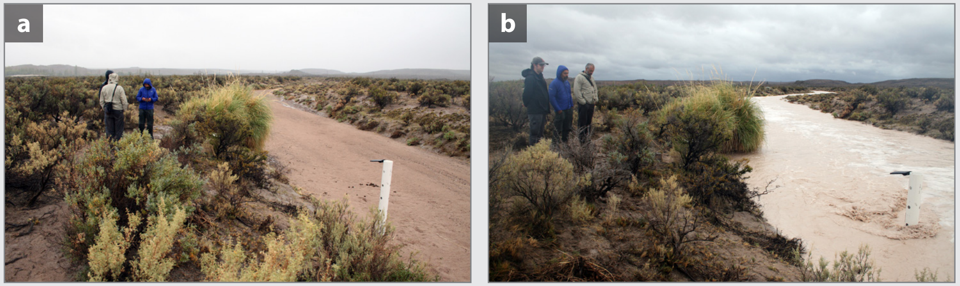


Figure 3. Example of a flash flood in an ephemeral river in eastern Patagonia, Argentina, during March 2019: **a**) before the flood; and **b**) during the flood peak. The two photographs were taken just a few hours apart. Flow is away from the camera, and the white vertical tube in the lower right is a flow gauging station (Photographs: Stephen Tooth).

INFORMATION BOX 6

Flash floods in the media

In the first decade of the new millennium, the Environment Agency (a UK government body covering England and Wales at the time) commissioned a report to look at how people understand and respond to flash flooding incidents. As part of the report, a media article analysis of flash floods concluded that: "… certain aspects of media reporting of flash flooding present an accurate picture of the characteristics of flash flooding. However, media reporting of the causative factors leading to flash flooding — from which people might learn about the precursors of flash flooding, and which might make them more able to predict, assess and identify an increasing risk of flash flooding — is not wholly accurate. Current media reporting of flash flooding therefore does well in descriptive terms but fails to help people understand much about the processes leading to flash flooding." [**Source:** Environment Agency, 2009. Understanding of and response to severe flash flooding. Science Report SC070021, Environment Agency, 118 pp.]

Assuming that such conclusions regarding media reporting could apply outside the United Kingdom, what lessons might be learned for improving understanding of flash floods in drylands? This booklet provides a small contribution to answering this question by outlining the factors and processes involved in flash flooding, the positive and negative impacts of flash flooding, and the management and policy decisions that can be taken to adapt to, or mitigate, flash flooding.

The **10 KEY POINTS that everyone should know about flash floods** are summarised in **TABLE 1**, both in abridged and extended form.

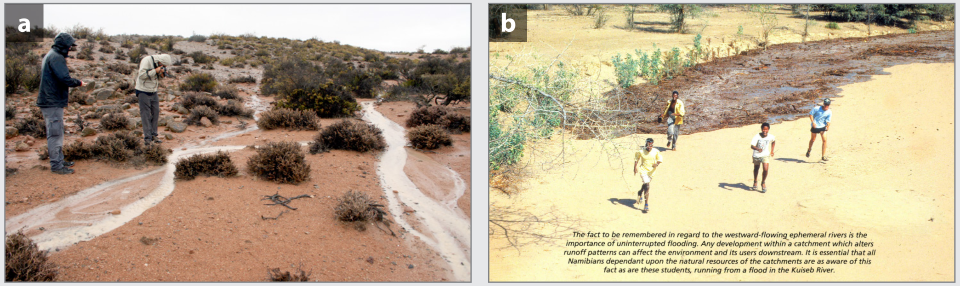
TABLE 1. Summary of the **10 KEY POINTS**

no. 1	**Many river landscapes are shaped by flash floods, which involve movements of mass**	Many dryland river landscapes are shaped by flash flood processes, which essentially involve the movement of mass – rock, sediment, water, organic material – across the Earth's surface
no. 2	**Flash flood processes are influenced by many different factors**	Various climatic, tectonic, geological, soil surface, and ecological factors directly and indirectly influence flash flood processes and the movement of mass
no. 3	**Flash flood processes operate at many different scales**	The climatic, tectonic, geological, soil surface, and ecological factors that influence flash flood processes and the movement of mass change with different time and space scales
no. 4	**Flash flood-prone landscapes are dynamic**	Dryland landforms and landscapes subject to flash floods are not static and unchanging, but are dynamic and develop through time
no. 5	**Flash flood characteristics and landscape dynamics are often complex**	In addition to changing climatic, tectonic, geological, soil surface, and ecological conditions, internal readjustments can also influence flash flood characteristics and their impact on landform and landscape development
no. 6	**Many landscapes are archives of past flash floods**	Landscapes contain histories of flash floods that potentially can be deciphered and reconstructed by studying the associated landforms and sediments
no. 7	**Global change is influencing flash flood characteristics**	Ongoing global environmental change is currently influencing flash flood characteristics, including by changing atmospheric, soil surface and vegetation characteristics
no. 8	**Human activities are influencing flash flood characteristics and landscape dynamics**	Increasingly, many flash flood processes and associated landform/landscape developments are influenced by human activities, either deliberately or inadvertently
no. 9	**Many landscapes are becoming more susceptible to hazardous flash floods**	Both global environmental change and human activities are increasing the magnitude and frequency of hazardous flash floods, which is impacting on land surface stability and leading to adverse socio-economic impacts
no. 10	**Successful flash flood management needs geomorphological knowledge**	Geomorphology can provide a key input to flash flood management, including by raising awareness of the importance of wetland conservation, restoration and construction

no. 1 Many river landscapes are shaped by flash floods, which involve movements of mass

Many dryland river landscapes are shaped by flash flood processes, which essentially involve the movement of mass – water, rock, sediment, organic material – across the Earth's surface. Following heavy rainfall or rapid snowmelt, large quantities of water can run across hillslope surfaces and down rills, gullies, and small tributary channels (Figure 4a). This flowing water can erode and transport weathered rock, sediment, and organic material such as leaves, twigs, and even branches and tree trunks towards the main river channel in the valley bottom. Some of this mass may be associated with contaminants, including agricultural chemicals such as nitrates or phosphates. In drylands, many channels are initially dry (so-called ephemeral or intermittent channels – INFORMATION BOX 4), but as increasing volumes of water filter into the main channel and move downstream under the influence of gravity, a flash flood can be generated. Flow arriving from different sources (e.g. different hillsides or tributaries) further swells flow volume in the main channel and as flood levels rise, mass supplied from the surrounding land surface is augmented by increasing amounts of mass eroded from the river bed and banks. As the flood continues to travel downstream, the initially dry channel is rapidly inundated. Photographs and videos of flash floods (see list of online resources at the end of the booklet) commonly show that the leading edge of flood waves (the 'flood bores') tend to be highly turbid. In catchments with at least partial vegetation cover, the flood bores may also include large volumes of coarse organic debris derived from trees and shrubs growing on the hillsides or along the river bed and banks (Figure 4b).

Figure 4



The fact to be remembered in regard to the westward-flowing ephemeral rivers is the importance of uninterrupted flooding. Any development within a catchment which alters runoff patterns can affect the environment and its users downstream. It is essential that all Namibians dependant upon the natural resources of the catchments are as aware of this fact as are these students, running from a flood in the Kuiseb River.

Figure 4. Examples of dryland hydrological events: **a)** runoff in small tributary channels following heavy rain in eastern Patagonia, Argentina (Photograph: Stephen Tooth); **b)** large volumes of organic debris associated with a flood bore in the Kuiseb River, Namibia. [**Source:** this eye-catching photograph provides the back cover for the following book: Jacobson, P.J., Jacobson, K.M. and Seeley, M.K., 1995. Ephemeral Rivers and Their Catchments: Sustaining People and Development in Western Namibia. Windhoek: Desert Research Foundation of Namibia.]

The concepts of flood hydraulics and bed and bank resistance are central to understanding the shaping of river landscapes by flash floods (INFORMATION BOX 7). The downstream transport of rock, sediment and organic material in successive flash floods means that mass is progressively transferred from higher to lower parts of the landscape. In the absence of significant tectonic uplift or volcanic eruptions – processes which tend to move mass upwards and/or generate new rock – flash floods thereby contribute to the slow but progressive downwearing of land surfaces. Downwearing tends to be much more rapid along channels than on surrounding hillslopes, so many channels tend to erode deeply into the land surface, in extreme instances forming deep valleys, gorges or canyons within which smaller scale erosional and depositional landforms can develop. The infrequent nature of large flash floods means that their significance is not always appreciated, but flash floods nonetheless have contributed to the formation of some of the Earth's most spectacular landscapes (Figure 5).

Figure 5

Figure 5. Examples of river landscapes formed in part by long histories of flash flooding: **a)** Fish River canyon, southern Namibia (flood flow is from right to left); **b)** Quebrada de Cafayate, northwest Argentina (flow in the main river is from middle left towards the bottom, with flash floods along a tributary periodically entering from the middle right); **c)** Standley Chasm, central Australia (flood flow is towards the camera) (Photographs: Stephen Tooth).

INFORMATION BOX 7

Flash flood hydraulics and bed and bank resistance

While flash floods are known to play a key role in shaping dryland river channels and the wider landscape, collecting specific field data on flood hydraulic characteristics remains difficult. Infrequent floods that can arise rapidly make it difficult to be in the right place at the right time to measure flow and sediment transport, and in many regions gauging stations are patchy or non-existent. Even where present, gauging stations commonly fail to accurately record flow data during large or extreme flood events, as the structures are commonly drowned out and/or suffer physical damage. This paucity of data hampers efforts to advance knowledge of flash flood hydraulic characteristics. Nevertheless, from the physical evidence left behind after flash floods, indirect estimates of flood hydraulic and sediment transport characteristics can still be made in ungauged or poorly gauged dryland rivers. Such evidence includes high water marks (e.g. 'trash lines' of organic debris), the size and shape of eroded channels, and certain sediment features such as the size and orientation of boulder accumulations (Figure 6).

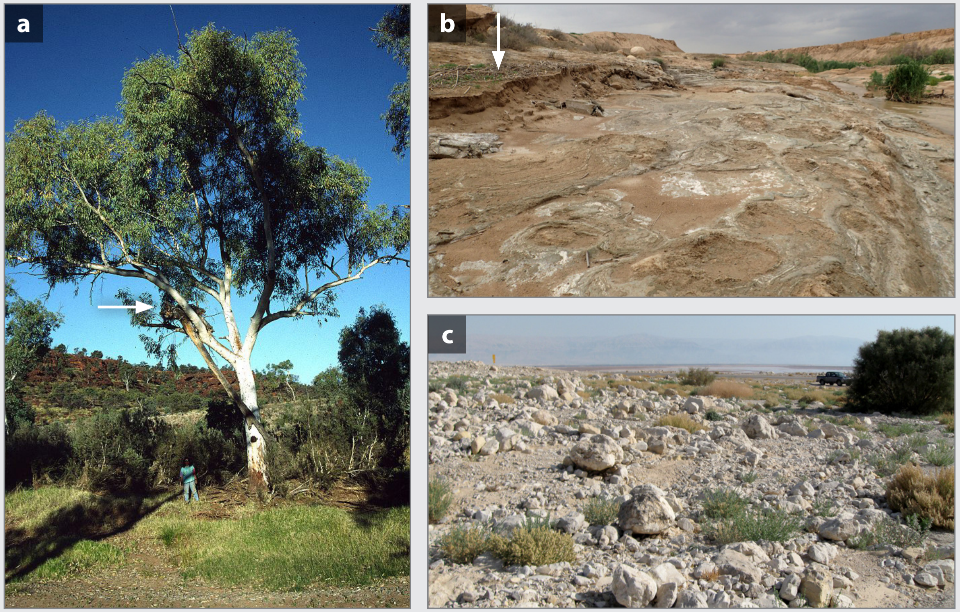


Figure 6. Physical evidence of flash floods in dryland rivers: **a**) roots of a small tree (arrowed) lodged in the branches of a larger tree, indicating a prior flood depth of 8-9 m in the Finke River gorge, central Australia. The dry bed of the Finke River is in the foreground and the flood flow was from left to right (Photograph: Stephen Tooth); **b**) organic debris (arrowed) and the eroded margin of fine-grained sediment, indicating flood extent along the lower Jordan River, Israel. The flood flow was towards the camera, with low flow in the main channel visible on the far right (Photograph: Nati Bergman); **c**) boulders, some in imbricated clusters, indicating high-energy flood conditions along the Nahal Mor, Israel. The flood flow was from left to right (Photograph: Nati Bergman).

