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Stormy geomorphology: geomorphic contributions in an age of climate extremes

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ABSTRACT: The increasing frequency and/or severity of extreme climate events are becoming increasingly apparent over multi-decadal timescales at the global scale, albeit with relatively low scientific confidence. At the regional scale, scientific confidence in the future trends of extreme event likelihood is stronger, although the trends are spatially variable. Confidence in these extreme climate risks is muddied by the confounding effects of internal landscape system dynamics and external forcing factors such as changes in land use and river and coastal engineering. Geomorphology is a critical discipline in disentangling climate change impacts from other controlling factors, thereby contributing to debates over societal adaptation to extreme events. We review four main geomorphic contributions to flood and storm science. First, we show how palaeogeomorphological and current process studies can extend the historical flood record while also unraveling the complex interactions between internal geomorphic dynamics, human impacts and changes in climate regimes. A key outcome will be improved quantification of flood probabilities and the hazard dimension of flood risk. Second, we present evidence showing how antecedent geomorphological and climate parameters can alter the risk and magnitude of landscape change caused by extreme events. Third, we show that geomorphic processes can both mediate and increase the geomorphological impacts of extreme events, influencing societal risk. Fourthly, we show the potential of managing flood and storm risk through the geomorphic system, both near-term (next 50 years) and longer-term. We recommend that key methods of managing flooding and erosion will be more effective if risk assessments include palaeodata, if geomorphological science is used to underpin nature-based management approaches, and if land-use management addresses changes in geomorphic process regimes that extreme events can trigger. We argue that adopting geomorphologically-grounded adaptation strategies will enable society to develop more resilient, less vulnerable socio-geomorphological systems fit for an age of climate extremes. © 2016 The Authors. Earth Surface Processes and Landforms published by John Wiley & Sons Ltd.

KEYWORDS: climate extreme; socio-geomorphological; palaeodata; extreme event; flood; storm

Introduction

The Intergovernmental Panel on Climate Change's (IPCC's) Fifth Assessment Report (AR5) concludes that many areas of the globe are already experiencing an increase in the frequency of extreme climate events (Table I) such as windstorms, floods and rainfall (e.g. extreme rainfall; Hartmann *et al.*, 2013) with some regions more affected than others (Christensen et al., 2013). Thus, according to the IPCC's AR5 (Stocker *et al.*, 2013), recent measured global increases in extreme rainfall events have strong 'global confidence' [that is they are *likely* to be attributable to anthropogenic climate change (Hartmann *et al.*, 2013)], even if confidence about long-term (centennial) global changes in the incidence of extreme rainfall, flooding, tropical cyclones and storminess is low (Hartmann *et al.*, 2013; Bindoff *et al.*, 2013). This low global confidence masks regional trends where evidence of increasing intensity of extreme climate events is 'virtually certain'. For instance, the increase in the frequency and strength of tropical cyclones in the North Atlantic since the 1970s appears to be clear

Table I. Outline of the Intergovernmental Panel on Climate Change (IPCC) definitions of extreme climate events and extreme weather events, and how we refer to these in this paper.

Topic	Explanation	Reference
IPPC Definitions	The IPCC glossary makes no distinction between extreme climate events and extreme weather events, as follows:	IPCC, 2013. Annex III, p. 1454.
Extreme Climate Event	"See *Extreme weather event*."	
Extreme Weather Event	It defines an extreme weather event as "an event that is rare at a particular place and time of year. Definitions of rare vary, but an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile of a probability density function estimated from observations. By definition, the characteristics of what is called extreme weather may vary from place to place in an absolute sense. At present, single extreme events cannot generally be directly attributed to anthropogenic influence. When a pattern of extreme weather persists for some time, such as a season, it may be classed as an extreme climate event, especially if it yields an average or total that is itself extreme (e.g. drought or heavy rainfall over a season)."	
Extreme climate and weather in this paper	In this paper we refer to both less persistent extreme weather events and to extreme climate events (as defined by the IPCC); we also confine the type of events covered in this paper to extreme hydrological, storm wave, and meteorological events.	See reference to both terms in the paper.

(Hartmann *et al.*, 2013; Horton and Liu, 2014); and although the processes driving these trends are still being attributed, they show that increases in extreme precipitation and temperature can be expected to impact river flood frequency and severity in Europe, driven by Arctic amplification of the jet stream (Francis and Vavrus, 2012, 2015; Screen and Simmonds, 2014). The increasing intensity of typhoons in East Asia (Oey and Chao, 2016) and the northwest Pacific Ocean (Mei *et al.*, 2015) over recent decades also seem to be definitive. In the future, predictions for increased El Niño severity associated with sea-level rise may lead to changes in the frequency and intensity of extreme coastal flood events in Latin America (Reguero *et al.*, 2015). It has been argued that future Arctic river flooding will be driven by changes in extreme rainfall (Crossman *et al.*, 2014); and increased extreme flood hazard is predicted for California (Dettinger, 2011). Climatologically, the north-eastern United States has experienced an increase of 71% in the magnitude of extreme (1%) precipitation events since 1960 (Melillo *et al.*, 2014), which is reflected in recent hydrological assessments showing shifts in streamflow under both moderate magnitude flows (e.g. bankfull) as well as for extreme events (Armstrong *et al.*, 2012, 2014; Collins *et al.*, 2014), with concomitant increases in soil saturation (Yellen *et al.*, 2016) ultimately altering regional boundary conditions. The profound social and economic impacts of these regional extreme events are increasingly felt. For instance, despite the concerted efforts of the US Army Corps of Engineers (USACE) to increase preparedness and reduce flood risk damages to society from extreme events, the human impacts and economic costs of extreme events have continued to rise in the United States. For example, recent world climate and health data (Bell *et al.*, 2016) has identified hurricanes and floods as the third and fourth most deadly hazards in the United States between 2003–2014 and the first and fifth most costly, respectively. The rise in social and economic damages associated with extreme events is not a proxy for flood risk (Pielke, 1999); instead it is symptomatic of population growth, planning rules that allow increasing numbers of people to live in hazard-prone environments (Pielke, 2014), and growing wealth (Pielke *et al.*, 2008; Lane, 2012). Recent extreme storms and their effects on society are increasingly used to recommend changes in policy such as building on floodplains (e.g. Committee on Climate Change, 2016).

Two primary influences probably explain why these regional changes are not manifest at the global level: (1) lack of available data at sufficient spatial and temporal resolution at the global scale (see Donat *et al.*, 2016, for an exception); and (2) the confounding effects of changes in land use and river and coastal engineering over time that make it extremely difficult to disentangle climate change impacts from other controlling factors. Overall, predicted future climate change impacts are regionally variable and differ in confidence between extreme event types (e.g. windstorms versus floods) at a regional scale.

Notwithstanding these uncertainties in the precise nature of future global trends of extreme event likelihood, it is imperative that geomorphology explores the changes in process regimes and landscape responses in a world of potentially greater weather and climate extremes. More specifically, a geomorphic contribution can: (i) provide field evidence of long-term (i.e. century to millennial) changes to the landscape in response to extreme weather and climate events; (ii) improve our understanding of the changes in geomorphic risks and vulnerabilities to landscapes and society that such extremes may bring; and (iii) support those geomorphologically-grounded adaptive strategies that might be deployed to lessen such risks and vulnerabilities where they infringe on human society. Geomorphologists have been relatively reticent regarding possible climate change impacts on geomorphic processes (Lane, 2013) despite the knowledge that they have (Macklin *et al.*, 2012b) and will continue to respond to climate forcing. These landscape changes may either accentuate or dampen many of the climate change impacts that society will experience in the near future. The aim of this paper is to describe the bi-directional research focus that is needed to address these challenges: first, the geomorphic impacts of extreme flood and storm events need greater saliency regarding the effects of future climate change on earth surface processes; and secondly, we urgently need research that can better understand the impacts of extreme events at the landscape scale – Slaymaker *et al.* (2009) defined landscape as 'an intermediate scale region, comprising landforms and landform assemblages, ecosystems and anthropogenically-modified land'. This scaleis very relevant to human lives and livelihoods (Schaller *et al.*, 2016). We achieve this aim through considering four dimensions.

First, our instrumental record remains short (typically <50 years in length) and spatially discontinuous (strongly biased towards the anthropogenically-modified landscapes of the 'global north'). From these data it is not possible to discern whether extreme storms and flooding experienced lately actually represents an increase over the past few 100 to 1000 years. We first need to know definitively if we are living in a world where extreme hydroclimatic events are increasing relative to past frequency – a global database of extreme palaeofloods and palaeostorms could help us answer this critical question. Geomorphologists can identify and measure whether past extreme hydroclimate events have had a substantive geomorphic impact. Such data are crucial for reconstructing past geomorphological process regimes and in identifying the type and magnitude of extreme events that have triggered substantive landscape scale change (e.g. Benito *et al.*, 2015a; Archer *et al.*, 2016). The next section shows how geomorphic evidence from past century to millennial timescales can usefully augment available instrumental records of extreme hydroclimatic events and the effects of these on landscape change. These data provide an important historical context for process measurements in, and the modelling of, contemporary and future landscapes. Conventional hydrological approaches to flood hazard estimation could be improved. Such work also extends record length so facilitating easier unravelling of the complex interactions that create non-linear, threshold-driven responses to environmental perturbations.

Second, geomorphological systems are often highly responsive to both external dynamics (both climatic and non-climatic) and to internal forcing factors (e.g. internal saltmarsh dynamics affecting saltmarsh margins). The combination of slow gradual change coupled with high magnitude, low frequency events has led to dramatic landscape responses throughout the Earth's history. These responses include the reshaping of coastal and riverine morphologies (e.g. Milan, 2012; Foulds and Macklin, 2016), the altering of sediment dynamics (Sargood *et al.*, 2015), the creation of landform instability (Van De Koppel *et al.*, 2005; Keiler *et al.*, 2010) and wholescale changes in catchment characteristics (e.g. Lane *et al.*, 2016). It is increasingly recognized that the effects of these antecedent geomorphic conditions, especially when coupled with climate extremes, are key parameters influencing the geomorphological impacts of extreme events (e.g. Yellen *et al.*, 2016). Geomorphologically-controlled patterns of catchment soil hydrology and drainage network organization have long been recognized as influences on runoff generation and routing (Anderson and Burt, 1978) and hence flood generation. Yet, alongside these traditional catchment hydrological controls, there is a growing appreciation that flood inundation is a direct function of geomorphic contexts, such as in-river sedimentation (e.g. Lane *et al.*, 2007; Slater *et al.*, 2015; Rickenmann *et al.*, 2016; Slater, 2016) and coastal topography (Spencer *et al.*, 2015a). The third section examines these issues for catchments, fluvial and coastal systems and outlines ways to better incorporate antecedent conditions into analyses, models and management tools.

Third, there is tremendous variability in the response of different geomorphic processes to extreme events. Whilst nearly all geomorphic process regimes will respond to extreme climatological and tectonic events, some systems are more at risk of a threshold-induced change in system state. Lenton (2013) has argued that these threshold-induced landscape changes are environmental tipping points, where an infrequent, short-term (typically extreme) event triggers a shift in landscape state (e.g. Croke *et al.*, 2016). However, other landscapes may be more resistant to climatic shocks (e.g. hard rock cliffs compared with soft cliffs) or are more resilient, through rapid recovery of landscape form and function following disturbance (Phillips, 2014; Phillips and van Dyke, 2016). Even apparently sensitive landscapes may display negative as well as positive feedbacks (e.g. Lane *et al.*, 2016) such that they can partially absorb the impacts of rapid climate change. Thus different geomorphic systems will respond differently to the same magnitude of forcing and the same geomorphic system may itself respond differently, depending on its condition at the time of the forcing. Over time, this response can lead to widely different outcomes depending on the chronology of events (e.g. Southgate, 1995; Mumby *et al.*, 2011). Alternative landscape states can result; these vary and change through space and time as geomorphic processes respond to extreme events (Phillips, 2014; Phillips and van Dyke, 2016). A key challenge is therefore to evaluate the effects of extreme events on geomorphological processes in the context of the interdependencies between internal, non-climate and climate-related controls on geomorphic processes. We explore these issues in the fourth section, assessing how we need to rethink magnitude and frequency in an age of weather and climate extremes.

The fourth dimension we address is the contribution geomorphological science can make to understanding, predicting and managing the impacts of extreme events on society (in the fifth section). We identify both shorter-term and future modelling interventions where geomorphological science can usefully aid our management and prediction of weather and climate extremes on geomorphological processes and societal impacts of these. We highlight the need for geomorphologists to work as part of larger, multidisciplinary scientific teams; and to work to capture and to explain the spatial and temporal variability in geomorphological responses to extreme events in more meaningful ways for practitioners.

