10 Flood hazards: the context of fluvial geomorphology

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10.1 Introduction

River flooding occurs as high water inundates the adjacent floodplain, and is controlled by a combination of discreet processes operating at local and watershed scales. A floodplain is the relatively flat alluvial landform adjacent to a river that is more or less related to the modern flood regime (Wolman and Leopold, 1957; Nanson and Croke, 1992; Knighton, 1998; Bridge, 2003). Most floods are natural events vital to river and floodplain geomorphological (Leopold *et al*., 1964) and ecosystem processes (Hupp 1988; Junk *et al*., 1989; Thoms, 2003). When humans are impacted, however, floods become "natural disasters" (Figure 10.1). For thousands of years floods have been among the most common and severe natural disasters on Earth, in terms of economic damage and loss of life.

Floods in most river basins are caused by excessive rainfall generated by a variety of atmospheric mechanisms (Smith and Ward, 1988; Slade and Patton, 2002). In cold-winter regions, large floods can be generated from snow/ice melt, particularly in combination with rainfall, while along coastal-draining rivers extensive flooding may be associated with storm surge events. Floods are also generated from catastrophic failure of artificial (reservoirs) and natural lakes, a category that includes dams created by ice, glacial moraines, volcanic lava flows, and landslides (Costa, 1988). Flood hazard refers to the potential of a given flood to threaten human life and property (Smith, 1996). Assessment of flood hazards is critical for appropriate flood risk management, which should span the before, during, and post flood event periods to understand, prevent, and mitigate flood hazards and their potential impacts on humans, ecosystems, and natural resources (Smith and Ward, 1998). Flood hazard management includes all planning measures implemented within the upper basin and floodplain to mitigate flooding, and usually includes physical modification of the floodplain and river channel (Goddard, 1976). Flood hazard assessment and management has been dominated by a legacy of "hard" engineering approaches, which in many cases has increased flood risk (White, 1945; Pinter, 2005; Pinter *et al*., 2008). Most approaches to flood management seek to minimize energy dissipation and increase channel conveyance, but effective flood management should also strive to maintain the "natural" geomorphological functioning of river channels and floodplains to retain lateral and longitudinal connectivity of water, sediment, and nutrients (e.g. Junk *et al*., 1989; NRC, 2005). Traditional engineering approaches use standardized probabilistic and hydraulic procedures defined by government agencies based on generalized accepted principles (e.g. 100-year flood) reproducible and defensible in a court of law if engineering structures fail (Wolman, 1971; Baker *et al*., 2002). Because of the lack of extensive instrumental flood data sets, however, modern rigorous hydraulic and hydrologic models cannot actually be validated without the base-line flood data provided by sedimentary and geomorphological approaches (Baker *et al*., 2002; Lastra *et al*., 2008).

Fluvial geomorphology has a substantial legacy in analyzing flooding from modern to millennial time-scales, and is increasingly recognized as a vital discipline to rigorously assess flood hazards in response to local and global scale environmental change (House *et al*., 2002a; Figure 10.1). Over the last two decades increased societal demands for the maintenance and restoration of fluvial ecosystems and dissatisfaction with continued flood devastation, even within heavily managed rivers, has stimulated scientific interest in the application of fundamental geomorphological concepts and methods as a complementary approach to flood mitigation and management