For instance, from knowledge of flood depth, channel size and shape, and channel slope, estimates can be made of velocity, discharge, shear stress and stream power during flash floods. Flow velocity (**v, in m/s**) can be estimated indirectly, using equations such as the Manning formula:

$$v = (R^{2/3}S^{1/2})/n$$

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 depth (**d**) in wide, shallow channels) and **n** (also termed Manning's n or Manning's coefficient) 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 m^3/s**) by incorporating **A** into the formula:

$$Q = (AR^{2/3}S^{1/2})/n$$

Many other hydraulic equations encompass these variables, such as those for bed shear stress (**τ, in N/m2**) total stream power (**Ω**, in **W/m**) and unit stream power (**ω**, in **W/m2**):

$$\tau = \gamma RS$$

$$\Omega = \gamma QS$$

$$\omega = \gamma QS/w$$

where **γ** is the specific weight of water and w is channel width.

In terms of landscape shaping, the key significance of these variables is their strong association with the potential to 'do work' (i.e. eroding and transporting rock, sediment, and organic material), which also influences many ecological processes and patterns.

The equations show that for given values of **γ**, **R**, **Q**, and **w**, steeper channels (higher **S**) will be more powerful (higher **τ**, **Ω** and **ω**). Relatively steep channels, such as those in mountain front locations, may have **τ** and **ω** values potentially competent to transport coarse-grained sediment such as large cobbles and boulders and erode bedrock, even during relatively moderate floods. Significant bed erosion may lead to channel incision, thereby forming a relatively narrow and deep channel (Figure 7a). For a given **Q** and **S**, such a channel increases **R**, **d**, and **τ** and **ω** values, thus creating a positive feedback that may continue channel incision.

By contrast, less steep channels, such as those in lowland settings, may have **τ**, **Ω** and **ω** values that are not competent to consistently transport large volumes of sediment. During low to moderate flood events, some sediment may be deposited within the channel, thereby leading to channel aggradation and the formation of a relatively wide and shallow channel (Figure 7b). For a given **Q** and **S**, such a channel reduces **R**, **d**, and **τ** and **ω** values, which may lead to further sediment deposition.

Figure 7

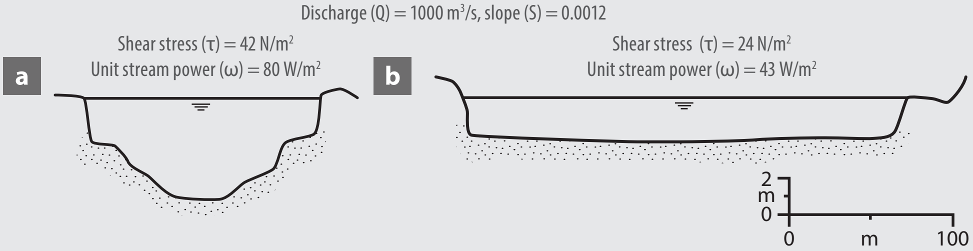


Figure 7. Schematic channel cross sections of similar size showing how width and depth are key influences on flash flood hydraulic parameters for a given discharge and slope: **a**) narrow, deep channel; **b**) wide, shallow channel.

The extent to which the potential to 'do work' results in actual geomorphic work (i.e. erosion and mass transport) depend on whether, and for how long, a given flash flood exceeds channel bed and bank resistance thresholds. In natural, unmodified dryland channels, beds and banks can be composed of bedrock, alluvium, or a mixture. Bedrock resistance to erosion is largely a product of rock hardness and is influenced by factors such as mineralogy, cementation, joint spacing and degree of weathering. Some rock types with widely spaced joints and minimal weathering (e.g. some granites or quartzites) will tend to be more resistant, while other rock types with closely spaced joints and higher degrees of weathering (e.g. some mudrocks and sandstones) will be less resistant. Alluvial resistance to erosion is largely a product of grain size and cohesion, the latter including the influence of vegetative root networks. Fine-grained (clay, silt), well vegetated beds and banks will tend to be more resistant, while coarser grained (sand, gravel), poorly vegetated beds and banks will be less resistant.

Figure 8

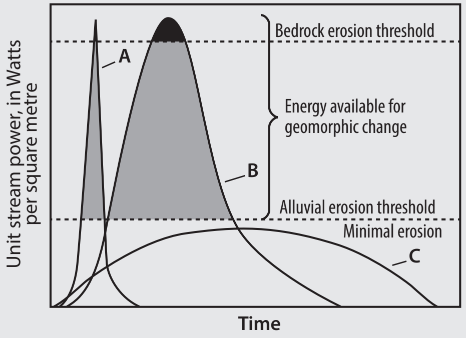


Figure 8. Schematic graphs of unit stream power during floods of different duration, illustrating how the potential for doing geomorphic work (i.e. channel erosion and sediment transport) depends on the length of time that alluvial and bedrock thresholds are exceeded by the flow. Even a very short-lived but powerful flash flood (curve A) can accomplish significant alluvial and bedrock erosion, while a longer lived yet less powerful flood (curve C) may result in only minimal erosion. [**Source:** redrawn after Costa, J.E. and O'Connor, J.E. 1995. Geomorphically effective floods. 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, pp. 45-56.]

For geomorphic work to take place, flash flood hydraulic conditions have to exceed the resistance of the channel bed and banks. Once resistance thresholds are exceeded, the amount of work done largely depends on the length of time that flood hydraulic conditions remain above that threshold (Figure 8). As shown by typical flash flood hydrographs (Figure 2), many flash floods are short lived, with rapid rises and falls of water levels meaning that hydraulic conditions only remain above the resistance thresholds for a few minutes or hours. Nonetheless, as the examples documented in this booklet will show, many flash floods can do abundant geomorphic work, even over these short periods.

DID YOU KNOW?

Many media reports tend to emphasis the negative aspects of flash floods, such as the damage to, or destruction of, riparian vegetation, housing and infrastructure, or the loss of human lives. While this emphasis is understandable, flash floods can also provide many societal and environmental benefits, including the replenishment of dams and reservoirs, groundwater recharge, and the supply of water and materials to dependent riparian ecosystems. Most previous investigations of material transport in flash-flood dominated dryland rivers have focused on the relatively coarse-grained clastic (e.g. sand, gravel) sediments moving in continuous or near-continuous contact with the channel bed (bedload and saltation load) or the finer-grained sediment (e.g. clay, silt) moving in suspension within the water column (suspended load). Less attention has been directed toward other components of material transport, such as the dissolved sediment load and the particulate organic load but these also can be important for ecosystem functioning.

For example, in a study focusing on downstream transport of large woody debris during a 2-day flood in January 1994 along the ephemeral Kuiseb River, Namibia, Jacobson et al. (1999) found that 65% of deliberately painted wood exported from marking sites was retained within debris piles associated with in-channel growth of large ana trees (*Faidherbia albida*). The flood discharge reached 159 m³/s at the upper end of the study reach and declined to <1 m³/s by 200 km downstream, so wood retention peaked in the river's lower reaches (for an example of an organic debris-laden flood bore on the Kuiseb River, see Figure 4b). Debris piles induced deposition of sand, silt and finer 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 for a diverse range of fungi, algae, liverworts, plants, insects, and other arthropods, and so became focal points for decomposition and nutrient cycling. These findings suggest that the lower Kuiseb River is a sink for materials transported from upstream, and that the large amounts of coarse organic matter form an important component of the food chain. [**Source:** Jacobson, P.J., Jacobson, K.M., Angermeier, P.L. and Cherry, D.S. 1999. Transport, retention, and ecological significance of woody debris within a large ephemeral river. Journal of the North American Benthological Society, 18: 429–444.]

no.

2

Flash flood processes are influenced by many different factors

Various climatic, tectonic, geological, soil surface, and ecological factors directly and indirectly influence flash flood processes and the movement of mass. In drylands and more humid settings alike, climate influences water availability on hillslopes and river channels, principally through the seasonal distribution and volume of precipitation (rainfall or snowfall), and through temperature, which affects the potential for water loss by evaporation or plant transpiration. Water and temperature are key influences on rock breakdown, with different lithologies (rock types) having different susceptibilities to weathering and erosion, which in turn influences hillslope sediment supply. Tectonic activity (e.g. uplift, faulting) can also influence hillslope sediment supply through seismic shaking and generation of associated mass movements (e.g. landslides) and by exposing fresh rock surfaces to the atmosphere, which then undergo subsequent breakdown. Water, temperature, and sediment supply collectively influence hillslope soil surface processes. In many drylands, physical crusts commonly form in the spaces between tightly-packed larger gravels embedded in the soil surface (Figure 9a). These physical crusts and the gravel packing tend to limit infiltration of water into the subsoil, which enhances surface runoff during rainfall or snowmelt, and so may result in increased erosion farther downslope. Water, temperature, and sediment (including nutrient) supply are also key influences on local ecosystems, as they are key determinants of vegetation type, density and distribution, and associated animal activities. In turn, plant and animal activities also can be important influences on hillslope water and sediment supply, in some cases limiting the potential for movement of mass (e.g. tree roots, microbial crusts or vegetation growth patterns that stabilise hillslope surfaces – Figure 9b) but in others enhancing the potential for movement of mass (e.g. the digging activities of insects and mammals). Interactions between many different factors therefore affect the potential movement of mass (water, rock, sediment, organic material) from hillslopes to channels. Within many dryland channels, vegetation (trees, shrubs, grasses) commonly establishes to exploit the water and nutrient supply, and this can also affect also affect the patterns and rates of the downstream movement of mass. In many Australian dryland channels, for instance, shrubs and trees in channel beds are a major obstruction to flash floods, commonly leading to scour around the roots and lower trunks on the upstream side and deposition on the downstream side (Figure 10).

Figure 9

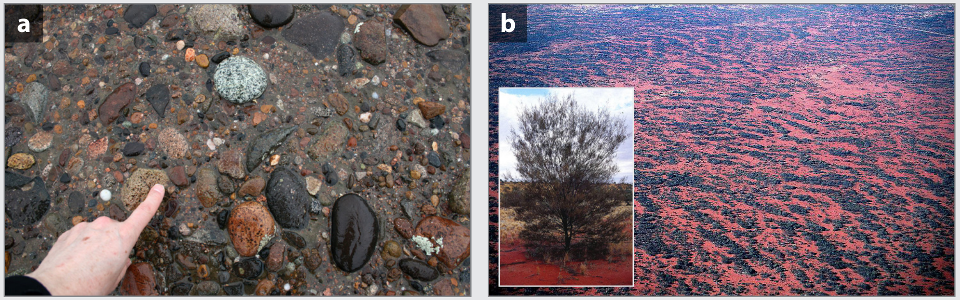


Figure 9. Factors influencing hillside runoff and flash flood generation: **a**) physical crusts of clay, silt and sand between tightly-packed gravels on a hillslope in eastern Patagonia, Argentina. The photograph was taken during heavy rainfall but infiltration into the soil surface was limited, with initial ponding and then shallow downslope water flow taking place instead; **b**) oblique view of a hillside in central Australia, showing how mulga trees (*Acacia aneura*) (see inset photograph) tend to be arranged in groves aligned along the contours. The hillslope decreases in elevation towards the upper right of the photograph. During heavy rainfall, enhanced runoff from the barer intergrove areas supplies water, sediment and nutrients to the downslope groves. This 'banded mulga' vegetation pattern has similarities with the structure of some other dryland hillslope vegetation communities, and tends to limit the potential for movement of mass from hillslopes to channels (Photographs: Stephen Tooth).