The geomorphic evidence of changing storminess

Geomorphic science has proven to be a powerful means of reconstructing the magnitude, frequency and/or spatial extent of past extreme flood and storm events in both coastal and fluvial environments (e.g. Macklin *et al.*, 2012a). These reconstructions serve not only to decipher environmental change at catchment and regional scales, but when further combined with instrumented and stratigraphic records across regions, they can be used to reconstruct broader synoptic climatic changes over 10^2–10^5 year timescales (Ely *et al.*, 1992; Knox, 1975, 1985, 1993; Macklin *et al.*, 2006; Benito *et al.*, 2015a, 2015b, 2015c). This extended spatial and temporal record has the potential to improve significantly predicted event occurrence probabilities in flood and storm risk assessments (e.g. Foulds and Macklin, 2016) and to question the extent to which these probabilities are stationary. It is possible that the mean and variance of a flow series vary deterministically. This non-stationarity may ultimately undermine many of the fundamental design criteria of dams and other at-risk infrastructure (Milly *et al.*, 2008); so questioning the dominant role instrumentally based recurrence intervals play in flood risk management. The need to extend the range of data underpinning recurrence interval was saliently argued by Merz *et al.* (2014, p. 1928) '... even with a changing climate, from a meteorological/mechanistic perspective, the laws of physics which result in rain, snow and floods are time invariant. Non-stationarity is produced by changes of these processes in their frequency, magnitude, location, persistence, intensity, and clustering. These are … partially deterministic … . Hence the extreme events of the past are indeed important indicators of what the atmosphere-catchment system is capable of, given the right interplay of factors. They have left evidence in the landscape of the occurrence of a real event (not something emerging from modeling)'. Palaeogeomorphological data can provide this crucial evidence for improving flood risk recurrence calculations.

How has geomorphology been used to provide evidence of extreme flood and storm events?

Over the last 30 years, since the development of quantitative palaeohydrology (Kochel and Baker, 1982), reconstructions of flood and storm events (and periods) are now available over multi-decadal, centennial and millennial timescales for many parts of the world (see recent reviews by Jones *et al.*, 2010; Woodward *et al.*, 2010; Benito and O'Connor, 2013; Gregory *et al.* 2015). Recent developments in dating techniques (see review by Jones *et al.*, 2015), core scanning (Turner *et al.*, 2015) and sediment source attribution (Woodward *et al.*, 2015), have facilitated a step change in the range and quality of palaeoflood data. For example, *event-scale* flood and storm data extending back centuries (or millennia in some cases) are now available in a growing number of upland (e.g. Macklin and Rumsby, 2007; Foulds and Macklin, 2016) and lowland (River Severn, UK: Jones *et al.*, 2012; River Rhine, Germany: Toonen *et al.*, 2016) riverine, lacustrine (European Alps: Swierczynski *et al.*, 2013) and coastal environments (northwest Spain: Feal-Pérez *et al.*, 2014). Multi-centennial length Holocene flood-rich and flood-poor periods have also been identified, and precisely dated, in Europe and North Africa (Benito *et al.*, 2015b), the American southwest (Harden *et al.*, 2010) and on an interhemispheric basis (Macklin *et al.*, 2012a). Meta-analysis techniques underpin this research by relating large carbon-14 (^{14}C) dated flood sediment databases to short-term (hundreds of years) climatic fluctuations. Greater detail on the influence of changing hydroclimates on river civilizations in the world's largest rivers over the last 5000 years is emerging (Macklin and Lewin, 2015; Macklin *et al.*, 2015) and crucially shows that climatically-controlled changes in the frequency of major floods have affected the development of riverine societies.

Despite the wealth of palaeohydrological studies now available globally, there has still been fairly limited and regionally patchy uptake of information derived from palaeoflood and palaeostorm data by government and policy-makers (see the case study on the United States later). There has also been limited visibility in the assessments made by international bodies such as the IPCC's 'low confidence' (Hartmann *et al.*, 2013) in evidence for long-term (centennial) changes in the incidence of extreme floods. Only instrumental river flow records were used in their assessment. These are very rarely more than 100 years in length and typically span less than 50 years (Jones *et al.*, 2010). Palaeoflood records by contrast do show both short- and long-term trends in extreme flood events and, most importantly, reveal regional and local variability in river and coastal response and flooding to recent climate changes influenced by El Niño-Southern Oscillation (ENSO, Maas *et al.*, 2001), North Atlantic Oscillation (NAO, Feal-Pérez *et al.*, 2014; Benito *et al.*, 2015c; Foulds and Macklin, 2016) and Pacific Decadal Oscillation (PDO, Greenbaum *et al.*, 2014). A single flood or storm can result in the complete transformation of river and coastal landscapes, which resets boundary conditions and strongly influences geomorphic evolution over multi-decadal and longer periods (e.g. Fruergaard *et al.*, 2013; Fruergaard and Kroon, 2016). Because of the generally short-term (typically <50 years) regulatory requirements of many environmental protection and management agencies, the significant role that extreme climate events can have on shaping local and regional river dynamics and trajectories are generally under-estimated (e.g. Macklin and Lewin, 2008; Macklin and Harrison, 2012). However, there is now some development of (typically non-statutory) longer-term risk assessments and management plans to address risks over century-long timescales that are underpinned by geomorphological science (e.g. Fitton *et al.*, 2016).

Extreme flood and storm events, such as the widespread flooding seen over both the 2013/2014 2014/2015 United Kingdom winters, provide an opportunity for the geomorphological science community to work with practitioners, legislators and influential international bodies as knowledge brokers (Naylor *et al.*, 2012; Science Advisory Group to UK Government, 2016) to improve the uptake and inclusion of palaeoflood data (and other geomorphological information) as part of flood risk assessments and development control on floodplains. Geomorphologists can usefully help policy-makers get the right 'weight of evidence' to improve existing (instrumental record based) estimations of flood and storm recurrence intervals.

What challenges are there in using geomorphic and sedimentary indicators to reconstruct flood and storm frequencies?

There are three key challenges in using palaeogeomorphological approaches to improve our understanding and management of flood and storm risks. First, until the last decade or so, geomorphic (e.g. river avulsion, entrenchment and terrace formation; Macklin *et al.*, 2013) and sedimentary (e.g. boulder berms, floodplain, floodbasin and slackwater deposits) records of floods and storms were perceived to lack the necessary temporal and spatial resolution to match computationally-rich historical approaches based upon palaeoecological data (e.g. fossil pollen, diatoms, or tree rings) for detailed palaeoclimatic reconstructions (e.g. Bell and Walker, 2005). Despite an initial reluctance of the palaeoclimatological community to use geomorphic data in hydroclimatic reconstructions, the quality of these data is now improving in two ways. First, new techniques in dating fluvial and coastal sediments and landforms, including the now routine use of accelerator mass spectrometry (AMS) ^{14}C and luminescence dating (see Jones *et al.*, 2015, for review), are reducing dating uncertainty. Second, large (i.e. containing several thousand dated flood units), statistically robust regional (Harden *et al.*, 2010) and continental-scale (Benito *et al.*, 2015b) databases are transforming our understanding of flooding episodes and their relationship to climate change over multi-decadal, centennial and millennial timescales.

Second, there are issues of data comparability between different palaeoreconstruction techniques and between palaeodata and more conventional instrumental records. For example, geomorphic and sedimentary data are perhaps best used for reconstructing hydrologic extremes at the event scale (Toonen *et al.*, 2016), whereas palaeoecological approaches better capture longer-term changes such as droughts or variations in average streamflow. Indeed, where dating resolution is within a few years as, for example, in lichenometry (Macklin and Rumsby, 2007; Foulds and Macklin, 2016), documentary records can be used to attribute a palaeogeomorphological flood deposit to a recorded event whose date (day, month and year) is known. Holocene and historical geomorphological and sedimentary archives thus complement the regional scale climatic data that are best captured by palaeoecological records, such as mean annual temperature or precipitation.

Similarly, despite the great utility of the sedimentary record in providing a critical benchmark for assessing changes in the magnitude and frequency of extreme events (Baker, 2000), the kind of information derived from geomorphic evidence differs from traditional (typically much shorter-term) instrumental records. For instance, the evidence provides event-based rather than quasi-continuous data records. It can thus be difficult to share these data with catchment planners or hydrometeorologists, who typically rely on data from the instrumented record of climate. Although there have been some important advances in incorporating evidence of past extreme events into traditional flood frequency analyses (Stedinger *et al.*, 1988; Ely *et al.*, 1991; Enzel *et al.*, 1993; Levish, 2002; O'Connell *et al.*, 2002; Benito *et al.*, 2004; Reis and Stedinger, 2005), more work is needed to develop corresponding metrics or statistical models that can combine these different forms of data. Such work will enable more effective uptake of palaeoflood data in river and coastal policy and planning (see later for more detail).

Finally, the historical impacts of human activity may muddy our interpretations of palaeogeomorphological and sedimentological data. With increasing awareness of the long-term and continuing anthropogenic impacts on river (Walling, 2006) and coastal (Syvitski and Saito, 2007) systems, it is important to identify and to disentangle human influences from natural variability. Indeed, palaeoreconstructions may represent a different set of conditions than today due to changes in a range of parameters including catchment land-use patterns, and natural and anthropogenic climate change and this potential non-stationarity needs to be considered when using these proxy data (Archer *et al.*, 2016). For example, we need to discern whether the imprint of human activity is coincident (or not) with major shifts in climate and the landscape changes that result. Improving data resolution and extending the climate signal are especially important for reducing uncertainties in the use of palaeogeomorphological datasets, so that wider uptake of these data in contemporary flood and storm management is facilitated. To address these issues, and thus generate more accurate assessments of past extreme storm frequency, intensity and variability and the (often bidirectional) effects on landscapes and society, multiple types and scales of data are required (e.g. Lacey *et al.*, 2015).

Why has there been limited use of palaeogeomorphological data in flood and storm recurrence intervals to date?

There are reasons for the limited use of palaeoflood and palaeostorm data by government and policy-makers. It is certainly in part due to the (over-) reliance on short-term instrumental data to inform policy which led, for example, to the 2015–2016 winter storms in the United Kingdom being called 'unprecedented' by central government (Hansard, 2015) when there have been similar events in the palaeorecord (Foulds and Macklin, 2016). Limited use of such data may also be because flood risk managers have tended to be trained in an engineering and/or hydrological background where determining 'uncertainty' in the flood series from a statistical viewpoint has become paramount. The origins of this statistical emphasis is a very particular view of how to manage risk, based upon structural measures (e.g. levees, river channel straightening), which can be traced back to the nineteenth century, in both Europe and North America. As with all government spending, in order to justify the investment, it was decided that the cost of proposed measures had to be judged against the associated benefits that would accrue, that is the economic damages that would be reduced by the associated spending (Lane *et al.*, 2011). The timescale over which this judgement should be based was set in the nineteenth century as 100 years, the supposed lifetime of infrastructure, and this policy remains the backbone of engineering hydrological analysis (Lane *et al.*, 2011), a traditional emphasis upon establishing the 100 year recurrence interval. As instrumental records of this length are still rare, the focus has been upon lengthening such records using statistical extrapolation (e.g. through growth curves, e.g. Robson, 1999) or through regional pooling (e.g. Das and Cunnane, 2012) where the bias in estimated flood frequencies that comes from a short record is compensated by pooling many short records in the belief that this should improve the representation of the range of possible events in the flood frequency analysis.

Palaeoflood and palaeostorm data imply that these approaches under-estimate the recurrence interval of the most extreme events. In particular, they challenge the widely held engineering hydrology assumption upon which they are based: that annual maximum flood peaks are distributed independently and identically (Franks *et al.*, 2015) in time and in space. Rather, flood peaks do not conform to this assumption and instead behave dynamically in response to significant climatic fluctuations (e.g. ENSO, NAO and PDO) and climate change. The implied assumption 'that the climate is statistically "static" at all timescales and the risk of a flood of a given magnitude is taken as being the same from one year to the next, irrespective of the underlying climate mechanisms' (Franks *et al.*, 2015, p. 31), admittedly with the benefit of hindsight, was always flawed.

The geomorphic drivers of flooding during storm events

Geomorphological processes drive flood and erosion risk in three important ways: (1) landscapes and geomorphic processes in catchments can shape the way in which rainstorms result in floods; (2) river morphodynamics can have a significant impact on flood inundation magnitude and frequency and hence flood and erosion risk; and (3) geomorphic processes in estuarine and coastal zones can significantly impact how sea level and storm surge variations translate into inundation/flooding and erosion.