Figure 10

Figure 10. The ephemeral Marshall River, central Australia, illustrating how inland teatrees (*Melaeuca glomerata*) and river red gums (*Eucalyptus camaldulensis*) grow within the channel bed. Many of these trees can withstand the occasional floods, and present obstructions to flow, which commonly results in deposits of sand and minor gravel on their downstream side. During floods, flow direction is towards the lower left. (Photograph: Stephen Tooth).

DID YOU KNOW?

The popular conception of a flash flood in an ephemeral channel commonly involves a rapidly moving 'wall of water' that overwhelms anyone unfortunate enough to be in its path. In fact, observations of the leading edge of flash floods (flood bores) in ephemeral channels typically reveal velocities of less than 1 m/s, which is low enough to be outpaced by brisk walking or a gentle run (see Figure 4b). The rapid rate of water level rise after the initial bore has passed – indicated by the steep rising limb of a typical flash flood hydrograph (see Figure 2) – is usually what catches people unaware and can lead to fatalities. In some steep, ephemeral channels largely free of sediment or vegetation obstructions, peak flood velocities of 3 m/s or higher can also present considerable hazards. In less steep ephemeral channels with well-developed riparian vegetation, however, flow velocities may be lower and more variable.

For instance, in Australian ephemeral dryland channels, shrubs and trees widely colonise the beds and banks (see Figures 6a and 10). Often growing densely over the bed surface, these shrubs and trees provide obstructions and serve as roughness elements that slow the flood flows; the effects can be heightened by substantial barriers of flood-transported debris which lodge against trunks and branches. Field mapping of channels in the Barrier Range, western New South Wales, where the river red gum (*Eucalyptus camaldulensis*) is widely established, enabled Graeme and Dunkerley (1993) to quantify the likely channel roughness during floods that can reach up to around 250 m^3/s. Results suggested that just under half of the total channel roughness (Manning's n values – see INFORMATION BOX 7) may be contributed by the in-channel vegetation, the remainder coming from boundary roughness effects (e.g. sediment particles). In these hydraulically rough channels, estimated mean peak flood velocities are typically much lower than 2 m/s and will vary considerably across the width of the channel depending on the location of vegetation and related obstacles. Site-to-site variations in vegetation density are significant, and without due incorporation of appropriate roughness correction, in these channels there could be substantial errors of overprediction of flood velocities, discharges, and related sediment transport. [**Sources:** Graeme, D. and Dunkerley, D.L. 1993. Hydraulic resistance by the river red gum, Eucalyptus camaldulensis, in ephemeral desert streams. Australian Geographical Studies, 31: 141–154; Reid, I. and Frostick, L.E., 2011. Channel form, flows and sediments of endogenous ephemeral rivers in deserts. In: Thomas, D.S.G. (Ed.), Arid Zone Geomorphology: Process, Form and Change in Drylands (3rd edition). Chichester: Wiley, pp. 301-332.]

no. 3 Flash flood processes operate at many different scales

The climatic, tectonic, geological, soil surface, and ecological factors that influence flash flood processes and the movement of mass change with different time and space scales. Some of the factors that influence flash floods and their role in shaping landscapes (key points 1 and 2) can be characterised as low frequency/high magnitude, as they act relatively slowly or irregularly through time but have a large influence on the amount of mass moved. Examples include long-term climate changes that increase annual rainfall totals and so enhance hillslope runoff, or decreases in regional tectonic uplift rates that reduce the frequency of seismic shaking and so limit hillslope sediment supply. Other factors are high frequency/low magnitude as they act relatively regularly but have a smaller influence on the amount of mass moved. Examples include short-term increases in wildfire frequency and intensity that reduce hillslope vegetation cover and so enhance runoff and sediment supply, or short-term decreases in rainfall (droughts) that can lead to reduced hillslope runoff.

Between the low frequency/high magnitude and high frequency/low magnitude ends of the spectrum, climatic, tectonic, geological, soil surface, and ecological factors can combine in many different ways to increase or decrease the potential for flash floods (key point 2). By distinguishing between relevant geomorphological processes that occur along this spectrum from low frequency/high magnitude to high frequency/low magnitude, we can also conceptualise how movement of mass occurs at different rates (Figure 11), and how different flash flood-influenced landforms develop across a spectrum of time and space scales (Figure 12).

Figure 11

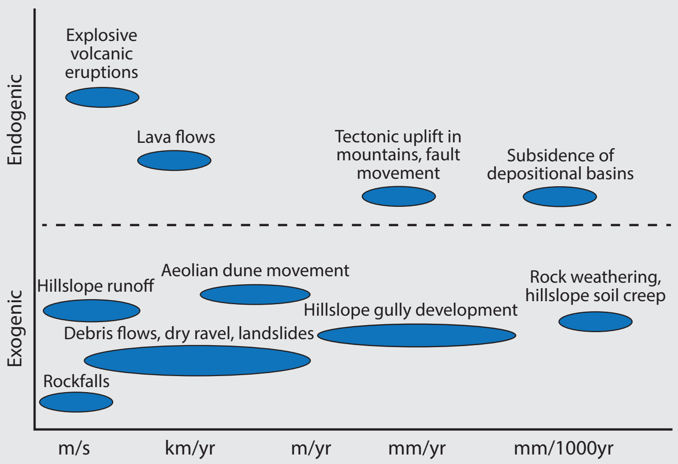


Figure 11. Geomorphological processes are driven by endogenic factors (powered from within the Earth such as volcanoes and earthquakes) and exogenic factors (powered by the sun's energy and working through the climate system, such as rain, wind and fire). In dryland river catchments, different processes result in different rates for the movement of mass, from very slow (e.g. basin subsidence, soil creep) to extremely rapid (e.g. volcanic eruptions, rockfalls). [**Sources:** adapted from Goudie, A.S. and Viles, H.A., 2010. Landscapes and Geomorphology: A Very Short Introduction. Oxford University Press, Oxford and Tooth, S. and Viles, H.A. 2014. 10 Reasons Why Geomorphology Is Important. British Society for Geomorphology. Available at: www.geomorphology.org.uk/what-geomorphology.]

Figure 12

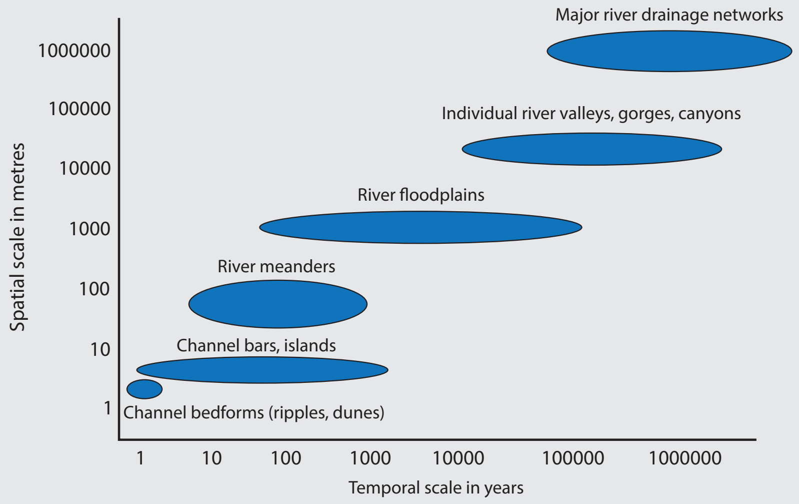


Figure 12. River landforms vary widely in spatial scale (size), and their development occurs across a wide range of time scales. Small scale landforms such as sand ripples and dunes form, erode and re-form on rapid time scales (e.g. individual flash floods), while large scale landforms such as valleys, gorges, canyons, and major drainage networks develop over far longer time scales. [**Sources:** adapted from Goudie, A.S. and Viles, H.A., 2010. Landscapes and Geomorphology: A Very Short Introduction. Oxford University Press, Oxford and Tooth, S. and Viles, H.A. 2014. 10 Reasons Why Geomorphology Is Important. British Society for Geomorphology. Available at: www.geomorphology.org.uk/what-geomorphology.]

DID YOU KNOW?

In dryland catchments with at least a partial vegetation cover, wildfires — a term for uncontrolled or naturally occurring fires — can be important influences on flash flood processes and the movement of mass. Depending on the amount and type of vegetation and litter burnt, the soil type, and particularly the heating duration and surface temperature reached, wildfires can fundamentally change soil surface properties, including by enhancing soil water repellency (hydrophobicity) and decreasing soil aggregate stability. These soil property changes have implications for patterns, quantities and rates of infiltration, and thus for hillslope runoff generation, soil erosion, and flash flood characteristics.

Clear responses are not always evident but many studies have reported higher flood discharges in burned dryland catchments that in large part are attributable to reduced infiltration and enhanced hillslope runoff. Changes in flood peak discharge are commonly larger than changes in annual runoff and are, therefore, more sensitive measures of catchment hydrological response to wildfire. As an example, Moody and Martin's (2001) study of the post-fire relations between rainfall intensity and peak discharge in three, small (17-27 km^2) mountainous catchments in the western USA showed marked changes in unit-area peak discharge (i.e. peak flood discharge divided by area burned). As 30 minute rainfall intensity increased above a threshold of 10 mm/hour, unit-area peak discharges increased ever more rapidly with further changes in rainfall intensity, suggesting that wildfire has the largest influences on catchment hydrological responses during the less frequent, higher intensity rainfall events.

When compared with pre-fire rates or rates from comparable undisturbed areas, other studies have reported marked increases in soil erosion in the first few years following wildfire. Although post-fire soil erosion is commonly associated with rainfall and runoff, in steep terrain that has been subject to fire, sediment redistribution can also occur by various mass movement processes, the most important of which are dry ravel (dry particle-to-particle sliding under gravity), debris flows, and shallow landslides. In areas of the southwestern USA that are characterized by steep chaparral terrain with Mediterranean-type climates (e.g. parts of Arizona and California), Florsheim et al. (1991) have documented how much sediment is stored upslope of vegetation obstructions (stems and litter dams). These obstructions tend to be destroyed or damaged by burning, initiating hillslope sediment redistribution by dry ravel in the post-fire period. In steep terrain, therefore, these processes link burnt hillslopes and river channels, and can deliver large volumes of sediment, ash and organic debris to the channel network for some time after wildfire. [**Sources:** Florsheim, J.L., Keller, E.A. and Best, D.W. 1991: Fluvial sediment transport in response to moderate storm flows following chaparral wildfire, Ventura County, southern California. Geological Society of American Bulletin 103, 504–511; Moody, J.A. and Martin, D.A. 2001: Post-fire, rainfall intensity-peak discharge relations for three mountainous watersheds in the western USA. Hydrological Processes 15, 2981–2993; Shakesby, R.A. and Doerr, S.H. 2006: Wildfire as a hydrological and geomorphological agent. Earth- Science Reviews 74, 269–307.]

no. 4

Flash flood-prone landscapes are dynamic

Dryland landforms and landscapes subject to flash floods are not static and unchanging, but are dynamic and develop through time. A popular conception is that drylands are 'timeless' landscapes: largely static and unchanging, with many landforms essentially fixed in form, size and position. This conception is challenged by the recognition that climatic, tectonic, geological, soil surface, and ecological factors change through time and over space, and that this can have a profound influence on flash flood processes and landform generation (see key points 1-3). Nonetheless, as illustrated in Figures 11 and 12, the rate of landform/landscape development can vary widely, depending on the processes operating and the amount of mass that needs to be moved for change to be recognisable. Small-scale landforms like ripples and dunes form and reform rapidly over time, as only small amounts of mass need to be moved to effect change (Figures 12 and 13a). Medium-scale landforms (e.g. bars and islands, meander bends) can adjust moderately rapidly over time (Figures 10, 12 and 13b). Large-scale landforms/landscapes (e.g. river valleys, canyons, gorges) typically develop only slowly over time because of the vast amounts of mass that need to be moved to effect change, and thus can be relatively persistent features on the Earth's surface (Figures 5 and 12).