Geomorphic controls of catchment flood risk

Geomorphic processes and human activity at the catchment-scale can significantly control downstream flood risk. There are multiple dimensions to this issue and we focus on the three most pertinent here: (a) geomorphic controls on runoff generation; (b) the (often human-influenced) geomorphic processes that follow, notably soil erosion; and (c) geomorphic controls upon hydrograph shape and flood routing.

First, geomorphic controls upon rapid runoff generation have been long-established. Work in the 1960s at the Coweeta experimental station in the United States began to challenge the classical model of infiltration-excess overland flow during storms and suggested that stormflow might be associated with the temporary extension of saturated groundwater, enough to increase the spatial extent of rapid overland flow

(Hewlettand Hibbert, 1963). This became known as the variable source area concept. Kirkby and Chorley (1967) suggested that saturated zones were more likely to be found at the base of slopes, in hillslope hollows, in concavities within slope profiles and in areas where soils were thinner (and hence had less volumetric storage). A classic field study by Anderson and Burt (1978) confirmed the importance of zones of flow convergence in generating saturated overland flow in temperate environments, and that that saturation in these zones was critical for rapid runoff response. In parallel, mathematical analysis (Kirkby, 1975) showed that a basic topographic index at a point (the ratio of the upslope contributing area to the tangent of the local slope) could be used to explain the propensity of that point to being saturated and hence capable of generating rapid overland flow. The spatial distribution of topographic index values within a catchment derived from these equations could then form the basis of modelling rapid runoff generation at the catchment-scale (Beven and Kirkby, 1979). This was later extended to control for the combined effects of topography and soil type upon runoff generation (for review, see Quinn *et al.*, 1995). That said, results have now shown that rapid runoff does not necessarily require overland flow, and that the latter is not necessarily topographically controlled. For instance, soil pipe development in peat can also lead to rapid runoff (Holden and Burt, 2002) but soil pipe density is not only related to topographic position (Holden, 2005) but also catchment morphology. For example, Archer and Fowler (2015) have recently found that initiation of flash flood induced steep wavefronts of water are more frequent in upland catchments compared to lowland ones, providing field and archival evidence of catchment control on flood processes.

Second, extreme rainfall events can lead to significant soil loss (e.g. Nadal-Romero et al., 2014; Boardman, 2015), with implications for downstream flood risk and sediment-related flood damages (Thorne, 2014). For example, Chartin *et al.* (2016) found that a significant correlation between the most extreme typhoons and the highest levels of soil erosion, causing the greatest mobilization of particle-bound cesium-137 (^{137}Cs) contaminants in Fukoshima prefecture, Japan. Extreme rainfall events are also responsible for a very particular kind of flood called a 'muddy flood' (e.g. Boardman, 2015), commonly but not exclusively involving direct runoff from fields into properties (sometimes referred to as 'direct flooding'). Certain cultivation practices have been shown to encourage this kind of flood (e.g. maize, potatoes, sugar beet; Boardman, 2015), notably those that leave soil bare during cropping cycles. Certain geologies appear to be more at risk than others because the probability of a muddy flood is increased if there is infiltration excess overland flow, and the development of soil crusts on certain soil surfaces can increase this risk significantly (e.g. on chalk, Boardman *et al.*, 2003). During heavy rain, soil properties can also evolve to reduce depression storage and to increase the connectivity of overland flow, which may also increase runoff generation (e.g. Zhao *et al.*, 2016). It has also been shown that the progressive removal of field boundaries and certain land management practices (e.g. plough directions) can also increase the risk of muddy floods (Boardman and Vandaele, 2016) and that suitable land management practices can significantly reduce their probability of occurrence (Renschler and Harbor, 2002). Not only does this reduce the frequency of direct flooding, it also conserves soil, itself a key resource. Recent catchment sensitive farming initiatives have been used to apply this geomorphic understanding in catchments particularly prone to soil erosion and downstream sedimentation problems (McGonigle *et al.*, 2012; Kleinman *et al.*, 2015); more knowledge exchange between geomorphologists and practitioners can hopefully lead to more widespread changes in land management practice.

Third, geomorphology has been recognized explicitly as a control upon the ways in which water moves through drainage networks and so influences downstream flood magnitude. If we imagine that a catchment is divided into units that each respond to rainfall to make runoff ('hydrological response units', HRUs) then the discharge at any one point in a catchment is a function of the summation of those units, that is the way in which runoff from each unit moves across the catchment through time (Rigon *et al.*, 2016). Where runoff from two HRUs arrives at the same time in the drainage network the associated discharge will be greater than if they arrive at different times. This was recognized in a classic paper in the 1970s (Rodríguez-Iturbe and Valdés, 1979), which proposed the 'geomorphic instantaneous unit hydrograph' effectively expressing geomorphic controls upon flood routing via travel times. These travel times will be a function of the time spent: (1) in overland flow (a function of land surface roughness and topographic routing, which controls flow accumulation); (2) moving through the river channel (a function of channel pattern channel cross-section morphology and other energy losses such as relating to vegetation); and (3) moving through floodplains if water leaves the channel during its transfer. Thus, a suite of geomorphic processes control these travel times and if geomorphic or human activity changes such controls, for instance where sediment deposition better connects a river to its floodplain or where biogeomorphic buffers are created (see later), then these travel times will evolve and/or can potentially be managed to reduce the flood risks associated with otherwise synchronized tributary discharge peaks.

Could geomorphic processes be more important than climate change in driving fluvial flood risk?

Fluvial morphodynamics, themselves partly driven by extreme flood events, modulate, and add complexity to, the relationship between changing climate and flood risk. For example, rivers are not merely static 'pipes' to accommodate and convey (or otherwise) the runoff generated by altered precipitation distributions. Rather, rivers themselves dynamically adjust to altered runoff regimes, meaning that extreme events can sometimes themselves alter channel capacities and river-floodplain geometrics, altering the risk of future flooding. This form of feedback means that, by inducing geomorphic response, extreme events can induce a legacy of altered flood risk to similar extreme events that occur in the future. Furthermore, geomorphic dynamics operating over timescales of decades or longer are, by definition, operating under conditions that are not always extreme (e.g. progressive channel infilling), and such evolution may substantially change flood frequency (Slater *et al.*, 2015).

Very significant advances have recently been made in our ability to model fluvial flooding and flood risk. A key outcome of these studies is that it has now become clear that the accurate representation of channel and floodplain topography is a critical factor in determining the quality of predictions made by models of flood inundation (Bates and De Roo, 2000) and flood wave propagation (Wong *et al.*, 2014). It follows that, if good representation of topography is needed for models to reproduce the magnitude and frequency of flood inundation correctly, changes in river topography could significantly change the magnitude and frequency of flood inundation and resultant impacts on society. Since river morphology is both a control on and a consequence of fluvial processes (Sear *et al.*, 2010), adjustments of channel and floodplain morphology may have significant implications for floodplain inundation, flow depth and flood wave propagation (Wong *et al.*, 2014; Trigg *et al.*, 2013). On the one hand, it is well known that flow events, particularly high-magnitude flow events, can erode, transport and deposit large volumes of sediment, potentially reshaping the river system (for example, see the case study on the Indus River later and Figure 1), with attendant impacts on channel capacity (the cross-section area of the channel) and hence flow conveyance (Bates *et al.*, 2004; Staines and Carrivick, 2015). On the other hand, increased flooding has also been shown to be caused by ongoing geomorphic changes (in-channel sedimentation) that progressively reduce channel capacity (Stover and Montgomery, 2001; Syvitski and Brakenridge, 2013; Wong *et al.*, 2014; Slater, 2016). These geomorphic changes in channel capacity are clearly a critical factor in altering flood risk (and societal impacts of floods) and may actually be greater than direct climate change impacts on flow magnitude and frequency (Lane *et al.*, 2007).

Geomorphologists have a well-developed understanding of the controls on such changes in channel capacity that can help us understand and predict fluvial responses to climate extremes. Specifically, statistically speaking, channel capacity scales with bankfull discharge, the latter typically being the discharge with a one to two year recurrence interval (Wolman and Leopold, 1957) although this return frequency may be less applicable in more arid to semi-arid environments. Thus, if there is a shift in discharge regime, we expect the river to respond morphodynamically to increased channel capacity. However, this is a statistical result, one that may not always hold. For instance, Downs *et al.* (2016) show that it is the discharge that overtops channel bars rather than the discharge that fills to the level of channel bank tops that appears to be the most effective in terms of shaping channel morphology (see also Klösch *et al.*, 2015). The relationships may vary between rivers in different environments. Crucially, statistical relationships overlook the fact that it is the dynamics of the channel during and

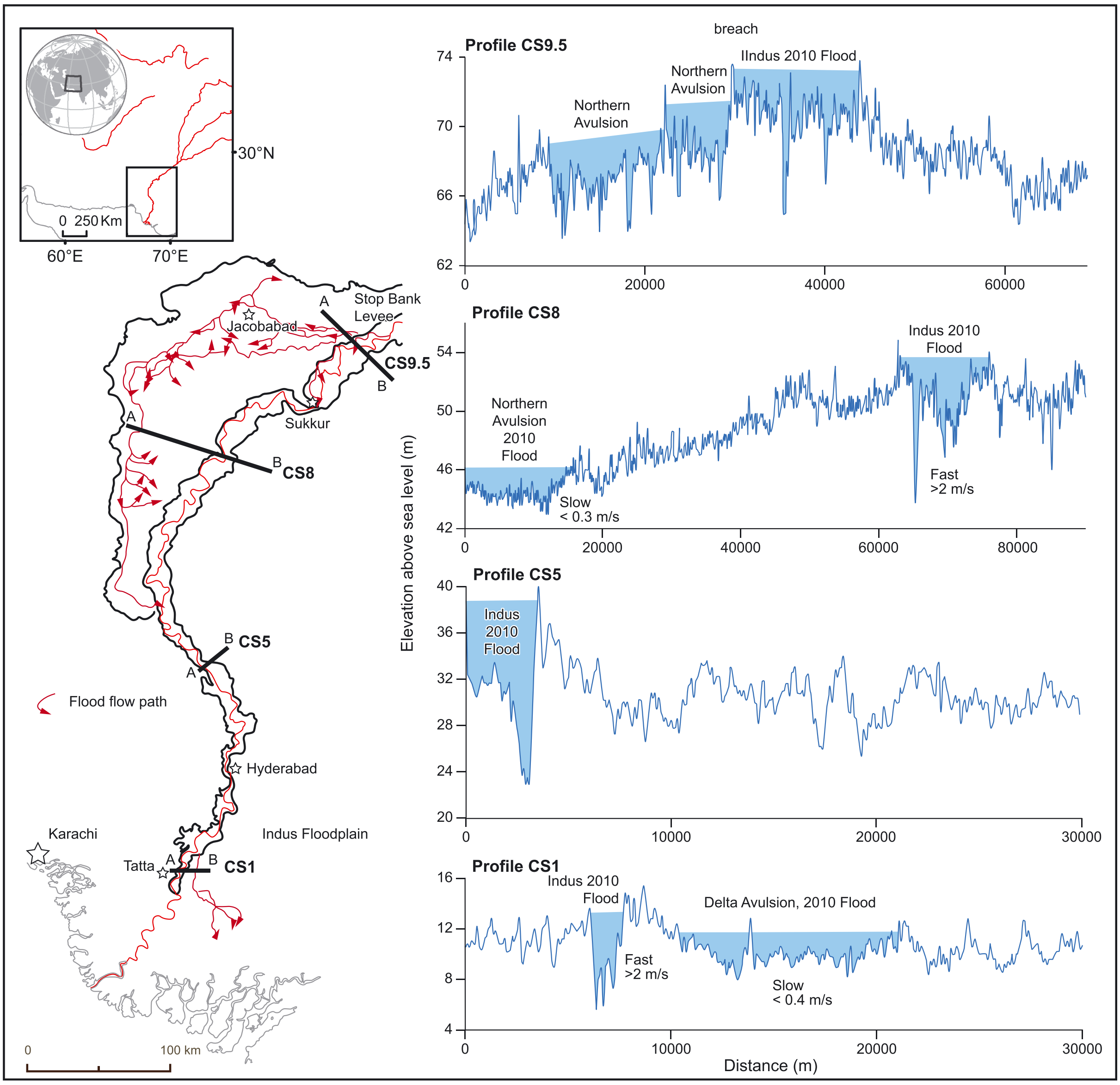

Figure 1. Major flood pathways associated with the 2010 flood on the Indus River in Sindh, Pakistan. The four cross-sections across the Indus floodplain show the maximum 2010 flood heights and indicate backwater-elevated flood waters of the Indus and the northern avulsion breach location (profile CS9.5), the super-elevated Indus floodplain, above the slower moving northern avulsion floodwaters (profile CS8), the Indus floodwaters contained within the levee stop banks (profile CS5) and the river flowing quickly beside the slower moving southern (delta) avulsion (profile CS1). Modified after Syvitski and Brakenridge (2013). [Colour figure can be viewed at wileyonlinelibrary.com]

between individual events that condition channel capacity. In this latter context, it is the *history* of the system dynamics that matters (Phillips and van Dyke, 2016). Using sediment characteristics recorded in off-channel lacustrine deposits, Yellen *et al.* (2016) show that Tropical Storm Irene in the northeastern United States led to some of the highest catchment erosion rates and that this effectiveness reflected the importance of event sequencing: it arose from an extreme rainfall event coupled with particularly wet, antecedent catchment conditions. Similarly, Tseng *et al.* (2015) were able to identify headward channel extension, erosion of channels upstream and in-channel deposition downstream due to the effects of Typhoon Morakot in Taiwan in 2009. This erosion–deposition linkage arises because high magnitude erosion events upstream can lead to the introduction of sediment slugs (cf. Nicholas *et al.*, 1995) which, because flood waves and sediment waves move through the drainage networks with different celerities, inevitably lead to substantial deposition and channel modification downstream (e.g. Tamminga *et al.*, 2015; Nelson and Dubé, 2016; Rickenmann *et al.*, 2016; Rinaldi *et al.*, 2016).

It is clear from the preceding discussion that sediment transport events, of both high and low magnitude, have the potential to reshape channel and floodplain topography, and thereby introduce an uncertainty in the quantification of future flooding. However, determining the extent to which such events actually reshape channel capacity is complicated. Not all floods cause major reshaping of the channel-floodplain landscape. Some large flow events have a minimal effect on the landscape, whereas some minor floods result in major morphological changes. A recent study examining this effect has been undertaken by Slater (2016), who, for example, looked for systematic shifts in the relationship between river water levels and river flow at gauging stations (cf. James, 1997). Such analysis is not straightforward because it is necessary to control for other impacts on channel capacity, notably river channel engineering, but Slater (2016) was able to show systematic shifts in flood frequency (increases and decreases) following from changes in channel capacity.

Geomorphic controls on coastal flooding and erosion

Recent coastal research is demonstrating that geomorphological processes exert considerable control on coastal flooding and erosion patterns at a range of scales. Here we identify and discuss geomorphic controls on erosion and flooding of sandy beach–dune complexes, fine-grained cohesive shores and rock coasts. In sandy beach–dune systems, the configuration of landforms prior to a storm event appears to exert a strong control on the nature and spatial variability of the response to an extreme storm event (or group of storms). Castelle *et al.* (2015) concluded that antecedent geomorphic conditions of the outer sandbar as well as wave conditions exerted a strong control over patterns of beach and dune erosion during extreme storms. Furthermore, assessments of the role of extreme events should deal not only with immediate (erosive) storm impacts but also with (accretionary) post-storm recovery. As the long-term monitoring of beach state at Moruya Beach, New South Wales, Australia has shown (Thom and Hall, 1991) this can be long delayed (up to eight years post-storm event). Knowing accretionary post-storm recovery rates may be particularly valuable for local communities reliant on beach tourism for their economies. In the 2013–2014 winter storms in southwest England, large quantities of sand were moved offshore revealing rocky substrata beneath them which made conditions much more treacherous for beach users and such areas had to be flagged as dangerous by the Royal National Lifeguard Institute (Andrew, 2014). In this sequence of major Atlantic storms, supratidal and intertidal sediment volumetric losses were often $>100\,\mathrm{m}^3$ per unit metre beach width, and many dune systems experienced frontal erosion of $>5\,\mathrm{m}$ (Masselink *et al.*, 2016). Limited recovery occurred over the 12 month-period following these storms, with generally less than 50% of the eroded sediment being returned to the beaches. The traditional model for beach morphodynamics assumes that beaches erode under high energy, 'winter' conditions and rebuild under more quiescent, 'summer' conditions. However, it is clear that, under big storms, sediments are taken to considerable depths offshore (in subtidal bars 6–8 m below mean sea level; perhaps as a result of mega-rip currents or in greatly expanded storm-scaled surf zones), and then require energetic, not calm, wave conditions to return the stored sediment from the offshore shelf or new alongshore positions to initiate re-establishment of former coastal profiles (G. Masselink, pers. Comm., 2015).

The regional assessment of the impacts of the 2013–2014 UK storm season also reveals an important finding: considerable geographical variability in beach response type. On north coast, west-facing beaches, westerly Atlantic storm waves approached the coastline shore-parallel, and the prevailing storm response was offshore sediment transport, resulting in extensive beach and dune erosion, with some beaches being completely stripped of sediment to expose a rocky shore platform. By contrast, on the south coast, the westerly Atlantic storm waves were refracted and diffracted, resulting in large incident wave angles and an eastward littoral drift; many south coast beaches thus exhibited beach volume rotation, with western beaches eroding and eastern sections accreting (Masselink *et al.*, 2016).

On fine-grained cohesive shores, the UK east coast storm surge of the 5 December 2013 illustrated the fact that whilst the general pattern of storm surge inundation could be explained by the interaction of storm surge and tidal level at the alongshore 1–10 km scale, local variations in wave run-up, and hence maximum surge-associated water level height were determined by local patterns of exposure, including the presence of intertidal mudflats and saltmarshes (Spencer *et al.*, 2014, 2015a). The presence of vegetated surfaces can significantly attenuate water levels during the propagation of sea flooding events. Modelling studies and networks of field water level gauges have shown that water level decreases with distance from the coast due to: (i) the drag force that vegetated land surfaces exert on water flow; (ii) the reduction in water level set-up in the presence of vegetation; and (iii) the sheltering effect against surface winds that arises from the presence of a vegetation canopy (Loder *et al.*, 2009; Gedan *et al.*, 2011).

On rocky shore platforms, local variations (10^1–10^2 m) in shore platform topography and morphogenic zones exerted a strong control on boulder transport patterns under an intense extratropical cyclone (Naylor *et al.*, 2016). Shore platform elevation has also been found to control boulder beach morphologies in Devon, UK where increased wave energies were associated with lower shore platforms; this increased wave heights at the beach–cliff junction (Brayne, 2016). Localized variation in transport distance and wave energy at the beach–cliff junction generates different boulder beach and cliff heights, showing there is strong, local scale geomorphological control on erosion and flood risks in rock coast systems.

The geomorphic consequences of extreme storm events

Extreme storm events may lead to major geomorphic impacts that can, in some situations, also generate major societal impacts. At a coarse scale, the geomorphic impacts can be either erosional or depositional, which may differ in intensity or location even during the same flood and/or within the same basin (Thompson and Croke, 2013; Gartner *et al.*, 2015) or along a stretch of coastline (Dissanayake *et al.*, 2014). In this section we evaluate both fluvial and coastal impacts before introducing two themes that merit emphasis: (1) how we conceptualize the geomorphic consequences of extreme storm events in analyses of magnitude and frequency; and (2) the need to examine large rivers and deltas, something that has only recently garnered significant geomorphic attention (Gupta, 2007).

Fluvial-driven impacts

Because of its role in undermining channel banks, houses and other infrastructure, most geomorphic attention in fluvial systems has focussed on river channel erosion. Erosion depends on bank susceptibility (e.g. sediment type or vegetation), channel planform, and, of course, flow conditions including flood magnitude, flow velocities, and other hydraulic characteristics. Although not a perfect metric, most attempts to estimate the likelihood of channel erosion use unit stream power (Fuller, 2007; Bizzi and Lerner, 2015; Marchi *et al.*, 2015). Based on an extensive review of the flood literature, Magilligan (1992) suggested a threshold value of $300\,\mathrm{W/m^2}$ for identifying reaches where major geomorphic adjustments occur. This threshold value of unit stream power has been supported in a variety of environmental settings (Lapointe *et al.*, 1998; Hooke and Mant, 2000; Cenderelli and Wohl, 2003; Hauer and Habersack, 2009; Ortega and Heydt, 2009; Thompson and Croke, 2013) and can be seen as a coarse filter for identifying potentially sensitive reaches. To better account for other channel properties, Buraas *et al.* (2014) included a bend stress parameter in combination with unit stream power to better identify reaches affected by an extreme event. Because most of the explanatory power in these approaches is conditioned by variations in slope, recent work has used changes in gradient to explain loci of geomorphic change (Singer and Michaelides, 2014; Gartner *et al.*, 2015; Lea and Legleiter, 2016). These new approaches use primarily the Exner equation (Paola and Voller, 2005) at discrete spatial scales to examine spatial changes in gradient – not merely its magnitude – as the predictor of geomorphic change. Gartner *et al.* (2015) expanded on the use of the Exner equation and included a lateral dimension to augment the normal longitudinal component of the Exner equation and in this way were able to improve identification and quantification of the magnitude and origin of lateral sources of material during extreme floods.

From a risk assessment perspective, an often overlooked discrepancy is differentiating those impacts associated with increased flow energy/velocity (i.e. erosion) from those due to inundation. From a hydroclimatological perspective, these differing responses (erosion versus inundation) may result from very different flood producing mechanisms, which in turn can produce very different geomorphic effects (Costa and O'Connor, 1995; Magilligan *et al.*, 2015; Surian *et al.*, 2016; Fryirs, 2016; Brooks *et al.*, 2016). For the United States, flood risk, as determined by the Federal Emergency Management Agency (FEMA), tends to be more inundation-based, usually around estimated flood depths for the one in 100 year flood event. For FEMA, risk is based less on erosion but more on the height and extent of the flood peak. As geomorphologists, we are acutely aware that different flood-producing mechanisms (e.g. snowmelt, rain on snow, hurricane, thunderstorm, etc.) generate not only large differences in the magnitude of a flood but also in its duration. As regional climates change, not only will the flood producing mechanism change, but so will the type of geomorphic response.

Coastal impacts

On coasts, spatially variable responses to individual extreme storm events have been observed where local topography exerts a strong control on geomorphic response and recovery. The subtidal to supratidal profile is also of critical importance in determining patterns of coastal dune regeneration. On the north Norfolk coast, eastern England, where the offshore profile is steep, storm impacts result in pulses of periodic shoreline retreat with sand dune scarping and little or no post-storm recovery. Where there is a shallow offshore profile and migratory onshore bars to bring intertidal sands to levels where they can be dried and entrained by aeolian processes, sand dune re-establishment and shoreline advance is seen in the years after storm trimming of the coastal duneline (Brooks and Spencer, 2016). Similarly, on a sandy beach – dune complex in northern France, Castelle *et al.* (2015) found spatial variability in geomorphic impacts of the winter 2013–2014 storms with localized areas having larger scale geomorphic changes such as the creation of megacusp embayments and erosional hotspots on dunes. Thus, antecedent geomorphic conditions (e.g. topography, length of recovery between storm groups) mediate geomorphic responses to extreme storm events, creating variability in geomorphic changes resulting from the same extreme event.

A growing body of research is demonstrating that geomorphic assessments of the impact of extreme events should deal not with individual storms, but with sequences of storms, or storm clusters (Ferreira, 2005). Dissanayake *et al.* (2015) modelled the effects of storm clustering during the 2013–2014 winter storm sequence on beach–dune evolution at Formby spit, UK. Importantly, they showed that conventional model input parameters including bed level change were not effective at modelling geomorphic responses of beach–dune systems to a sequence of tightly coupled storms, where the short timescales between events meant beach recovery was impossible. Instead, their model was more accurate when beach profiles from the previous event in the cluster were used to model erosion risk (thus taking account of erosion caused by the previous storm), demonstrating how geomorphic responses to storms are crucial to improved model validation. Similarly, Vousdoukas *et al.* (2012) found that not only did nearshore bars appear to be critical for storm wave attenuation in Portugal but that nearshore bar dynamics appeared strongly related to storm sequences rather than responding to individual storms. Nearshore bed parameters (based on beach profile surveys of geomorphic change) have been used to improve coastal engineering models (e.g. Callaghan and Wainwright, 2013). They also found that where storm recovery was slow and storm groups were common, model results were improved where slower beach recovery was taken into account by merging of event clusters based on their geomorphic recovery to storm sequences (Callaghan and Wainwright, 2013). These recent papers demonstrate the effects of nearshore geomorphologic processes on coastal erosion during storm events and how an understanding of geomorphic recovery rates can be used to improve our ability to predict risks associated with these storm events. On the north Norfolk coast, eastern England, barrier island shoreline retreat, of typically 5–8 m, is primarily driven by individual events, separated by varying periods of barrier stasis. Interestingly, infrequent storm surge events on this coast – frequently seen as the extreme event – do not in themselves necessarily lead to shoreline erosion. This requires a synchroneity between surge, high spring tides and, crucially, wave activity on top of the surge (Brooks *et al.*, 2016). Research by Naylor *et al.* (2016) examining shore platform erosion and boulder dynamics on a Welsh rock coast suggests a similar synchroneity is required for rock coast erosion to occur.