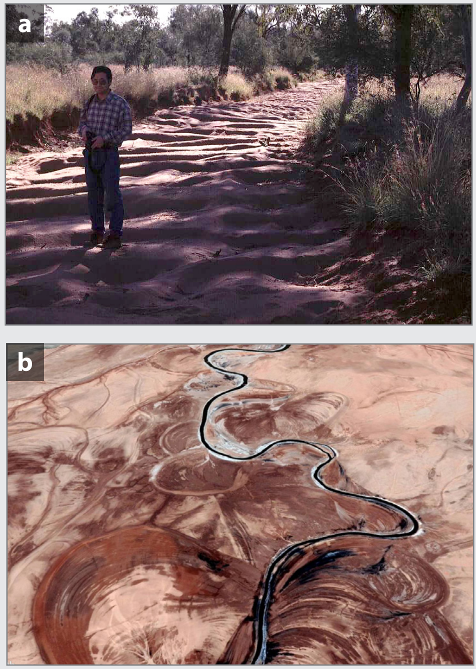
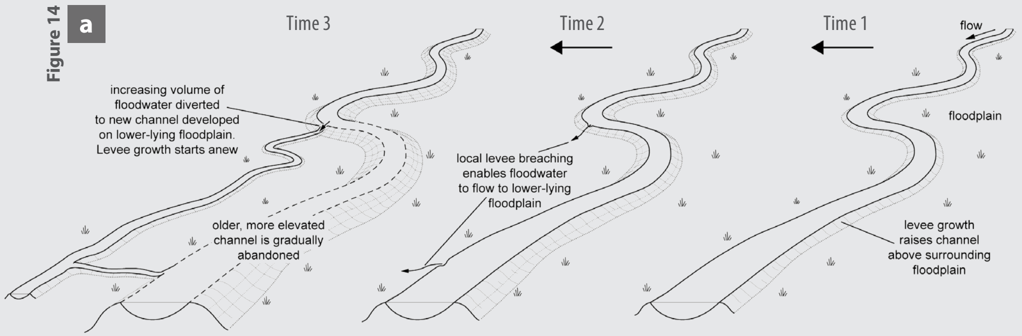


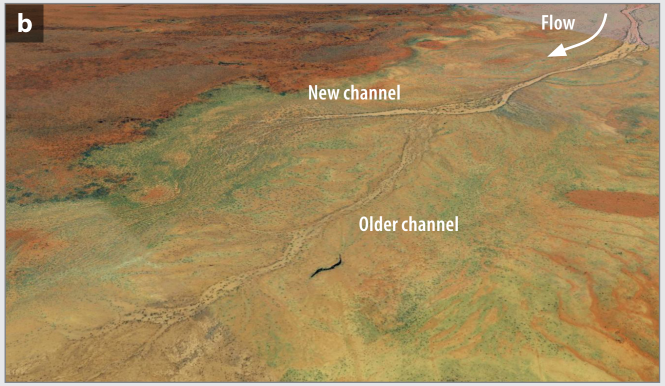
Figure 13. Examples of dryland river landforms that form over different space and time scales: **a**) dunes on the bed of an ephemeral channel in central Australia are shaped by individual flash floods lasting from hours to a few days. The flow direction was towards the camera (Photograph: Stephen Tooth); **b**) active and abandoned meander bends along the ephemeral Río Colorado, Bolivia, are shaped by successions of flash floods that occur over multi-annual to multi-centennial timescales. [**Source:** Google Earth.]

Other river landforms may develop slowly for a while, then develop rapidly as a threshold is crossed. For example, some river channels can remain in largely stable positions between levees that slowly increase in height over time, and that effectively raise the channel above the level of the surrounding floodplain (Figure 14a). The channel may remain stable until change is triggered by an external event, such as heavy rainfall that leads to a particularly large flash flood. As shown by the example of the Sandover River in central Australia, in such a flood, the banks are eroded and levees fail. A new channel is then eroded in a lower position on the floodplain, and the old channel is abandoned (Figure 14b).

Figure 14. Example of rapid channel change following the crossing of a threshold: **a**) deposition of sand, silt and clay along and adjacent to river channels can lead to the growth of levees and the raising of flow above the level of the surrounding floodplain. During floods, levee breaching can divert increasing amounts of flow to parts of the lower-lying floodplain. Eventually, a threshold is crossed whereby a newly-formed channel carries an increasing proportion of the flow, and the old, higher-elevation channel is gradually abandoned. [**Source:** adapted from Tooth, S. and Viles, H.A. 2014. 10 Reasons Why Geomorphology Is Important. British Society for Geomorphology. Available at: www.geomorphology.or.uk/what-geomorphology]; **b**) the lower Sandover River in central Australia provides a dramatic illustration of how this process of avulsion can reconfigure the channel and floodplain. In this location, a large flood in 1974 provided the final trigger for channel shifting, with a new channel being formed and the old channel being abandoned. [**Source:** Google Earth.]

Figure 14





DID YOU KNOW?

Long-term field studies of dryland rivers are relatively rare but where monitoring data are available they provide essential baselines for understanding the impacts of flash floods on channel and wider landscape dynamics. On 28th September 2012, moderate to extreme floods affected the semiarid Murcia region in southeast Spain. The floods resulted in ten fatalities, much damage to infrastructure including roads and bridges, and impacts on agriculture. The floods also impacted a series of long-tem monitoring sites on two ephemeral rivers in the Guadalentín basin (Rambla de Nogalte and Rambla de Torrealvilla). Hooke (2016) presented detailed morphological data that were collected before and immediately after the floods, and explained how this enabled the amount of channel change, erosion, and deposition to be related to peak flow conditions at the sites. At the downstream end of the braided, gravel-bed Nogalte channel, peak flow reached 2500 m^3/s in less than 1 hour. At the upstream monitoring sites where peak flow was <1000 m^3/s, net changes to channel cross-sectional areas resulting from erosion and deposition were closely related to peak discharge and total stream power but less clearly related to other hydraulic measures such as velocity, shear stress, and unit stream power (See INFORMATION BOX 7 for definitions of hydraulic variables). The main impact of the flood was net aggradation, with many large, flat-topped bars forming in wider channel sections. Along the predominantly single, gravel-bed Torrealvilla channel, peak flow was <500 m^3/s and fewer significant changes were evident, but net erosion tended to occur at the sites. Overall, less morphological change took place in the extreme event on the Nogalte than predicted from some published hydraulic relations, probably reflecting the high sediment supply and the short flood duration (a few hours) that to some extent counteracted or limited potential erosion (see INFORMATION BOX 7). These results demonstrate the high degree of adjustment of these and other similar ephemeral dryland rivers to the irregular flash floods. In addition, the long-term monitoring data provide valuable quantitative constraints for models that attempt to project the impacts on channels of altered flood flow regimes resulting from climate or land-use changes (see key points 7 and 8). [**Source:** Hooke, J.M. 2016. Geomorphological impacts of an extreme flood in SE Spain. Geomorphology, 263: 19-38.]

no. 5 Flash flood characteristics and landscape dynamics are often complex

In addition to changing climatic, tectonic, geological, soil surface, and ecological conditions, internal readjustments can also influence flash flood characteristics and their impact on landform and landscape development. Flash floods vary widely in size, with floodwaters commonly remaining well within the channel banks. These relatively small floods typically result in few major erosional or depositional changes, especially in dryland channels with well-vegetated banks. Larger flash floods that approach or exceed bankfull, however, may be associated with more rapid, dramatic changes (see key point 4), either because of the potential for large movements of mass from hillslopes and channel beds, especially following wildfires (key point 3), or because of the high stream powers that can be generated in steep channels (INFORMATION BOX 7). Despite short flash flood durations (typically hours – see Figure 2), rapid, dramatic, erosional changes can occur if the resistance thresholds of the channel bed and banks are exceeded for periods of time (INFORMATION BOX 7). Dryland channels with little or no bank vegetation are particularly susceptible to change because: i) flow velocities are largely unaffected by organic roughness elements (key points 1 and 2); ii) channel beds, banks and floodplains tend to be exposed to the full force of flows; and iii) in the absence of extensive root networks, bank resistance may be limited. In some cases, this may result in frequent changes to channels and floodplains during large flash floods, with channels being particularly susceptible to dramatic widening (Figure 15a). Following large, erosive flash floods, many channels may remain in overwidened conditions for years because subsequent smaller floods that are capable of renewed deposition and channel rebuilding tend to be limited in number. Nevertheless, an overwidened channel can influence these subsequent smaller floods because flows are spread across a wider channel bed and remain relatively shallow with lower unit stream powers (INFORMATION BOX 7). These internal channel-flow readjustments tend to reduce erosion and instead encourage deposition. Over time, deposition may gradually return the channel to the size and shape existing prior to the large flood, a process termed 'channel recovery'. Where the re-establishment of riparian vegetation is occurring, this can enhance channel recovery rates. Even sparse vegetation growth can help to trap sediment, stabilise bars, and encourage island coalescence, all of which contribute to the narrowing of overwidened channels (Figure 15b).

Figure 15

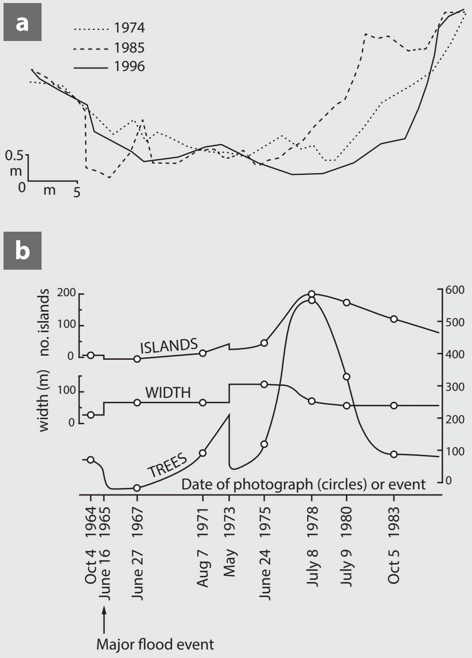
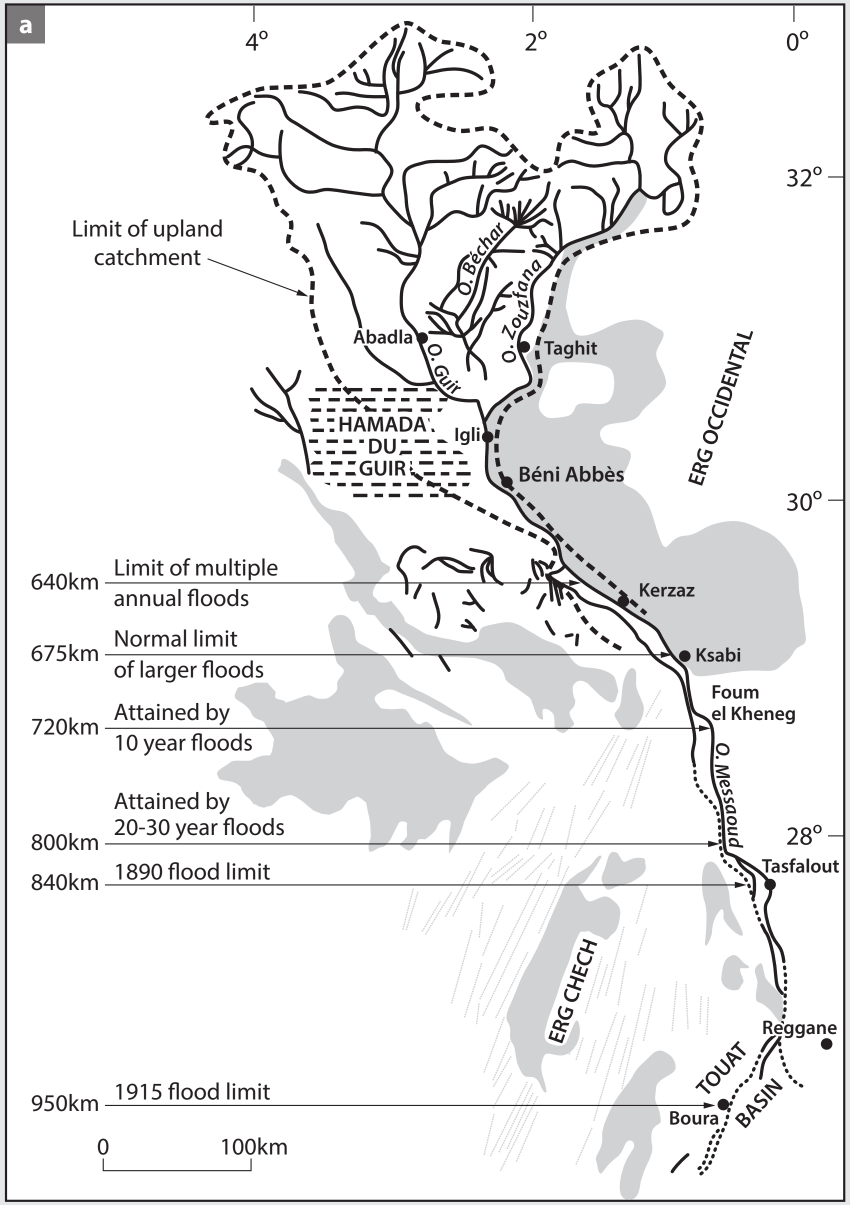