The need to rethink magnitude and frequency in impact assessment

Magnitude–frequency relationships have underpinned the theoretical dimensions and practical applications of geomorphology, including informing the design of critical infrastructure such as bridges, culverts and dams. The interplay between the magnitude of an event and its frequency or recurrence interval was perhaps best formalized as the Wolman–Miller (Wolman and Miller, 1960) principle that posited that stream channel properties (size, slope, and sinuosity) were primarily controlled by moderate magnitude flows – typical of the bankfull discharge, observed to have a two year return period. Large floods may spawn major geomorphic adjustments but because they are so rare, frequently recurring flows, over time, re-establish pre-flood dimensions and maintain a dynamic equilibrium between channel dimensions and both water and sediment discharge. The Wolman–Miller principle has served as an important template for understanding fluvial landforms and in articulating the processes of floodplain formation, but subsequent research has shown the strong role of climate and geology that limits the extension of the Wolman–Miller principle to all environments (Wolman and Gerson, 1978).

Moreover, channel recovery to disturbance may not follow the simple, general linear trajectory suggested by Wolman and Miller (1960) where pre-flood dimensions are routinely re-established (see earlier discussion on coasts). In some instances the system has been so destabilized from the disturbance that the timeframes of recovery are too vast and may exceed the normative flows of the existing regional climate (Baker, 1977; Wolman and Gerson, 1978) or that the system has transitioned to a new state which may result in a markedly different landform, geomorphic environment, or landscape unit (Phillips, 2014; Fruergaard and Kroon, 2016). Although considerable research has shown that under appropriate conditions, channels can recover pre-flood dimensions (Schumm and Lichty, 1965; Costa, 1974), the recovery trajectory requires sufficient flows, available sediment, and minimal change in extant boundary conditions. Implicit within the recovery narrative is that channels are tending towards a relatively fixed equilibrium. However, considerable research has shown that some geomorphic systems may exhibit greater sensitivity to shifting driving forces (Brunsden and Thornes, 1979; Brunsden, 2001; Knox, 2000; Fryirs, 2016) and may not realize the pre-disturbance equilibrium (Lewin *et al.*, 1988; Renwick, 1992). The sensitivity of the system depends on intrinsic or extrinsic thresholds that condition the suite of potential outcomes. In highly sensitive systems where dynamically unstable feedbacks can exaggerate disturbances, perturbations may be amplified (Phillips, 2010) or may be spatially and temporally complex (Dethier *et al.*, 2016) potentially leading to radical shifts in landform/landscape properties that may not be re-attainable (Phillips, 1992, 2009, 2014). These landform and landscape state changes can have catastrophic effects on people (see next section).

Although much of the discussion of state transitions has been more conceptually based, the palaeorecord reveals that major changes in climate may generate significant shifts from one equilibrium state to another, where, for example, channel planform in large streams in the southeast United States shifted from braided channels to a more meandering planform during the transition from the Late Glacial Maximum (LGM) to the early Holocene (Leigh, 2006). Even without the profound shift in boundary conditions during the LGM to Holocene transition, pre-historical fluvial systems have been shown to dramatically shift flooding regimes for extreme events with even modest changes in climate (Knox, 1993). Palaeo analogues reveal that with the projected future changes in storm magnitude and frequency, the potential exists for dramatic shifts in fluvial and coastal processes and landforms that may be radically different from contemporary conditions and well beyond the scope and design of current management alternatives. At the very least, the analysis of magnitude and frequency needs to develop to address geomorphic impacts and different recovery trajectories (see earlier).

Floods in large rivers and big deltas

Flooding, and the role of geomorphic processes in modulating flood generation and flood risk, clearly presents a challenge to societies across the globe. Nevertheless, it can be argued that these issues will be expressed most acutely on the world's large rivers: some 18% of the total global population at risk of fluvial flooding inhabit the floodplains of the world's 20 largest rivers (as ranked based on mean annual runoff, see Ashworth and Lewin, 2012). One in 14 people globally (some 600 million) live in deltaic regions where land surfaces are sinking from the combination of sea level rise and high rates of land subsidence, from both natural short-term compaction of soils and long-term geological subsidence, exacerbated by the extraction of water, oil and gas and drainage for agriculture (Syvitski *et al.*, 2009; Vörösmarty *et al.*, 2009). Such low elevations (in places below sea level) make deltas, and their growing urban populations highly vulnerable to the impacts of storms, cyclones and hurricanes (Hinkel *et al.*, 2014). Subsidence can be counteracted by riverine sediment inputs but many large deltas have lost these inputs due to upstream damming (Giosan *et al.*, 2014) or artificial levees which reduce river to floodplain sediment transfer. Further, artificial levees create hydraulically efficient channels which encourages sediment flux to the deep water region beyond the delta mouth where it is effectively "lost" from the nearshore system. Unlike in the past, it is doubtful that society will be able to continue to engineer its way out of delta defence in the future (van Wesenbeeck *et al.*, 2014). In summary, "little of the natural system remains for many deltas. Unless delta cultures and inhabitants can develop approaches and infrastructure to survive future extreme weather systems, then the advantages of world deltas (flat-lying food sources and transportation hubs) will become disadvantages" (Day *et al.*, 2016a, p. 3).

There is now a recognition that large rivers and their deltas present a distinctive set of morphological processes and attributes, setting them apart from their smaller counterparts in terms of how their floodplains function during floods. Recent research in the Mekong river illustrates sensitivity of these large river systems to storms and the profound effect the wet-cyclone season has on river bank erosion (two-fold increase) and suspended sediment (fourfold increase) (Leyland *et al.*, 2017). Of particular relevance in this regard is the point that many large rivers anabranch dynamically and have a tendency to avulse (Latrubesse, 2008; Lewin and Ashworth, 2013;

Kleinhans *et al.*, 2013). It is this avulsion that leads to the progressive spatial redistribution of sediment, that is, it counters the effects of historical sedimentation on delta subsidence. The underpinning cause of avulsion in these large, sediment-rich, rivers is frequently intrinsic geomorphic processes, even if a moderate to high-magnitude flow normally triggers these events. This means that unless the geomorphic processes driving flooding are considered, the relationship between flood risk and extreme climate events is likely to be distorted or blurred.

These points are well illustrated through analysis of one of the most significant flood disasters of the last decade, namely the catastrophic 2010 monsoon flood along the Indus River in Pakistan (Syvitski and Brakenridge, 2013). The bare statistics regarding the human impacts of this event are, in many respects, difficult to assimilate: It is estimated that there were close to 2000 fatalities, with some 20 million people displaced from their homes for periods of weeks or months (Chorynski *et al.*, 2012; Brakenridge, 2012). Despite the extreme social impacts of the flood, Syvitski and Brakenridge (2013) are nevertheless clear in their assessment: whilst extreme rainfall was generated in northern Pakistan, overall July–August precipitation totals were not extreme. Consequently, peak flows (estimated at between 32,000 and 33,000 m^3/s between 8–11 August 2010) experienced during the flood were large, but not exceptional compared to other late twentieth-century events (ranging between 31680 and 33970 m^3/s) that did not cause extensive flooding (Syvitski and Brakenridge, 2013). Instead, the cause of the 2010 Indus flood was erosion and not flood inundation. A series of levee breaches triggered at flow discharges of around 20,000 m^3/s, not levee overtopping, led to avulsion from the super-elevated channel onto the lower surrounding floodplains (Figure 1). As Syvitski and Brakenridge (2013, p. 5) put it, "The proximate cause for this flood disaster was the intersection of (1) a suite of ongoing, non-stochastic, and relatively predictable depositional mechanisms exhibited by a confined, sediment-rich river flowing on an alluvial ridge; and (2) the lack of explicit engineering and societal accommodation to these natural geomorphological processes" (see later).

It is important to emphasize that the erosional processes driving the Indus flood, if not its impacts, are representative rather than unusual. Similar processes have been documented along many other sediment-rich rivers that are prone to avulsion, including the well-known example of the 2008 flood caused by the avulsion of the Kosi River in India (Kale, 2008). In the cases of both the Kosi and Indus, avulsions occurred during high, but not extreme, flow discharges that were less than the design capacity of the engineered levee system (Sinha, 2009). This illustrates well our earlier point that geomorphic processes may be of equal or greater importance than climate change in driving flood risk and that the geomorphic impacts from extreme events may be greater where rivers are already heavily engineered and there is not enough lateral or accommodation space for channel adjustment and/or sediment deposition (see earlier and section on flux zones and vulnerability points later for details). It follows that in order to appraise flood and erosion risk adequately – and to contextualize appropriately the risks of altered climate extremes – dynamic flood-risk assessments that explicitly include the influence of geomorphic change (and engineering controls on this) remain a fundamental requirement. It is quite possible that fluvial processes trump climate change impacts in shaping flood risk in some situations (Lane *et al.*, 2007).

Major deltas show patterns of growth and decay at a number of nested time and space scales. Delta lobe switching occurs at centennial to millennial timescales across deltaic plains of thousands of square kilometres (Roberts, 1997) and is accompanied by coincident patterns of regional wetland growth and decay (Reed, 2002). At the spatial scale of the individual distributary within one delta lobe, interdistributary bays are filled through episodic connections between the river and the embayment over time. We know this is how the lower Mississippi delta developed over the period of historical mapping, with levee breaks leading to sand sheets, or "crevasse splay deposits", extending over areas of 100 to 200 km^2 with sediment additions 2 m thick (Coleman, 1988). These episodes are in turn overlain by the pulsed sediment inputs resulting from the passage of hurricanes, cyclones and winter storms (Cahoon, 2006). They are thus dynamic geomorphic landscapes that societies choose to inhabit.

Over the shorter timescales, it is now possible to track wetland vertical growth by high resolution measurements of surface elevation change and near-surface accretion, the so-called "SET-MH" methodology (Cahoon *et al.*, 2002), although the global distribution of such measurement sites remains highly uneven (Webb *et al.*, 2013). Such an approach can give insight into delta health; one might consider a delta as geomorphically sustainable over a set timescale if the net change in surface elevation is greater than the rate of relative sea level rise and if the change in plan area is greater than or equal to zero (Day *et al.*, 2016a). Yet almost no large deltas currently meet this condition (Giosan *et al.*, 2014). In the Mississippi deltaic plain, where the value of coastal wetlands in protecting lives and livelihoods from hurricane-associated storm surges is well established (Barbier *et al.*, 2013), *c.* 25% of the delta's wetlands have disappeared over the last century; if present trends continue then all will be lost by 2100 (Blum and Roberts, 2009; Couvillion *et al.*, 2013). It is very clear that sustainable management of major deltas into the near-future will require the re-establishment of system functioning (Day *et al.*, 1997) and that this may be best achieved through an in-depth understanding of the natural bio-physical processes that operate within the delta system.

Such actions have been termed "ecological engineering" (Mitsch and Jørgensen, 2004) although in fact there is a strong geomorphological component in such thinking. An example of this approach is the re-connection of flows of water and sediment from delta distributaries to inter-distributary bays. In the Mississippi delta, the creation of an artificial break to protect the city of New Orleans during the great flood of 1927 resulted in the creation of 130 km^2 of new delta substrate with 45 cm of deposition over a three month period (Day *et al.*, 2016a, 2016b). The opening of the flood relief spillway of Bonnet Carré has typically added 20 cm to wetland surfaces per event, with accumulative vertical accretion of over 2 m over the period of spillway openings (Day *et al.*, 2016c). Even small diversions of water and sediment have led to accretion rates of 1 cm/a or greater (DeLaune *et al.*, 2013). Geomorphological expertise is needed to best design the scale and location of such interventions and the resulting patterns of sedimentation and their impacts on ecological processes (Day *et al.*, 2008). Thus, for example, the spraying of dredged spoil into degraded wetlands shows that the depth of applied sediment is crucial: too thin and there is little effect, too thick and the wetland vegetation becomes buried beneath the sedimentary capping (Ford *et al.*, 1999).

Working with geomorphological processes to reduce the impacts of floods and storms

The economic and social damage associated with climate-related hazards including extreme storms and floods is rapidly increasing, with recent events being the most expensive natural hazards experienced by some countries (e.g. Calgary, Canada's 2013 floods: Milrad *et al.*, 2015). The sheer scale of impact of some of these recent events such as Typhoon Haiyun (Laipdez *et al.*, 2015) is prompting some researchers to contextualize these events and the human impacts they cause as examples of post-normal or Type 2 science (Gibbons *et al.*, 1994) where risks are high, decisions are urgent but where scientific evidence is often uncertain (Turnpenny, 2012). Such science needs an interdisciplinary focus. Social scientists are increasingly advocating that transformation is required where we radically re-think how society adjusts to a rapidly changing world (Kates *et al.*, 2012). This has parallels to discussions by global change scientists who have described rapid global change as involving tipping points and tipping elements (i.e. thresholds where small perturbations trigger a large response) that will alter the Earth's climate (e.g. Lenton *et al.*, 2008) and transform socio-ecological systems (Anderies and Janssen, 2011). In a review of environmental tipping points, Lenton (2013, p. 22) concluded that "The scope for future landscape (biogeomorphological) tipping points to be triggered should be explored, alongside their interaction with other types of environmental tipping points." The impacts of recent extreme storm and flood events create an opportunity to transform how we (scientists, the public, policy-makers, practitioners) perceive extreme storm and flood events and the landscape and landform effects of these.

Geomorphological research can help provide evidence for changes in events, from being exceptional to occurring with greater frequency or intensity which in some cases may lead to substantive human impacts [e.g. Typhoon Haiyun (Laipdez *et al.*, 2015) and Superstorm Sandy (Hapke *et al.*, 2013)]. We can thus encourage people to think of socio-geomorphological systems (Ashmore, 2015) alongside the more conventional socio-ecological system (Adger, 2000). Socio-ecological system theory aims to find synergies and benefits from managing human activities and the landscape to increase the resilience (i.e. ability to absorb or adapt to change) of both social and ecological systems to external stresses and disturbances such as climate change (Adger, 2000). A socio-geomorphological system is one where the interactions between people, their activities and the landforms they live on or near are understood and managed to improve socio-economic resilience to geomorphic dynamics, especially those associated with extreme events. Geomorphologists refer to resilience in a more detailed manner in terms of: (a) resistance of a landform to external stresses; (b) resilience, which refers to the capacity to recover; (c) recovery of a system from a disturbance; and (d) state changes which are thresholds where the external stress on a system (such as an extreme storm event) leads to a change in the geomorphic system (Phillips and van Dyke, 2016). Geomorphologists are interested in which geomorphic disturbance conditions (human and natural) trigger a change in state, whether a system can recover (resilience), how long it takes the system to start responding (response time) and to respond fully (relaxation time) and how frequently these events occur (Phillips and van Dyke, 2016). We can identify systems that have high resistance and resilience, and have rapid relaxation times which respond well to disturbance compared to those which have low resistance and resilience to disturbance with slow relaxation times and feedbacks that create long-lived impacts (Phillips and van Dyke, 2016). An example of long-lasting (centennial-scale) changes to the landscape from geomorphic disturbances are threshold changes in geomorphic state precipitated by climate extremes, as evidenced by the creation of new barrier islands after an extreme storm (Fruergaard and Kroon, 2016). The challenge with a landscape changing from, for example, a stable barrier bar beach system to one that is more dynamic or indeed disappears for a few centuries, is how humans make use of these landforms. Thus, there is a pressing need to better understand how threshold changes in geomorphic state impact on human activities, and in turn how human activities add pressure that may trigger a state change. If we are more aware of geomorphological resilience to perturbations, the likelihood of threshold changes in geomorphic systems and how these systems naturally evolve through time (e.g. migrating barrier beach systems or delta lobe switching) we can perhaps reduce risks to society by learning to live in dynamic geomorphic systems (rather than actively trying to maintain or reinstate the current landscape configuration).

To contribute effectively to reducing the impacts of extreme floods and storms, geomorphological work needs to sit within this wider transformative context. As Baker (1994) perceptively recognized many years ago, much of the flood hazard paradigm comes from engineering, where nature is seen as a set of limitations to be overcome whereas the geomorphological viewpoint might rather better view the impact of extreme events as a set of opportunities from which we can learn. From such a standpoint, geomorphologist's might contribute to reducing the impacts of extreme events on landscapes and society in three main ways. First, we can provide a clear scientific basis for how geomorphic systems influence and respond to extreme events (see earlier). Second, we can assist with identifying the shorter-term, near-future interventions (next 50 years) needed for adaptation to evolving flood and erosion hazards, notably where these may benefit from incorporation of geomorphic dynamics. For example, flood risks could be assessed in terms of both conventional inundation risks as well as velocity-driven erosion risks. Such interventions may improve the resilience of natural and coupled socio-geomorphological systems to the impacts of extreme events. Third, using anticipatory modelling approaches (> 100 years), different trajectories of future landscape responses to extreme events could be modelled. This approach could help provide a science-basis for the kind of anticipatory governance which Fuerth and Faber (2012) argue is required in the Anthropocene.

Shorter-term, near future interventions (next 50 years) to manage the risks, resilience and recovery of socio-geomorphological systems from extreme floods and storms

Geomorphologists have made substantive contributions to shaping the policy, guidance and risk-assessment methods used by practitioners in the fields of flood risk, coastal erosion (Temmerman *et al.*, 2013) and river restoration (e.g. Fryirs and Brierley, 2008) so that natural dynamics of geomorphological systems have been incorporated. Most of these contributions to date have been focussed on geomorphological processes in non-extreme conditions, with a few noteworthy exceptions including geomorphological and Quaternary science inputs to the UK's Foresight Future Flooding Programme (Evans *et al.*, 2004); helping insurance companies understand the long-term (e.g. 10 000 year) erosion and flood risks for nuclear power plants and assisting with geomorphologically-aware legislative changes or recommendations emerging after extreme events (see Table II for a summary). For example, following the devastating Tropical Storm Irene flood of 2011 that generated ~$1 billion in damages, the Vermont state legislature, in conjunction with the Agency of Natural Resources (ANR), strengthened its existing river corridor protection plan and in 2013 and 2014 passed Acts 16 and 107 which mandated that town plans include flood resilience as part of their future regional planning and further authorized ANR to include river corridor protections in the new state floodplain rules (Kline, 2016). Moreover,

Table II. A summary of different ways in which geomorphologists' have worked with policy-makers and practitioners to help manage the risks of extreme events and better adapt to these to improve socio-geomorphological resilience.

Type of engagement	Role(s)	Examples	Reference/links
• Advisory board • Steering committee	• Advise on activities to fulfill statutory and/or strategic goals	• Adaptation Scotland Advisory Network • Working with Natural Processes	• http://www.adaptationscotland.org.uk
High-level policy and/or science analysis	• Provide scientific advice and evidence to underpin strategic programmes and/or state of science reports	• Intergovernmental Panel on Climate Change (as author or editor); Prof. Marcel Stive, coastal geomorphologist, was an author. • Foresight Future Flood Risk; Prof. Colin Thorne, fluvial Geomorphologist was an author	• E.g. Wong *et al.*, 2014 • E.g. Evans *et al.*, 2004, https://www.gov.uk/government/publications/future-flooding
Risk Assessments	• Develop risk assessment tools • Revise recurrence intervals	• Coastal Erosion Susceptibility Mapping • Revised recurrence intervals • Geomorphic flux zones • Environmental risks to infrastructure	• E.g. erosion mapping, Fitton *et al.*, 2016 (see text) • E.g. improved recurrence intervals, see Bureau of Reclamation example in text. • E.g. freedom rivers, Biron *et al.*, 2014 (see text) • E.g. coastal flooding and erosion risks for nuclear power operations, ARCoES: https://www.liverpool.ac.uk/geography-and-planning/research/adaptation-and-resilience-of-coastal-energy-supply/
Extreme event response planning	• Geomorphological input to post-event recovery planning • Changes in legislation post-event	• Hurricane Sandy • Hurricane Irene prompted improved legislation	• E.g. Geomorphology recovery paths assessed, see text • Agency of Natural Resources, Vermont, see text and Kline, 2016.
Local scale adaptation	• Site to reach scale restoration or management activities	• River restoration designed to improve flood risk resilience of local properties	• E.g. Orangefield Park, Connsway Community Greenway, www.connswatergreenway.co.uk • Swiss River Rhône (see text)

these new river corridor bills are based on well-established geomorphic principles to help guide floodplain protection. Besides developing state programmes to teach stream equilibrium concepts to local agencies (e.g. Department of Transportation), the Vermont legislature further adopted two sets of state rules to protect infrastructure and to maintain stream channel functioning simultaneously. These new rules establish a set of performance-based standards for assessing and maintaining stream equilibrium, connectivity, and river corridor protection, with the goal of promoting fluvial processes that connect rivers and floodplains (Kline, 2016). Similarly, a United States Geological Survey (USGS) task force examined the geomorphic impacts of Hurricane Sandy and examined the knock on effects of these on society (Department of the Interior Strategic Sciences Group, 2013), thus assessing the socio-geomorphic risks associated with an extreme event. They conclude that, "coastal geomorphology is critical to regional resilience and ecosystem services," (Department of the Interior Strategic Sciences Group, 2013, p. 35).

These examples (Table II) demonstrate the potential for geomorphologists to serve as knowledge brokers at the science–policy–practice interface (Naylor *et al.*, 2012). We first outline how the science of geomorphology can be used to improve our risk assessments to improve society's ability to predict and manage their use of the landscape to improve resilience. We then identify ways in which we can work with natural geomorphic processes to help to attenuate the effects of floods and by working with these dynamics rather than seeing particular geomorphic features as static landscape units, to improve management of the socio-geomorphological risks associated with extreme weather and/or extreme climate events.

Revised flood and storm recurrence intervals

Geomorphologists can usefully improve flood risk calculations in two ways: (1) by enhancing our scientific capacity to understand and model the geomorphic responses to different combinations of flood and storm characteristics; and (2) by working more closely with flood risk agencies to improve coastal and flood risk assessments so that key aspects, such as palaeogeomorphological data and erosion risks, are included. Examples from the United States and Scotland illustrate this potential. As is typical elsewhere, flood frequency assessments in the United States rely on annual extreme value approaches such as Gumbel analyses or log Pearson Type III. Because annual floods series are generally limited temporally, they often lack a series of extreme events to include in the calculus. To combat these temporal shortcomings, the USGS provides regional skew coefficients to augment gauging stations with temporally limited flood series. The key reference for flood frequency analysis (FFA) in the United States follows guidelines established in "Bulletin 17" which was last updated (Bulletin 17B) in 1982 (USGS, 1982). Stedinger and Griffis (2008) recommend updating Bulletin 17B to address a key shortcoming by including historical information beyond the gauge record, especially the incorporation of outliers. They argue that these improvements would maintain the statistical credibility of its guidelines and improve the accuracy of risk and uncertainty assessments [although see Klemes (1986) on "hydrological dilettantism"]. Geomorphological approaches on both contemporary and palaeo timecales can help supply this crucial missing information (Baker, 2000; Foulds and Macklin, 2016; Toonen *et al.*, 2016).

For most of these statistical approaches, dealing with outliers represents the most significant conundrum as few approaches can effectively deal with maverick, but real, outliers. For example, as Pitlick (1997) showed for the Mississippi River flood of 1993, estimates of its recurrence interval are especially sensitive to the particular techniques used and their inherent assumptions. Estimations of the recurrence interval for the main stem ranged from a 500 year return period flood to a 1000 year return period flood depending on which outliers are included/excluded. Geomorphic contributions can and have offered important approaches for dealing with outliers (as described later). These field-based contributions have been incorporated by federal agencies, especially the Bureau of Reclamation that is concerned with dam safety issues, especially dam failure from exceptional precipitation or streamflow. Usually relying on traditional "probable maximum precipitation" (PMP) and "probable maximum flood" (PMF) approaches to model extreme events, the Bureau has begun to advocate the inclusion of historical and geomorphic approaches to enhance prediction of the magnitude of extreme floods (Levish, 2002; O'Connell *et al.*, 2002; England *et al.*, 2003, 2010). Within these approaches, the palaeoflood data are used to establish exceedence bounds for extreme floods. In a recent example of a geomorphological approach, Greenbaum *et al.* (2014) incorporated a well-dated and detailed stratigraphic analysis to show that two relatively recent floods (pre-historical but within the past 500 years) exceeded the PMF for the Colorado River. Depending on which hydraulic scenario is used, approximately 34 floods have exceeded the gauge-estimated 100 year flood in the past 2100 years. This alarming difference has important management implications but shows how a relatively straightforward geomorphic assessment can greatly enhance traditional flood frequency analyses. More recently O'Connor *et al.* (2014) have used palaeoflood techniques to evaluate nuclear power plant safety in the United States. This example shows that the power of geomorphological flood research lies in making better use of the historical record; that which has happened definitely can happen (Baker, 1998).