Figure 15. Contrasting dynamics in alluvial dryland channels: **a**) the upper Jordan River in the Middle East, showing fluctuations in channel depth and width between 1974 and 1996 that resulted from flash floods up to 150 m^3/s. [**Source:** redrawn from Inbar, M. 2000. Episodes of flash floods and boulder transport in the Upper Jordan River. In: The Hydrology-Geomorphology Interface: Rainfall, Floods, Sedimentation, Land Use. Proceedings of the Jerusalem Conference, May 1999. International Association of Hydrological Sciences Publication no. 261: 185-200]; **b**) Plum Creek, Colorado, USA, showing channel width, island and vegetation changes following a major flood event in June 1965. In this catastrophic flash flood, which peaked at 4360 m^3/s (see Figure 2d), the channel widened and the number of trees on channel islands decreased. Subsequent floods further widened the channel and influenced tree numbers but through the mid-late 1970s and early 1980s, tree re-establishment led to an increase in the number of vegetated islands. As islands increased in number, many coalesced and attached to the channel banks, contributing to channel narrowing. These processes resulted in a gradual recovery towards the width existing prior to the 1965 flood. [**Source:** Osterkamp, W.R. and Costa, J.E. 1987. Changes accompanying an extraordinary flood on a sand-bed stream. In: Mayer, L. and Nash, D. (Eds), Catastrophic Flooding. Binghamton Symposium in Geomorphology, Vol. 18. London: Allen and Unwin, pp. 201-224.]

Internal channel-flow readjustments can also occur in the downstream direction. As individual flash floods travel downstream from the upper catchment, some flow is lost through seepage into the initially dry channel bed, banks and floodplain (a process known as transmission loss). Nevertheless, flow volumes may initially still increase as tributaries supply flow to the main channel. In many dryland catchments, however, the number of tributaries tends to decrease dramatically in the middle and lower catchment so the decreasing flow volumes are not replenished by tributary inflows (Figure 16a). Combined with the typical decreases in channel slope in the middle and lower reaches, this tends to lead to a downstream transformation in flash flood characteristics, with hydrographs having less steep rising and recession limbs and a broader time base. Eventually, flows may dissipate entirely, with many flash floods failing to travel the full channel length (Figure 16a). In some catchments, only the very largest flash floods reach the lower end the catchments (Figure 16a; see also key point 1, 'DID YOU KNOW?').

Exceptions to these temporal and spatial patterns of internal channel-flow readjustments can be found. For instance, flow variations can occur within a given flood event, with pronounced rises and falls of discharge rapidly occurring in response to irregular rainfall in time and space and asynchronous tributary inputs (Figure 16b; see also 'DID YOU KNOW?'). These examples from different dryland catchments illustrate how internal readjustments can influence flash flood characteristics and their impact on landforms and landscapes in diverse ways.

Figure 16



DID YOU KNOW?

While many flash flood hydrographs are of the single peak type (see Figure 2), rainfall characteristics and catchment network configurations can sometimes result in more complex flood hydrographs. The November 1972 flood in the Wadi Watir, southeastern Sinai Desert, Egypt, provides a case in point (Figure 16b). The 3100 km^2 catchment covers rugged mountainous terrain and drains through a 20 km long canyon to the Gulf of Aqaba. In late November, irregular storm rainfall fell across the catchment; recorded totals on the eastern and northern margins ranged from 14.3 to 28.5 mm but may have been greater in the central catchment. On the 23rd and 24th November, a series of very short flood peaks were recorded, with discharge rising within a few minutes from low flow levels to peaks of around 45 to 320 m^3/s, followed by abrupt recessions back to lower flow levels (Figure 16b). Schick (1988) suggested that the complex hydrograph resulted from several factors, including the fact that: i) the discharge rises on the 23rd, and the initial smaller rises on the 24th, were fully or partially dissipated owing to flow transmission losses into the not-yet-fully wetted channel bed sediments; ii) later discharge rises were less affected by transmission losses, and being larger and faster, united with smaller preceding rises to create even larger rises; iii) the patchy storm rainfall distribution resulted in asynchronous tributary inputs that alternately led to rises and falls in discharge in the main channel. In effect, flows generated at different times and in different parts of the drainage network combined to give rise to the complex hydrograph. [**Source:** Schick, A.P., 1988. Hydrologic aspects of floods in extreme arid environments. In: Baker, V.R., Kochel, R.C. and Patton, P.C. (Eds), Flood Geomorphology. Wiley, New York, pp. 189-203.]

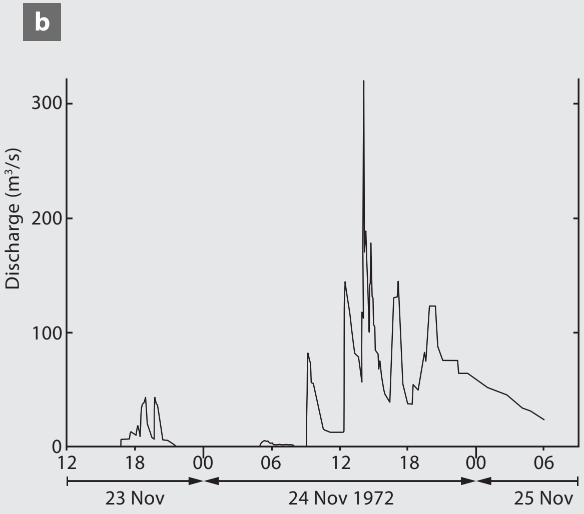


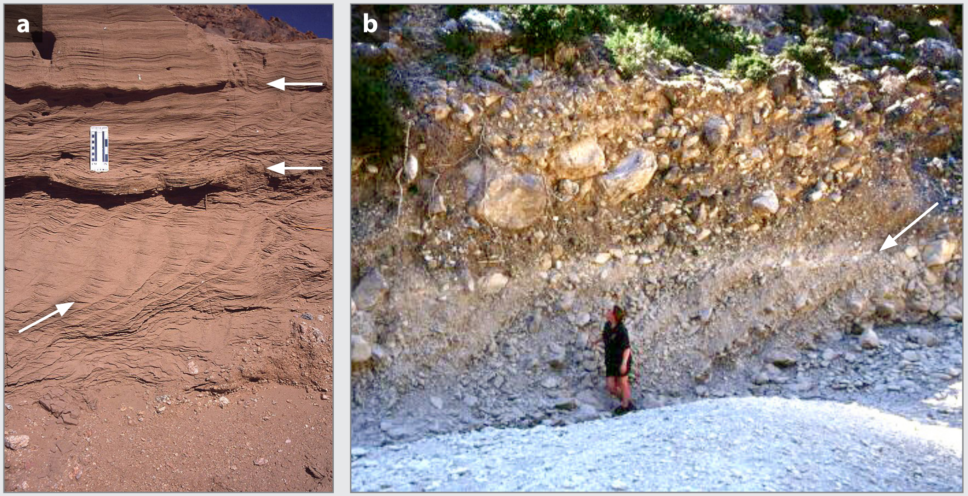
Figure 16. Downstream changes in flash flood characteristics: **a**) limits of different size floods, indicating a downvalley decrease in flood frequency in the Guir-Saoura-Messaoud catchment, northwestern Sahara. [**Source:** redrawn from Mabbutt, J.A., 1977. Desert Landforms. Canberra: Australian National University Press, after Vanney, J.-R. 1960. Pluie et Crue dans le Sahara Nord-Occidental. Monographies Régionales 4. Institut de Recherches Sahariennes de l'Université d'Alger]; **b**) hydrograph of the November 23rd-25th 1972 flood along the Wadi Watir, Egypt, showing rapid rises and falls of discharge that resulted in part from tributary inputs. Numbers above the calendar dates are hours of the day. [**Source:** redrawn from Schick, A.P., 1988. Hydrologic aspects of floods in extreme arid environments. In: Baker, V.R., Kochel, R.C. and Patton, P.C. (Eds), Flood Geomorphology. Wiley, New York, pp. 189-203.]

no. 6 Many landscapes are archives of past flash floods

Landscapes contain histories of flash floods that potentially can be deciphered and reconstructed by studying the associated landforms and sediments. Many of the world's drylands have been subject to long histories of changing climates, tectonic activity, and ecosystems. These changes have impacted on water and sediment supply and therefore on flash flood frequency and magnitude. The response of dryland rivers to these changing conditions may be complicated by internal readjustments (see key point 5), and evidence for past flash floods and associated channel-floodplain changes is commonly partially erased by later river processes. Nonetheless, many dryland landscapes host river landforms and sediments that bear the distinctive signatures of past flash floods, including enlarged channels, slackwater sediments, and flood-transported boulder accumulations (Figure 17).

Figure 17. Sedimentary evidence for past flash floods in dryland channels: **a**) fine-grained (silt, sand) slackwater sediments recording flood sequences in a locally widened section of the Orange River gorge downstream of Augrabies Falls, northwestern South Africa (see Figure 21b for a view of the gorge). The inclined arrow is pointing to sedimentary structures termed 'climbing ripples', which indicate rapid deposition under sediment-laden floods (flow direction was from left to right). The horizontal arrows indicate the initial erosion that commonly occurs at the onset of a subsequent flood, with more deposits then accumulating atop the older deposits; **b**) coarse-grained (cobble, boulder) deposits recording high-energy floods in the Anapodaris River gorge, southern Crete. The inclined arrow is pointing to sedimentary structures termed 'planar cross strata', which indicate downstream gravel bar migration during floods (flow direction was from right to left). Higher up the exposure, evidence for subsequent, higher energy floods is provided by the larger boulders that have overridden these older deposits (Photographs: Stephen Tooth).

Figure 17



These river landforms and sediments thus can provide archives of flash floods ('palaeoflood records'). Even if only partial and fragmentary, these palaeoflood records can be compiled and combined with other lines of evidence for past environments, including changes in catchment vegetation assemblages. Collectively, this enables coherent landscape developmental histories to be deciphered and reconstructed, including evidence for changes in flash flood frequency and/or magnitude. Establishing the timing of any changes in flood regime enables assessment of the likely external factors driving this change, including regional and global palaeoclimates. In addition, reconstruction of river landscape development histories provides essential context for: i) assessing the nature of historical and more recent dryland river changes (key points 4 and 5); ii) constraining or projecting possible trajectories of future river changes under global climate change scenarios (key point 7); and iii) evaluating the importance of human impacts (key point 8). Indeed, given the absence or short length of many dryland river gauging records, a problem compounded by the damage to gauges that commonly occurs during the largest flood events (see INFORMATION BOX 7), these palaeoflood records are vital for enabling more comprehensive assessments of dryland flood hazards.

DID YOU KNOW?

Slackwater deposits (SWDs) (Figure 17a) are typically formed of silt and sand that accumulates rapidly from suspension during large floods in areas where flow velocities are locally reduced. In many dryland river canyons and gorges, SWDs can develop in locally widened sections, in recesses or caves in the canyon/gorge walls, or at tributary junctions. Along with the use of geochronological techniques to determine sediment age (e.g. radiocarbon or luminescence dating) and other indicators of former river levels, SWDs can provide some of the key long-term records of large or extreme past floods (palaeofloods), including peak discharges.

In the 35 km^2 Nahal Netafim catchment, located in the hyperarid southern Negev desert, Israel, SWDs were found in a 3 m by 4 m cave in the canyon walls. The cave opening was 1.7 m above the current channel bed and was nearly filled with a 3.3 m thick sequence of SWDs that recorded 27 large palaeofloods ranging from 200-600 m^3/s. Using luminescence dating, these floods were shown to have occurred between 33 000 and 29 000 years ago. The average frequency of large palaeofloods during this time period was about one flood per 150 years, while in more recent millennia there has only been one large flood per 1000 years. In comparison to these more recent floods, eight of the 27 older palaeofloods were anomalously large, suggesting a different past climate and hydrology. The hypothesis is that an increased frequency of an intensified Red Sea Trough low-pressure system affected the southern Negev, resulting in increases in regional rainfall intensity and/or duration that generated the anomalously large palaeofloods. These episodes of increased storminess in the region punctuated, but did not permanently alter, the general hyperarid conditions. [**Source:** Greenbaum, N., Porat, N., Rhodes, E. and Enzel, Y. 2006. Large floods during late Oxygen Isotope Stage 3, southern Negev desert, Israel. Quaternary Science Reviews, 25: 704-719.]

no. 7 Global change is influencing flash flood characteristics

Ongoing global environmental change is currently influencing flash flood characteristics, including by changing atmospheric, soil surface and vegetation characteristics. Archives provide evidence of flash floods in the distant past (hundreds to many tens of thousands ago – key point 6) while documentary evidence such as eye-witness accounts, photographs and limited gauging data exists for more recent flash floods. Wikipedia provides a selection of notable historical flash floods worldwide, including many that have occurred in drylands (see en.wikipedia.org/wiki/Flash_flood), and additional examples are documented every year in scientific articles and media reports (Figure 18; for other examples of recent media reports, see the end of this booklet).

Figure 18

Boat submerged by flash flooding at Lake Powell

By Faith Heaton Jolley | Posted - June 9, 2015 at 10:32 p.m.

(Courtesy of Dennis Slavensky)

Figure 18. Screenshot from an online news report of flash flooding at Lake Powell, Utah, USA in June 2015. [**Source:** KSL.com. Available at: www.ksl.com/article/35007255.]

Given their erratic nature, and the limited number and short duration of gauging records for dryland rivers, identifying any changes in the numbers or sizes of flash floods that can be attributed to global environmental change is particularly problematic. The influence of climate change on any single weather or flood event, for example, is difficult to determine because the natural variability and limited data make it difficult to isolate trends (i.e. increases or decreases in flash flood-producing storms) from background noise. Nevertheless, our scientific understanding of the global hydrological cycle provides good reason to think that flash floods may increase in a warming world. For every 1°C rise in global average atmospheric temperatures, the moisture-holding capacity of the lower atmosphere increases by 7%. Ocean surfaces are also warming, which increases evaporation and transfer of moisture into weather systems, including so-called atmospheric rivers (see 'DID YOU KNOW?'). Both atmospheric and oceanic warming trends thus can contribute to larger and more intense rainfall events, which increases the potential for floods, especially flash floods. Flash flood potential is enhanced even further when heavy rain falls on land surfaces with vegetation that is stressed by drought or that has recently been subject to wildfire (key point 3).

DID YOU KNOW?

Atmospheric rivers (ARs) are 'rivers in the sky': long, narrow corridors of water vapour in the lower atmosphere that extend from the tropics to higher latitudes. Estimates suggest that ARs can carry as much moisture as up to 15 Mississippi Rivers combined, and so are key elements of the global hydrological cycle. Over the last few decades, particularly with developments in microwave remote sensing from satellites, scientists have learned more about ARs. Although best documented from the Pacific coast of North America, ARs also affect the west coast of other major land masses, including western Europe and drylands in southern Europe, Chile and South Africa. As ARs are forced to rise over coastal mountains, they cool and large volumes of vapour condense, generating rainfall or snowfall. While some ARs are relatively weak systems, some of the larger, more powerful ARs can create extreme rainfall. ARs thus play a dual role: positive impacts include replenishing water supplies and quenching wildfires, while negative impacts include increasing potential for flash floods and mass movements, including landslides and debris flows. In January 2021, for instance, an AR generated heavy rainfall over coastal California, including several large areas affected by the devastating 2020 wildfire season. This generated severe flash floods and mudflows, resulting in significant damage to a section of State Highway 1 between Los Angeles and San Francisco.

With atmospheric and oceanic warming, ARs are predicted to grow longer, wider and wetter, and so may be key for determining how changing climate patterns influence extreme precipitation and floods. Consequently, much research is aimed at better physical understanding, monitoring, and forecasting of ARs. [**Sources:** Ralph, F.M. and Dettinger, M.D. 2011. Storms, floods and the science of atmospheric rivers. Eos: Transactions, American Geophysical Union, 92: 265-266; Corringham, T. 2020. Atmospheric river storms can drive costly flooding – and climate change is making them stronger. The Conversation, 27th January 2020. Available at: theconversation.com/atmospheric-river-storms-can-drive-costly-flooding-and-climate-change-is-making-them-stronger-128902; Petley, D. 2021. Rat Creek: a large washout generated by an atmospheric river in California. Available at: blogs.agu.org/landslideblog/2021/02/01/rat-creek-1.]

no. 8 Human activities are influencing flash flood characteristics and landscape dynamics

Increasingly, many flash flood processes and associated landform/landscape developments are influenced by human activities, either deliberately or inadvertently. More and more evidence is accumulating to enable global climate change and changes in hydrological extremes – river floods and droughts included – to be attributed to human activities, specifically the release of atmospheric greenhouse gases that are leading to atmospheric warming (key point 7). Many other human activities may have a more direct, deliberate influence on dryland rivers, particularly dam and reservoir construction, and flow abstraction, flow diversion or inter-catchment water transfer schemes that tend to alter natural flood regimes. In dryland rivers, these changes can decrease the number of large floods (e.g. dams that absorb flash floods and so buffer downstream reaches from their effects) but increase the number or small or moderate floods (e.g. as a result of deliberate flow releases from dams to supply downstream irrigation). Other human activities can either suppress natural rates of change (e.g. river bank protection works – Figure 19a) or enhance natural rates of change (e.g. encouraging river meander cutoffs as part of channel straightening projects). Human activities may also have an indirect, inadvertent influence on natural dryland catchment processes, such as through vegetation clearance and conversion to agricultural land that increases hillslope runoff and sediment supply, or through translocations of plants and animals that influence hillslope and channel processes, such as some exotic (non-native) trees that become invasive (Figure 19b). In urban areas, increased coverage of concreted or tarmacked surfaces restricts the amount of rainfall that can soak into the ground, which encourages surface runoff into drains and so speeds the rate at which rainfall is transferred to river channels. Many of these runoff and sediment supply changes are associated with water quality changes, including an increased supply of agricultural chemicals such as nitrates and phosphates, sewage, and other water-associated contaminants.

Figure 19

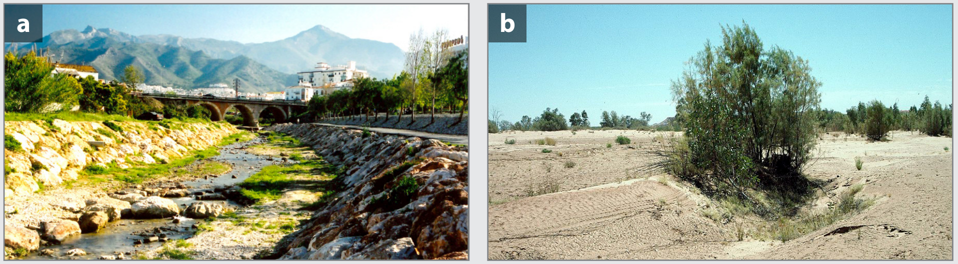


Figure 19. Examples of human-influenced dryland channels: **a**) ephemeral channel in Nerja, Spain, artificially lined with large boulders to prevent bank erosion during flash floods. Flow direction during floods is towards the camera; **b**) example of an invasive athel pine (*Tamarix aphylla*) in the middle Finke River, central Australia, showing scour around the flanks and deposition on the downstream side (flood flow direction is towards the lower left). This exotic species originated from shade plants grown at settlements along the river, and their seeds were dispersed downstream during floods. Although this is an isolated specimen, other reaches of the river have been infested with dense stands of the athel pine, leading to displacement of the native river red gums (*Eucalyptus camaldulensis*). These vegetation changes have resulted in alterations to downstream flow and sediment transport, and changes to local channel dynamics (Photographs: Stephen Tooth).

These sorts of physical and chemical changes to the hydrology of dryland catchments are now so widespread and so profound that very few — if any — moderate or large dryland rivers worldwide (i.e. rivers with lengths over 50 km) are likely to be unaffected. Changes to river flood regimes and water quality have dramatic knock-on implications for dryland river aquatic ecology, the impacts of which may be less visible but no less profound. Changes may be to the benefit of a few species (e.g. phragmites reeds that exploit increased nutrient supply in runoff from agricultural land) but commonly are to the detriment of many other species and overall ecosystem diversity and function. Displacement of the native eucalyptus trees by athel pine along the middle Finke River (Figure 19b), for instance, has resulted in lower vegetation diversity, and reductions in the numbers of native birds and reptiles. In the Front Range, Colorado, USA, geomorphologist Ellen Wohl has referred to 'virtual rivers' as those that have the appearance of natural rivers but have lost much of their natural ecosystem functions. Increasingly, the term 'virtual river' could also be applied to many dryland rivers worldwide.

DID YOU KNOW?

In many drylands, human settlements are increasingly expanding into mountain front areas and creating hazards related to the conveyance of flood water and sediment. Few studies have focused on the effects of urbanization on dryland rivers, however, especially in steep terrains. Development of the town of Fountain Hills, located in the foothills of the McDowell Mountains in the Sonoran Desert in Arizona, southwest USA, provides an example of ephemeral dryland channels (locally termed 'washes') adjusting to urbanisation over several decades. From the 1970s onwards, urbanisation has introduced numerous impervious roads that have been built directly across channels (dip crossings) and so slope from the channel banks toward the channel centre. Consequently, the dip crossings commonly deliver large volumes of stormwater during heavy rains and also fragment the channels into segments, effects which cause management challenges. Field surveys in 1987, 2006, and 2016 showed that the ephemeral channels in urban areas are now up to three times wider and up to ten times larger than comparable natural channels. The roads have exerted a spatial pattern of geomorphic influence, with some deposition occurring upstream of dip crossings and erosion occurring downstream as a result of urban drainage inputs, so the channels downstream of dip crossings are narrower and deeper than those upstream. Nevertheless, repeat measurements show that the pattern of deposition upstream and incision downstream of dip crossings has become less evident over time. The muted response by 2016 resulted from evolving management practices that have improved the conveyance of flood water and sediment, including stormwater controls and erosion protection. Furthermore, comparison of channel changes at dip crossings with channel changes at crossings with culverts under the road reveals less impact at the latter. The more limited morphological changes at pipe or box culverted crossings suggests more effective throughput of water and sediment. These results demonstrate successful adaptive management strategies, including decisions to install culverts in recent developments. The still developing Fountain Hills landscape may provide insights that can be applied to other dryland mountain fronts undergoing urban expansion in response to population pressures. [**Source:** Chin, A., Gidley, R., Tyner, L. and Gregory, K.J. 2017. Adjustment of dryland stream channels over four decades of urbanization. Anthropocene, 20: 24-36.]

no. 9 Many landscapes are becoming more susceptible to hazardous flash floods

Both global environmental change and human activities are increasing the magnitude and frequency of hazardous flash floods, which is impacting on land surface stability and leading to adverse socio-economic impacts. Flood and drought hazards have been a threat throughout human history, but mounting evidence suggests that atmospheric warming may be associated with increases in the magnitude and frequency of weather and associated hydrological extremes, including river flooding and drought (key point 7). Other human activities are also changing the nature of hydrological extremes, such as through dam and reservoir construction (key point 8). Many dams have been built in dryland catchments with the purposes of controlling floods and regulating flow for agricultural, domestic and industrial supply, and arguably have been successful. But this success may come with a long-term cost to river ecosystem health (key point 8) and ironically may also have increased exposure to flash flood hazards in some cases.