In Scotland, the Scottish Environmental Protection Agency (SEPA) has recently worked with coastal geomorphologists and revised their coastal flood risk maps in January 2016 to include coastal erosion susceptibility (Hansom *et al.*, 2013; Fitton *et al.*, 2016). These mapping outputs represent a substantive shift in flood risk policy by SEPA to consider both inundation flood and erosion risks, demonstrating the capacity for geomorphological science to influence flood risk policy. Dissanayake *et al.* (2015, p. 74) suggest that inclusion of more accurate erosion rates in their models of coastal risk will "form the foundation to move away from the traditional return period approach used to determine coastal damage in which erosion levels can be significantly underestimated". Further interactions with key stakeholders are needed at the interface between policy, science and practice to identify how best geomorphologists can work pragmatically (Baker, 2007) with practitioners to improve the use of current process, modelling and palaeogeomorphological data as part of policy and practice.

Using understanding of geomorphic dynamics to inform nature-based risk assessments

Nature-based approaches to flood risk management are increasingly being adopted by government agencies across Europe, in the UK and Australasia where the aim of practitioners is to reduce the reliance on engineered flood and coastal defence solutions and increase the amount of green engineering solutions that work with nature (e.g. coastal: Gewin, 2013; Vriend *et al.*, 2014; Arkema *et al.*, 2015; European Environment Agency, 2015; fluvial: Barlow *et al.*, 2014). The United Kingdom Environment Agency (Barlow *et al.*, 2014, p. iv) states "Working with natural processes [WWNP] means taking action to manage fluvial and coastal flood and coastal erosion risk by protecting, restoring and emulating the natural regulating function of catchments, rivers, floodplains and coasts." Geomorphological science can contribute to this rapidly expanding management approach in three ways.

First, it is increasingly recognized that understanding how geomorphic dynamics impact flood risk can be the means of more intelligent risk management (see earlier). For instance, in relation to fluvial flood risk, Lane *et al.* (2007) showed that there was an alternative to dredging upland rivers of gravel to reduce flood risk. Instead, high rates of gravel delivery were linked to historical deforestation that had increased the ease with which streams could incise into, and so mobilize, late Quaternary sediment deposits. By using intelligent (i.e. spatially targeted on the zones of highest erosion risk) native woodland expansion, it was possible to reduce gravel delivery rates, so reducing the need for ecologically damaging dredging.

Second, whilst landforms are by definition the result of the dynamic interaction of deposition and erosion of materials over the lifetime of their existence (with often complex temporal fluctuations in volume), they have the capacity to act as energy dissipaters and water flow diverters ("buffers") over the timescale of infrequent, high energy events. Arguably, hydrological and hydrodynamic knowledge of river and tidal water flow routing as well as of wind and tsunami wave dissipation processes has expanded exponentially since the mid-twentieth century. The importance of small (< tens of metres; e.g. Leonard and Luther, 1995; Smith *et al.*, 2016) to larger (tens to thousands of metres; e.g. Loder *et al.*, 2009) spatial scale landform surface characteristics in influencing flow patterns is increasingly recognized. Small scale studies on the effect of the surface roughness and/or drag caused by the presence of vegetation on floodplains (e.g. Antonarakis *et al.*, 2009), saltmarshes (e.g. Möller, 2006; Möller *et al.*, 2014; Lara *et al.*, 2016), seagrass beds (Paul *et al.*, 2012), and mangroves (Mazda *et al.*, 2006) provide key examples of how both laboratory and field studies have been used to improve the representation of these bio-geomorphological effects within hydrodynamic models. This geomorphological science is informing the design of coastal protection schemes that integrate natural systems within flood protection schemes in several countries (Costanza *et al.*, 2006; Kabat *et al.*, 2009; Borsje *et al.*, 2011). However, whilst the design rules for traditionally engineered structures in relation to the frequency of extreme events are well established, and their long-term maintenance costs well estimated, the likely future performance of soft engineering solutions is not well known, particularly under extreme water level and wave loading. Geomorphology, therefore, has an important role to play in both the design and subsequent post-emplacement monitoring of natural river and coastal protection.

Thirdly, much recent geomorphological research has begun to address how this knowledge can be used to help society mitigate and/or adapt to environmental change (see e.g. Borsje *et al.*, 2011; Spalding *et al.*, 2013; European Environment Agency, 2015; Dixon *et al.*, 2016). For example, Dixon *et al.* (2016) model the potential for floodplain forests to help attenuate floodwaters; the modelling results show that there is some potential for this to be part of a suite of green engineering approaches to natural flood management. One important finding is that the flood risk benefit of these interventions is delayed

(> 25 years), due to the lag between planting and flood attenuation benefits. Recent research also demonstrates that river typology exerts a strong control on buffering capacity of vegetation. For instance, Surian *et al.* (2015) showed that the reduction of flood erosion vulnerability of vegetated bars is much more rapid in braided river systems than single thread systems. These examples demonstrate how geomorphological knowledge is crucial to working more effectively with natural processes as part of flood mitigation activities, and that geomorphological solutions will be most successful at reducing risk or attenuating flows if implemented sooner rather than later.

While the use of landforms as "buffers" against extreme events is now widely recognized and discussed in practical terms, the lack of knowledge of the potential impact of extreme events on the resistance and recovery potential of these buffering landforms still challenges hazard management approaches that rely on these landforms function. Adequate assessments of stability and recovery times after extreme events must be established for the range of landforms that fulfill hazard mitigation functions. Geomorphological observations of storm and storm surge impacts in the field (e.g. Spencer *et al.*, 2015a; Naylor *et al.*, 2016; Terry *et al.*, 2016) and the laboratory (e.g. Möller *et al.*, 2014; Spencer *et al.*, 2015b) as well as systematic global analyses of controls on bio-sedimentary landform evolution (Balke and Friess, 2016) begin to address this knowledge gap and point the way to a quantification of energy and material thresholds that govern processes, rates, and impacts of erosion and sedimentation (recovery) phases.

Present day floodplain and channel morphodynamics in many parts of Europe (Dotterweich, 2008; Lewin, 2013; Macklin *et al.*, 2014), Asia (Zhuang and Kidder, 2015) and North America (Knox, 1977) have been shown to be strongly conditioned by historical and pre-historic land-use as well as the deliberate and inadvertent effects of engineering (Lewin and Macklin, 2010). This has considerable implications for flood risk mitigation as many river systems worldwide can be considered as "genetically" modified (cf. Macklin and Lewin, 2010; Lewin, 2013) where "natural" river and coastal processes are more constrained, producing a suite of dynamic and evolving semi-natural river channel and floodplain or coastal landforms. For "working with nature" approaches to be successful, we need to understand how "genetically modified" landforms behave differently from those in more natural geomorphic contexts, and manage the risks of climate change accordingly.

Although the semi-natural condition of catchment and fluvial systems has been recognized in recent WWNP reports (DEFRA, 2014), more geomorphic understanding may improve our ability to deliver successful WWNP. For example, reconnecting rivers to their floodplains could be improved in two ways. First, the floodway capacity in embanked systems could be improved to restore more natural floodplain function. Embanked systems usually have internal drainage systems but where these are no longer available or efficient, return-flow scour may create new channels by rapid headward extension through soft floodplain sediments (Macklin and Lewin, 2010). Sedimentation restricted to a near-channel zone by flood embankments leads to a build-up of material and elevation of the channel zone above general floodplain level. The floodway capacity between embankments is significantly reduced, whilst the potential for avulsion into the floodplain is increased (Lewin and Macklin, 2010). This may have substantial human impacts (see earlier). Designing re-connected floodplains with greater floodway capacity may reduce the risks of avulsions in more engineered settings. Secondly, a good understanding of industrial landscape history (and toxins stored) may reduce the risk of WWNP schemes resulting in very significant health impacts caused by re-mobilizing these contaminants, as happened following major flooding in mid-Wales during summer 2012 (Foulds *et al.*, 2014). Geomorphologists can thus aid managers to understand how human impacts alter the natural regulating function of semi-natural catchments, rivers, floodplains and coasts and enable improved emulation of natural processes when using WWNP methods to manage flood and erosion risks.

Geomorphological flux zones and vulnerability points

Landscapes are comprised of a series of landforms, which change over time, and there are strong feedbacks between the processes operating and the form of the landscape [see, for example, the description of these feedbacks in the coastal context in Cowell and Thom (1994)]. These dynamics are a fundamental part of the science of geomorphology. However, many land management practices often overlook these dynamics by seeing particular landforms (e.g. river channels) or boundaries (such as the coastline) as fixed in space and time. For example, whilst recent shoreline management planning in England is forward looking (to 2100) in terms of coastal erosion and change of the landscape in the future, the language used (e.g. "hold the line") still projects a very fixed view of the landscape (DEFRA, 2014). By understanding these dynamics under historic, recent and predicted future extreme events, geomorphologists can help identify zones of active geomorphic change where human developments are likely to be impacted (e.g. through cliff erosion, high sedimentation or river channel migration) by extreme events. These data can help identify zones of landscape change which can aid planners and regulators in identifying areas least able to recover on short (i.e. years–decades) timescales and thus may be less suitable for development. This approach has been proposed by Macklin and Harrison (2012) who recommended that rates and patterns of historical and present-day channel change (derived from serial Ordnance Survey maps, aerial photographs and remote sensing) enable the identification of "vulnerability points" within river corridors. These are reaches where the probability of flood-related channel movement is high and where properties and critical infrastructure are most at risk. For example, sections of rivers which are most likely to be frequently flooded and highly mobilized leading to substantive changes in river morphology, such as those experienced in the Calgary 2013 floods in Canada (Tamminga *et al.*, 2015). Biron *et al.* (2014) presented a framework for this form of river management and argue that it can aid fluvial and ecological river resilience to climate and land-use changes. Similarly, the Swiss government has been pursuing its "third correction" of the Swiss River Rhône (http://www.rhone3.ch), which is based upon setting back embankments to create a wider active zone, most likely with an anastomosing character. We propose that these innovative ideas can be used as a framework for shifting our perceptions and practice of flood risk alleviation. Instead of focussing solely on producing flood risk maps, it is perhaps more advantageous to also produce geomorphic flux zones in fluvial systems that clearly identify where extreme events will most likely lead to substantive reworking of sediment and reorganization of key morphological features (e.g. rivers moving across the historic floodplain) that will adversely impact on riverside communities. These zones could usefully inform development plans and flood management policy to identify areas where natural processes are likely to be the most dynamic, with the greatest effect on society – so that appropriate management interventions such as planning restrictions can be put into place (Biron *et al.*, 2014). Adopting this approach as the basis for long-term strategic planning, may lessen the human impacts caused by sediment and erosion during "extreme flood and storm events" (see earlier). It also ties flood risk management into wider approaches to river restoration based upon the identification of the "historical range of variability" (e.g. Rathburn *et al.*, 2013).

Similar principles could be applied at the coast and in estuaries, to identify those coastal regions most at risk of substantive geomorphic change due to extreme storm surge and flood events. Here, fluxes refer to substantive changes in the morphological configuration of a coastline as well as to erosion risks. Estuaries are often heavily influenced by human activity that can lead to regime shifts (Winterwerp *et al.*, 2013). Future management of these systems will thus require these shifts and thresholds to be identified, along with the generating mechanisms behind them. Estuarine sedimentary evolution is still commonly addressed via aggregated models predicting bulk sediment volume changes (Rossington *et al.*, 2011). However, these models lack the spatial resolution and process representation to be able to inform how, and where, the internal response of the estuarine system leads to persistent changes. Instead, models ought to rely on approaches better suited to reproduce the detailed estuarine sediment pathways (Brown *et al.*, 2013) due to internal dynamics and feedbacks, external forcing, and antecedent conditions [e.g. for the vegetated upper intertidal regions that act as important coastal protection features (Spencer and Reed, 2010)].

Recovery times of coastal systems would need to be incorporated, as palaeogeomorphological studies have shown that large-scale coastal landform shifts in response to extreme events, such as the creation of new barrier islands (Fruergaard and Kroon, 2016), can take decades. Identifying regions prone to large-scale landscape state changes (e.g. gain or loss of barrier beaches or islands) would aid managers in identifying those areas where geomorphological adjustment to extreme events may be too large and too slow, for affected communities to occupy the new landform state (e.g. a new barrier island). Other systems may change too frequently for communities to be sustained in the future. Identifying zones of substantive geomorphic flux has the potential to signpost these risks, alongside areas that are likely to experience substantial erosion.