For example, owing to the sense of security from hazardous floods engendered by dam building, many humans now live in greater densities in areas that historically would have flooded more frequently (e.g. river floodplains). At the same time, many channels downstream of dams have shrunk in size as a consequence of the reduced frequency of erosive floods and/or owing to encroachment from sediment-trapping vegetation that has established in response to the more reliable lower flows (Figure 20). In many cases, water quality has also declined dramatically within and below dams; for example, in drylands with high evaporative demands and return flows from irrigated areas, chemicals such as nitrates and phosphates can reach very high concentrations. These changes increase hazard exposure in several ways. First, houses and infrastructure downstream of the dams are at risk of catastrophic flooding in the event of dam failure, deliberate dam releases that become necessary for dam safety, or if dam overtopping occurs during the highest magnitude rainfall-runoff events. Second, the smaller channels downstream of the dams are more prone to overtopping during flash floods generated in tributaries that enter the main river downstream of the dam. Third, during flash floods, people are exposed to poor quality water, a situation made worse if sewage systems are affected and further contaminate the floodwaters. A lack of appreciation for these human influences on dryland river hydrology and geomorphology, coupled with pressure on building space and poor planning controls, in many cases is leading to increased susceptibility to hazardous flash floods downstream of dams. The consequences may be damage to housing and infrastructure, social dislocation, and even loss of life.

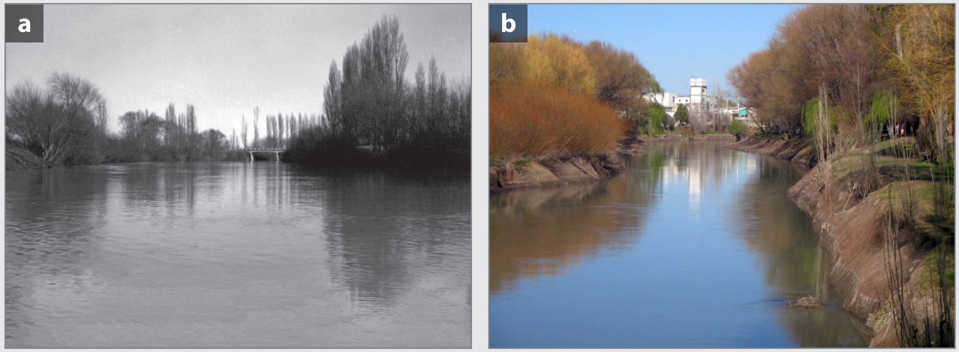


Figure 20

Figure 20. Comparative photographs illustrating shrinkage of the lower Rio Chubut below the Florentino Ameghino dam, eastern Patagonia, Argentina: **a**) view from the center of the channel looking upstream from the gauging section located downstream of the Gaiman bridge in 1946; **b**) same reach in 2007. Both photographs were taken in September but flow discharge is notably different. The average flow in September in 1946 was 144.8 m^3/s but in 2007 was only 18.1 m^3/s. [**Source:** Kaless, G., Matamala, F., Monteros, B. and Greco, W. 2015. Cambios hidrológicos y morfológicos en el Río Chubut aguas abajo de la presa Florentino Ameghino, Proceedings of the V Congreso Argentino de Presas y Aprovechamientos Hidroeléctricos, San Miguel de Tucumán, 2008; older photograph from Pronsato, A.D. 1950. Estudio Geohidrológico del Río Chubut. Parte II. Dirección General de Agua y Energía Eléctrica. Revista Agua y Energía. Año IV. No. 29.]

DID YOU KNOW?

Even in catchments without dams, many landscapes are becoming increasingly susceptibility to hazardous flash floods. The city of Comodoro Rivadavia in Chubut Province, southeastern Argentina, illustrates how a lack of planning at the catchment scale contributed to the environmental and societal impacts of extreme rainfall and flooding in 2017. The city is crossed by seven small, steep, ungauged ephemeral rivers that ultimately flow into into the Atlantic Ocean. In late March to early April, persistent and heavy rainfall totalled nearly 400 mm, and the associated hillslope runoff and river flooding resulted in major erosional and depositional changes, including gully formation, channel widening and aggradation, and coastal delta progradation. Severe damage to urban and industrial infrastructure resulted, including loss of housing, contamination of drinking water supplies, and disruption to electricity and telephone services. The flood impacts were made worse by the reduced catchment vegetation and increased area of impervious surfaces resulting from urban and industrial developments, human alterations of channel shape, and additional coarse-grained sediment supply that was derived from roads, oil well locations and aggregate quarries. Impacts were also heightened as a consequence of uncontrolled, disorganised urban growth that had enabled housing developments to take place in low-lying, flat zones with a natural flooding risk (including enclosed basins and even some low-order channels), and the many under-sized human-made waterways within the city that become blocked during the floods. The situation in Comodoro Rivadavia is not unique, with many urban areas in Argentina and other dryland countries demonstrating increased susceptibility to hazardous flash floods as a consequence of poor planning controls. [**Source:** Paredes, J.M., Ocampo, S.M., Foix, N., Olazábal, S.X., Valle, M.N., Montes, A., Allard, J.O. 2021. Geomorphic and sedimentological impact of the 2017 flash flood event in the city of Comodoro Rivadavia (central Patagonia, Argentina). In: Bouza, P., Rabassa, J. and Bilmes, A. (Eds), Advances in Geomorphology and Quaternary Studies in Argentina. Springer Earth, pp.3-29.]

no. 10

Successful flash flood management needs geomorphological knowledge

Geomorphology can provide a key input to flash flood management, including by raising awareness of the importance of wetland conservation, restoration and construction. Many flood-prone dryland river landforms and landscapes may be conserved for their own intrinsic beauty or rarity, including many in national parks. Examples of the latter include Death Valley National Park in the USA, Augrabies Falls National Park in South Africa, and Finke River Gorge National Park in central Australia (Figure 21); these are all places where dryland river landscapes are the main drawcard for tourists. Within these and other dryland landscapes, river processes and landforms provide the template upon which many ecological processes and patterns are developed; drainage networks commonly support greater densities of vegetation (Figure 22), and at a smaller scale, many channels and floodplains typically exhibit a zonation of plants and animals that reflects differences in the frequency, depth and duration of flooding. Embedding greater awareness of role of flash floods in shaping landscapes and ecosystems in tourist documentation and related educational activities may help to encourage a change in perceptions of flash floods, with emphasis not just on the negatives (e.g. danger to life) but also their beneficial aspects.

Figure 21

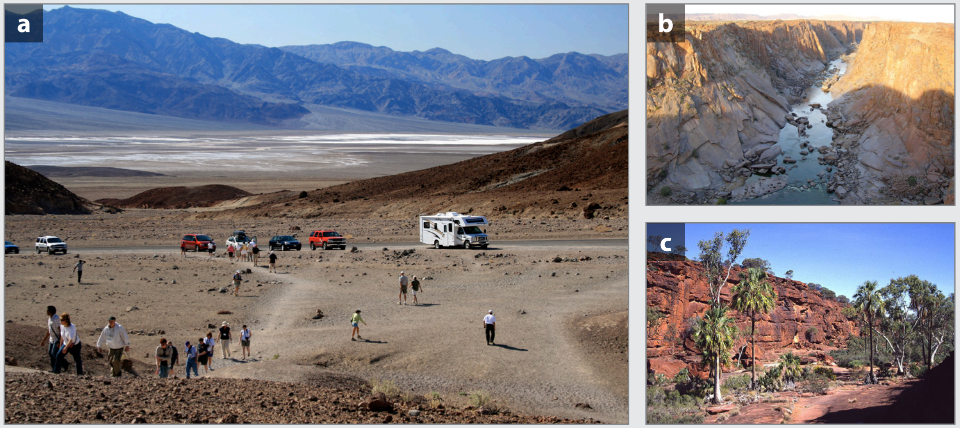


Figure 21. Examples of national parks worldwide that have flash flood-influenced landforms and landscapes as their centrepieces: **a**) Death Valley National Park, California-Nevada border, USA; **b**) Augrabies Falls National Park, northwestern South Africa. The view is looking up the Orange River gorge towards the main waterfall (not in view); **c**) Palm Valley in Finke Gorge National Park, central Australia. Palm Valley is home to many rare, unique plant species, including the Red Cabbage Palm (*Livistona mariae*) shown here (Photographs: Stephen Tooth).

More generally, the importance of ephemeral and intermittent rivers for the health of larger drainage networks is now increasingly recognised, particularly in terms of nutrient cycling. There is also increased awareness that healthy dryland aquatic and semi-aquatic ecosystems can help with flash flood management, enabling a shift away from an overreliance on structural approaches to flood management (e.g. hard engineering options such as dams and concrete bank protection) to less costly, non-structural, more sustainable alternatives. These approaches – commonly termed 'green engineering' or 'blue-green infrastructure' – include making use of wetlands to buffer downstream reaches from flash floods, and making more space for floodwaters by improved land-use zoning to prevent housing and industrial developments taking place in flood-prone locations. In short, these approaches can help transform floods from short events with high peak discharges (erosive flash floods) to longer events with lower peak discharges (less erosive, less flashier floods) (Figure 2 and Information Box 7). An understanding of dryland river geomorphology, including the role of flash floods in shaping landforms and landscapes, can help with restoration planning for degraded channel, floodplain and associated wetlands, as well as conservation strategies for more pristine systems. In decades to come, geomorphology is also likely to play an increasingly important role in active landscaping for management of hydrological extremes and other aspects of ecosystem service delivery, including through greater construction of artificial wetlands (Figure 23).

Figure 22

Figure 22. Aerial view of a drainage network in central Australia, showing how the channels support greater vegetation densities than the surrounding hillslopes (Photograph: Stephen Tooth).

Figure 23

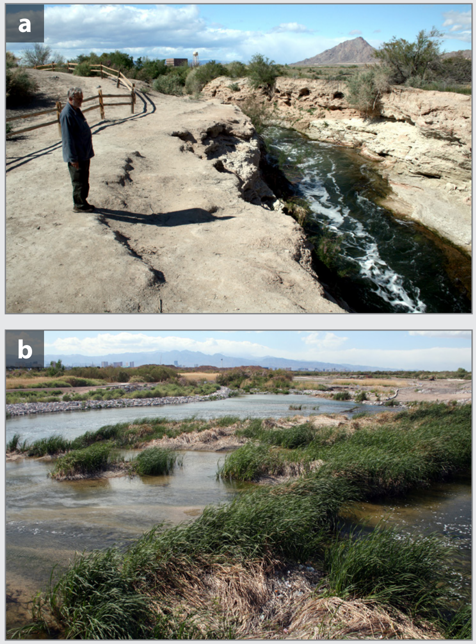
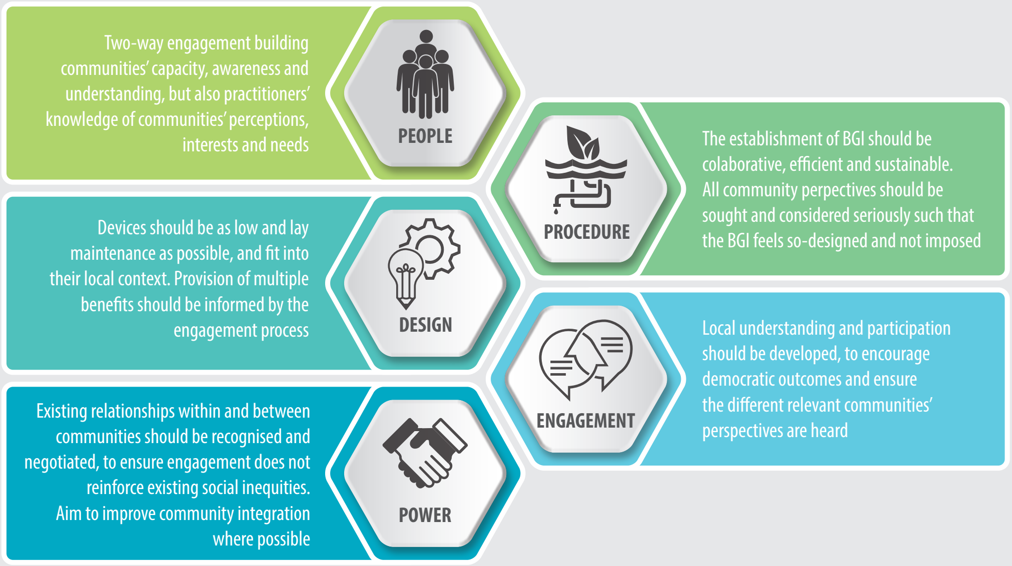


Figure 23. Example illustrating the use of constructed wetlands to manage flash floods: **a**) the Las Vegas Wash (view looking upstream) showing the deep (4-5 m) erosion resulting from flash floods in the 1980s and 1990s; **b**) subsequent design and construction of The Wetlands Park Nature Preserve adjacent to the Wash was partly in response to the impacts of this particular geohazard and consists of a series of constructed wetlands that are being actively managed using surface runoff, reclaimed water, and water level control structures. The streams, ponds and plants help restrict erosion and provide habitat for wildlife, while trails and overlooks provide nature viewing and other recreational opportunities. High rise buildings along The Strip in Las Vegas are visible in the far distance (Photographs: Stephen Tooth).

Alongside other specialist disciplinary knowledge, skills and perspectives, geomorphology can thus provide an input to successful flash flood management (Figure 1). Of importance for the success of many schemes, however, is input from other groups and individuals, including local communities, environmental managers and policymakers. Studies in the United Kingdom, for instance, have argued that in order to maximise the function and multiple benefits of blue-green infrastructure in urban flood projects, community engagement may need to be more developed and longer-term than other engagement efforts around hard engineering approaches, and should encompass the entire life of installations. Figure 24 illustrates some key principles that could encourage a greater sense of community ownership, appreciation, and care in blue-green infrastructure projects for developing urban flood resilience. These principles could apply both in humid and dryland urban settings.

Figure 24



PEOPLE

Two-way engagement building communities' capacity, awareness and understanding, but also practitioners' knowledge of communities' perceptions, interests and needs

PROCEDURE

The establishment of BGI should be colaborative, efficient and sustainable. All community perpectives should be sought and considered seriously such that the BGI feels so-designed and not imposed

DESIGN

Devices should be as low and lay maintenance as possible, and fit into their local context. Provision of multiple benefits should be informed by the engagement process

ENGAGEMENT

Local understanding and participation should be developed, to encourage democratic outcomes and ensure the different relevant communities' perspectives are heard

POWER

Existing relationships within and between communities should be recognised and negotiated, to ensure engagement does not reinforce existing social inequities. Aim to improve community integration where possible

Figure 24. Some fundamental guiding principles for more effective community engagement in blue-green infrastructure (BGI) projects. [**Source:** adapted from Urban Flood Resilience Research Consortium, 2019. Achieving Urban Flood Resilience in an Uncertain Future: Key Project Outputs. Available at: www.urbanfloodresilience.ac.uk]

DID YOU KNOW?

The Las Vegas Wash (Figure 23) is a dryland river that drains past one of the USA's fastest growing cities, typically conveying 150 million US gallons (567 million litres) of water per day, including urban runoff, reclaimed water, shallow groundwater and natural thunderstorm runoff. In the 1980s and 1990s, major flash floods caused severe erosion along the Wash and its associated wetlands, causing damage to wildlife habitat and threatening homes. At downstream Lake Mead, sediment deposition led to the formation of a delta, forcing relocation of the marina at Las Vegas Bay. In one flash flood in 1999, 4.5 billion US gallons (17 billion litres) of water surged along the Wash in a 24 hour period, providing enough water to fill an Olympic-size swimming pool roughly every 3.5 seconds. Subsequent engineering and construction of The Wetlands Park Nature Preserve (Figure 23) was partly in response to acknowledgement of the need to manage these flash floods, and was achieved using funds from a state wildlife bond. [**Source:** information from Parks and Recreation, Clark County, Nevada.]

Are there any examples of flash flood stories in the media?

Flash flood events regularly feature in online media articles. Understandably, rather than focusing on the causes or processes of flash floods, the emphasis is usually on the damage to housing and infrastructure, social disruption, or loss of life. A recent selection from the BBC News website (2015 onwards) highlights how flash floods impact many areas worldwide, including drylands:

‘Australia warned of 'life-threatening' flash floods’
(20th March 2021): www.bbc.co.uk/news/world-australia-56466310

‘Deadly flash floods tear through Bolivia’s Sucre city’
(5th January 2021): www.bbc.co.uk/news/world-latin-america-55545348

‘Storm Alex: Deadly flash floods hit France and Italy’
(5th October 2020): www.bbc.co.uk/news/world-europe-54417223

‘Afghanistan flash floods kill dozens and destroy 500 homes’
(26th August 2020): www.bbc.co.uk/news/world-asia-53918137

‘Aberystwyth hit by flash flooding after thunderstorm’
(10th August 2020): www.bbc.co.uk/news/av/uk-wales-53728201

‘New Zealand flash floods leave tourists stranded’
(4th February 2020): www.bbc.co.uk/news/av/world-asia-51380141

‘Indonesia flash flood sweeps away entire longhouse’
(25th January 2019): www.bbc.co.uk/news/av/world-asia-46998988

‘Jordan flash floods: Eleven killed and tourists evacuated from Petra’
(10th November 2018): www.bbc.co.uk/news/world-middle-east-46161276

‘Jordan flash floods: School bus swept away near Dead Sea’
(25th October 2018): www.bbc.co.uk/news/world-middle-east-45983337

‘Majorca flash flood kills at least 10 on Spanish island’
(10th October 2018): www.bbc.co.uk/news/world-europe-45807978

‘Corsica flash flood kills five in French canyoning group’
(2nd August 2018): www.bbc.co.uk/news/world-europe-45043778

‘Israel flash flood: Nine teenaged hikers dead in south’
(26th April 2018): www.bbc.co.uk/news/world-middle-east-43912019

‘Vietnam flash floods and landslides kill dozens’
(12th October 2017): www.bbc.co.uk/news/world-asia-41591784

‘Arizona flash flood: Nine dead as deluge hits swimmers’
(17th July 2017): www.bbc.co.uk/news/world-us-canada-40627025

‘India rail crash: Trains derail in Madhya Pradesh flash flood’
(5th August 2015): www.bbc.co.uk/news/world-asia-india-33783060

‘Two dead as flash flooding hits Chile Atacama desert region’
(26th March 2015): www.bbc.com/news/world-latin-america-32062039

Where can I go for further information?

The British Society for Geomorphology (BSG) is a professional organisation for geomorphologists and provides a community and services for those involved in teaching or research in geomorphology, both in the UK and overseas.

BSG British Society for Geomorphology

(**www.geomorphology.org.uk**).

This booklet is based on an adaptation of the BSG-sponsored booklet entitled '10 Reasons why Geomorphology is Important', which has been translated into several languages including Welsh, Persian and Spanish (**www.geomorphology.org.uk/what-geomorphology**).

The Society's flagship international journal, Earth Surface Processes and Landforms (**www.onlinelibrary.wiley.com/journal/10969837**), is published by Wiley-Blackwell and online access is available free to members **(www.geomorphology.org.uk/publications/earth-surface-processes-and-landforms)**. For non-members, many articles are also open access, including some related to flash floods.

What would you recommend as further introductory reading?

Many specialist dryland geomorphology textbooks include information on flash floods, including their hydrological and sediment transport characteristics, most commonly as part of wider treatments of dryland river processes and forms. Examples include:

Powell, D.M. 2009. Dryland rivers: processes and forms. In: **Parsons, A.J.**, **Abrahams, A.D.** (Eds), Geomorphology of Desert Environments (2nd edition). London: Springer, pp. 333–373.

Reid, I. and Frostick, L.E. (2011). Channel form, flows and sediments of endogenous ephemeral rivers in deserts. In: **Thomas, D.S.G.** (Ed.), Arid Zone Geomorphology: Process, Form and Change in Drylands (3rd edition). Chichester: Wiley, pp. 301-332.

Tooth, S. and **Nanson, G. C.** (2011). Distinctiveness and diversity of arid zone rivers. In: **Thomas, D.S.G.** (Ed.), Arid Zone Geomorphology: Process, Form and Change in Drylands (3rd edition). Chichester: Wiley, pp. 269–300.

Examples of studies of individual flash floods, including desert flood bores, are:

Hassan, M.A. 1990. Observations of desert flood bores. Earth Surface Processes and Landforms, 15: 481-485.

Schick, A.P. and **Lekach, J.** 1987. A high-magnitude flood in the Sinai Desert. In: **Mayer, L.** and **Nash, D.** (Eds), Catastrophic Flooding. Binghamton Symposium in Geomorphology, Vol. 18. London: Allen and Unwin, pp. 381-410.

Walters, M.O. 1989. A unique flood event in an arid zone. Hydrological Processes, 3: 15-14.

The following book (featured in Figure 4b) considers flash floods as part of the wider management of Namibia's ephemeral rivers and the associated water resources:

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

More popular accounts of drylands and deserts commonly provide anecdotal accounts of flash floods including:

Welland, M. 2015. The Desert: Lands of Lost Borders. London: Reaktion Books.

This book compiles statistics and descriptions of some notable flash floods, including the drowning of the famed writer Isabelle Eberhardt in a Saharan flash flood in 1904.

And what about online resources?

Google Earth is an invaluable resource for exploring dryland rivers and the wider landscape. Other online sources offer abundant video footage of floods in dryland rivers. For instance, a search on 'flash flood' in YouTube brings up many contrasting examples, ranging from high energy flash floods in upland and piedmont settings to lower energy floods in desert lowlands:

Flash Flood in Zion National Park, southwest USA
www.youtube.com/watch?v=W3akkSEGFhI

Flood Water in Vadi Fija, Saudi Arabia
www.youtube.com/watch?v=hi8D_jz31ls

Floodwaters entering Kati Thanda-Lake Eyre, central Australia
www.youtube.com/watch?v=F1_JUITOLHI

————————————

A search on 'flash flood' on the United States Geological Survey (USGS) webpages (www.usgs.gov) also provides much useful information, including video footage, downloadable educational material, and links to scientific reports and publications about flash floods. For example, slider imagery reveals the extent of flash flooding in Kandahar, Afghanistan, in March 2019:

www.usgs.gov/media/before-after/flash-floods-soak-kandahar

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Vignettes: Key Concepts in Geomorphology
www.serc.carleton.edu/vignettes/index.html

These Vignettes are stand-alone electronic case studies that teach about geomorphology and related topics. A word search on 'flash flood' will reveal case studies that illustrate the importance of flash floods in dryland river developmental histories, e.g.:

When streams unravel: the tale of Plum Creek, CO
serc.carleton.edu/68948

Floodplain formation and environmental change in the Cape region, South Africa
serc.carleton.edu/31996

Arroyo cutting in the southwestern U.S.
serc.carleton.edu/39736

Stream response to climate change, Atacama Desert, Chile
serc.carleton.edu/41078

Influence of dam operations on geomorphology and sediment in the Colorado River corridor, Grand Canyon National Park, Arizona
serc.carleton.edu/68946

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Virtual reality simulations increasingly are being used to demonstrate the characteristics of flash floods, warn people of the dangers, and provide advice on what to do in a flood emergency. Examples from more humid regions include:

The Weather Channel
www.youtube.com/watch?v=PvJuocemHS4

SeriousGeoGames
seriousgeogames.wpcomstaging.com/activities/flash-flood

Use of the SeriousGeoGames 'Flash Flood!' activity to engage the public is described in the following article:

Skinner, C. 2020. Flash Flood!: a SeriousGeoGames activity combining science festivals, video games, and virtual reality with research data for communicating flood risk and geomorphology. Geoscience Communication, 3: 1–17.

10 points that everyone should know about

Flash Floods

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