Where flux zones are not feasible such as in already built up urban areas, two alternatives to conventional practice may improve resilience to extreme events. First, in places where hard engineering of rivers and coasts prevents natural reshaping of systems over time, there may be value in exploring how to manage these geomorphic changes so that coupled human-geomorphic systems can become more resilient to extreme events (i.e. they are less impacted by or recover more swiftly). Secondly, it may be helpful to move to a perspective on urban areas which views the city as a catchment which can be reshaped and managed under extreme events to create a more geographically-informed, geomorphologically sensible solution to living with extreme events. In this regard, a good example of managing the effects of intense rainfall is provided by the Copenhagen cloud burst plan (City of Copenhagen, 2012). This concept can be extended to include identifying areas of high sedimentation risk that may be mediated by applying biogeomorphic buffers to trap sediments in parks and open spaces that are designed to attenuate flow and capture these sediments during extreme rainfall events. Geomorphologists could work alongside urban hydrologists and landscape architects to test some of these ideas.

Anticipatory futures modelling (near future to >100 years)

To adapt and to improve resilience to an increasingly extreme world, scenarios and models of how geomorphic systems have responded to past, and may respond to future, extreme events are required (Van De Wiel *et al.*, 2011; Lane, 2013). Futures modelling is needed to explore risks and probabilities of geomorphic change, even where data is uncertain and where geomorphic systems have been seen as too complex to model in this way (Lane, 2013). Specifically, simulations of future landscape and landform responses to extreme events are needed to demonstrate the potential reshaping of our landscape and to estimate the potential for geomorphological interventions to buffer the social and ecological impacts of future extreme events. Fruergaard and Kroon (2016) demonstrate how one extreme coastal storm led to a radical reshaping of the coastline in the Wadden Sea over a few decades. Such changes to a coastline today would potentially be economically and socially catastrophic, as evidenced by the effects of Typhoon Haiyan (Lapidez *et al.*, 2015), Hurricane Katrina and Superstorm Sandy. A useful futures modelling exercise could be to use palaeostorm events to model the impacts of future events in the same region based on the current configuration of the coast. What would happen if a 1:1000 year event happened today? Lapidez *et al.* (2015) have applied this idea by modelling the effects of Typhoon Haiyan on the entire Philippines coastline to identify areas that are most at risk of a similar magnitude event.

Antecedent condition scenarios

Scenarios of different antecedent trajectories may be usefully modelled to aid understanding of how coupled shifts in geomorphological conditions, land-use changes and climate patterns such as more persistent weather in Northern Europe might increase or decrease the effects of extreme climate events. For example, the effects of an extreme storm on a set of landscape dynamics and associated human impacts could be tested under a scenario of extreme rainfall induced flooding after periods of persistent wet, cold and dry conditions. Projected future changes in human impacts on the landscape and the growth of nature-based approaches to flood and coastal erosion risk could then be tested against extreme storm and flood frequencies to inform policy about their utility under more extreme conditions. Data to underpin these models can be drawn from recent flume experiments by Möller *et al.* (2014) who demonstrated that saltmarshes buffered up to 60% of wave energy under simulated extreme inundation/wave events and from palaeoreconstruction studies that demonstrated coastal vulnerability to storms increased after anthropogenic over-harvesting of oyster beds (Brandon *et al.*, 2016).

Contributions to earth surface models and climate models

The recent assessment by the IPCC has shown that the effects on ecosystems of changes upon the frequency or intensity of climate-related extreme events are understudied and poorly represented in earth system models (Settele *et al.*, 2014). Recent model simulations examining the effects of climate change on soil moisture properties using coupled climate and earth surface models has suggested that further work is needed to evaluate "the underlying processes in existing climate models" (Seneviratne *et al.*, 2013, p. 5216). Moreover, Taylor *et al.* (2012) argue that there is considerable uncertainty over how soil moisture properties will affect the impact of convective storms due to a lack of observational data and model uncertainty. Geomorphologists are well-suited for measuring spatial and temporal variations in the surface moisture distributions of a range of landforms, such as sand dunes (e.g. Nield *et al.*, 2011), that may affect convective storms and thus rainfall models under a changing climate.

For coastal regions, the IPCC reports that the relative lack of detailed studies of severe storm surges and their effects on flood and erosion hazards, geomorphic systems and society creates

Table III. Five grand challenges for geomorphological science in an age of climate extremes.

Challenge number	Grand challenge	Disciplines and roles required
1	Revising theories of expected behaviour and process-form response trajectories in light of how geomorphic systems have responded to past and recent extreme storms and floods.	Geomorphologists and critical zone scientists
2	Establish a coordinated, focussed portfolio of interlinked research activities and research network on the geomorphological interactions with climate extremes that couples long-term palaeodata with sufficient current process monitoring and modelling of multiple types of data, at a range of scales.	Geomorphologists, palaeoclimate scientists, hydrologists, sedimentologists and ecologists
3	Joint projects with climate scientists to better incorporate geomorphology into climate models to reduce land surface uncertainties.	Geomorphologists alongside climate and ecological modellers
4	Enhance relationships with practitioners and policy-makers so that the latest geomorphological science can usefully inform key geomorphologically-based topics including "Working with Natural Processes", "Nature-based solutions" and flood and storm recurrence interval calculations.	Geomorphologists with practitioners and policy-makers (engineers, risk assessors, practicing geomorphologists) at national and finer management scales
5	Improve our geomorphological datasets on landform instability and landform changes associated with extreme climate events. Work more closely with land-use planners to consider geomorphic flux zones alongside flood inundation risk maps to improve resiliency of future human development to socio-geomorphological risks.	Geomorphologists with risk assessors, land-use planners and policy-makers

considerable uncertainty in predicting storm surge results (Wong *et al.*, 2014). Thus they have assigned low confidence for these impacts, although extreme flooding associated with severe storm surges is deemed a key hazard (Wong *et al.*, 2014). More energetic and more frequent storms (even if not directly linked to climate change) will exacerbate climate change influences on coastal erosion (Wong *et al.*, 2014), but more examples of the impacts of extreme storms on geomorphic responses are needed (Masselink and Russell, 2013). Geomorphic understanding of coastal responses to palaeo and current extreme storms and floods is rapidly growing and can increase the evidence base on the impacts and resilience of coastal systems to storm surges. These data need to inform earth surface system models so that the geomorphological shifts and flood buffering capacity can be better encapsulated in these models. This is required to characterize landscape-scale responses to climate-related extreme events more accurately. These geomorphologically-informed earth surface system models could then be meaningfully coupled with climate models to predict future landscape-scale responses under different climate change scenarios. These models would help us to identify geomorphological risks associated with particular climate "tipping elements". Such models could also be validated by hindcast modelling, using palaeoflood frequency datasets (e.g. Benito *et al.*, 2015b; Foulds and Macklin, 2016; Toonen *et al.*, 2016).

Conclusions

In this state of science paper we identify how geomorphology may assist climate impact scientists, and society in general, towards a better understanding of coupled human–landscape vulnerabilities and responses to extreme storms and floods in an age of climate extremes. The recent increases in flood and erosion damages globally reflect a combination of not only changes in temperature, precipitation and storminess but also changes in land use and inappropriate development (e.g. in floodplains). Many climate-related drivers often occur simultaneously or in swift succession where antecedent geomorphic, land-use and climatological conditions exert a strong influence on the resilience of geomorphic and human systems to cope with individual extreme events. Indeed, recent research has also shown that even non-extreme events can be amplified by antecedent geomorphic and land-use conditions, resulting in substantive societal impacts and landscape change. The response, resilience, relaxation and recursion of geomorphic systems to these interacting, cumulative risk factors is only just starting to be explored. Further research on this topic is required (Phillips and van Dyke, 2016).

Geomorphological science adds important scalar dimensions to understanding flood risks, whether this flooding manifests itself either temporally or spatially – at scales which rarely get attention from the engineering community or by policy-makers (Baker, 1994, 1998). In essence, considerable geomorphic attention over the years has not only focussed on extrinsic controls on flood generation (e.g. precipitation magnitude/intensity, flood hydro-climatology, etc.) but also on the important inherited geologic boundary conditions that act as first-order controls on flood magnitude and timing. As Croke *et al.* (2016) point out, the Pleistocene aggradational and incisional history of rivers in southeast Queensland (Australia), in concert with the inherited geologic controls on reach scale slope, largely condition and explain the loci of flood inundation – in terms of both water level and flood duration. Hence communities at risk are not randomly situated within a catchment or determined merely by channel proximal locations as the longer-term geologic controls dictate flood risk. Moreover, a geomorphic acumen that is aware of geologic and geomorphic settings can be an important planning and management view that can help alleviate (or explain/dictate) flood risk. Nowhere is this more evident than in arid to semi-arid settings, such as the American southwest, where urban expansion into flood-risk alluvial settings continues in an unabated fashion. Here policy-makers and regional planners appear unaware of the geologic setting where currently "dryland" climatic conditions are inset geomorphologically and climatically into more active Pleistocene settings. In the Pleistocene, the impacts of channel processes, seemingly dormant on contemporary timescales, were extremely profound (Pelletier *et al.*, 2005; Youberg *et al.*, 2014). Thus it is imperative that the geomorphological community finds ways to work with policy-makers and practitioners, to develop more resilient land, flood, storm and erosion risk management policies. Table II provides a useful starting point for the ways in which the global geomorphological community can work at the science–policy–practice interface.

This paper highlights the complex, spatially-explicit interactions and interdependencies between geomorphic processes, landform and landscape characteristics on the one hand and flood and erosion risks from moderate to extreme weather events on the other hand. Recent research shows the strong potential for geomorphological processes and current landscape topographies to amplify or dampen the risks of inundation, erosion and resultant effects of these process-form responses on society. For example, Spencer *et al.* (2015a) demonstrate that substantive spatial variability of storm surge flood elevations can result from local scale variations in coastal bathymetry, topography and the extent of different coastal habitats. This has implications for predictions of flood risk under storm surges. How can we use such data to inform engineering and flood risk assessments, such that inclusion of local variations in system sensitivity to extreme events leads to effective flood and risk management for coastal communities? Details mentioned earlier clearly illustrate a pressing need to better account for both erosion and flood inundation societal risks from high to extreme river flows. This means that traditional models of flood and storm impact and geomorphic recovery patterns (e.g. winter erosion and summer recovery of beaches) may no longer be fit for purpose in an age of extremes. A key challenge for the geomorphology community is: (1) to capture and to explain geomorphological variability in a meaningful way; and (2) to identify metrics to help predict and characterize these complex interactions for use by allied disciplines and managers alike.

Landforms respond to energy exposure by re-configuring the materials of which they are composed when energy levels exceed the thresholds of motion of these materials (be they rock, sediments, biota, or a combination of all these components). At this fundamental level, landforms are no different to human constructions, such as sea walls or flood embankments. The relative geometric and geotechnical simplicity of the latter, however, facilitates quantification of failure thresholds. Thus it is a relatively straightforward task for an engineer to calculate a specified failure probability under a given extreme event with a given likelihood of occurrence (Spalding *et al.*, 2013). By contrast, the geometric and geotechnical complexity of "structures" that result from the cumulative action of geological, climatic, hydrodynamic, and biological processes over long (> decadal) timescales, makes generalizations about their risk of failure almost impossible and the identification of "stability indicators" a necessity (Renaud *et al.*, 2013; Temmerman *et al.*, 2013).

We urgently need to work more closely with engineers, ecologists and landscape planners to identify local to regional scale stability indicators, geomorphic fluxes (e.g. Biron *et al.*, 2014; Croke *et al.*, 2016), erosion susceptibility maps (e.g. Fitton *et al.*, 2016) and areas at risk of geomorphic state changes (Phillips and van Dyke, 2016). This will allow us to make geomorphologically informed land-use planning designs, thereby improving our socio-geomorphological resilience to increasing climate extremes. This would enable society to better understand and to plan for the landform instability and landscape changes associated with extreme climate risks. To facilitate this process, we identify the following opportunities for further work by geomorphologists, in close coordination with a range of other disciplines, practitioners and policy-makers (Tables II and III).

Table III presents five grand challenges that will help embed geomorphological science more fully within the global climate change science on the one hand and with the adaptation policy and practice community on the other hand. For example, by working more closely with climate modellers, we could improve land surface uncertainties in these models and sharpen our predictions of climate change risks and impacts on society. Similarly, we have outlined the strong potential for geomorphologists to work alongside policy-makers and practitioners to improve our risk assessments and resilience to extreme events. We encourage the global geomorphology community to build on these examples through improved knowledge exchange and applied research activities with key sectors such as government agencies, infrastructure owners and insurance companies. Whilst this paper focussed solely on the geomorphological impacts of, and interactions with, extreme floods and storms, our approach can be usefully extended to other types of climate-extreme effects on geomorphic dynamics and landscape responses, such as coping with droughts, urban heatwaves and rapid snow and ice melt.

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