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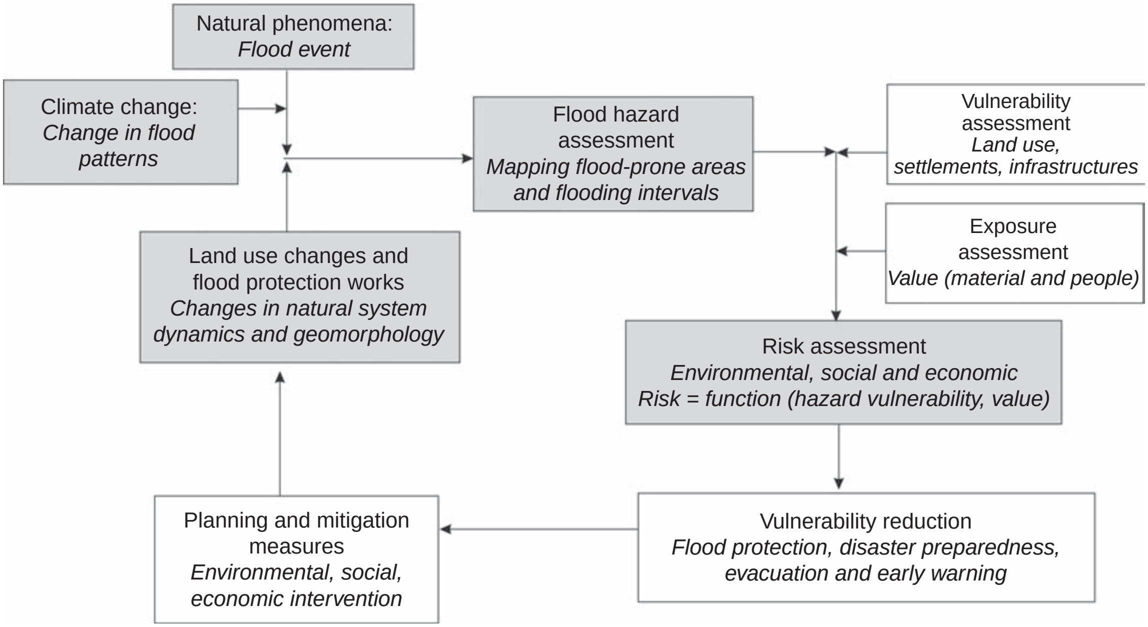

FIGURE 10.1. Basic components for flood risk assessment and management. Geomorphological studies and contributions are mainly directed to fields shown by gray squares.

(Gilvear, 1999; Baker, 2008). Fluvial geomorphology is increasingly contributing to flood management science (Gregory *et al*., 2008) and the evolution of the discipline parallels complementary advances in computational fluid dynamics, digital remote sensing and geographical information systems (GIS), and geophysical data acquisition and analysis (e.g. Bates *et al*., 2006), enabling a more comprehensive understanding of how geomorphological approaches are relevant to flood hazard analysis (Lewin, 1989; Baker *et al*., 2002).

This chapter examines flood hazard assessment and management from the context of the scientific discipline of fluvial geomorphology. The chapter reviews fundamental concepts and methodological approaches commonly utilized within fluvial geomorphology to understand and analyze flooding, spanning from watershed to local spatial scales. The chapter highlights the linkages between flood hazards with different floodplain styles and flood processes, illustrating distinctions between small upland rivers and large lowland rivers. In addition, it provides an overview of approaches to exploit the Quaternary and historical sedimentary flood record, and illustrates its importance for estimating flood risk in the context of global climate change. The chapter concludes by discussing the geomorphological impact of fundamental flood management approaches, and outlines a new paradigm in flood management that strives to enhance and restore "natural" geomorphological and ecological processes.

10.2 Fluvial geomorphology in flood hazard assessment

Fluvial geomorphology has approached flood hazard analysis from several angles. The first approach estimates the hydrological response of small basins ($\leq 50\,\text{km}^2$) utilizing parametric models relating flood hydrograph characteristics (e.g. peak runoff, lag time) to quantitative drainage network and shape indices (catchment area, shape, drainage density, stream network geometry). These concepts were developed by Horton, Strahler, and Schumm in the 1940s and 1950s, and have become increasingly robust (e.g. Rodriguez-Iturbe and Valdés, 1979; Gupta *et al*., 1980). A second approach delineates flood hazard zones in broad alluvial valleys by mapping flood-related landforms and deposits, soil and plant associations, and flood observations. A third approach involves energy-based inverse hydraulic modeling of discrete paleofloods located in appropriate settings as slackwater deposits (SWD) and other paleostage indicators (Kochel and Baker, 1982; Baker, 2008). This approach is limited to bedrock and confined valleys, but provides accurate discharge estimates of rare floods and subsequent flood frequency analysis, with numerous applications to flood hazard problems (Benito and Thorndycraft, 2005). All three perspectives have tremendously benefited in recent decades with advances in numerical modeling, geospatial methodologies such as global positioning systems (GPS), digital photogrammetry and high resolution remote sensing (e.g. ALS, SAR, LiDAR), and geographical information systems (GIS) (e.g. French, 2003; NRC, 2007), as well as increasing use of computational fluid dynamics (Bates *et al*., 2005).

10.2.1 Flooding and flood hazards at the drainage basin scale

Because the drainage basin is a fundamental control on stream hydrology (Horton, 1945; Gregory and Walling, 1973), the characteristics of flooding are influenced by a range of factors at the watershed scale. Relevant hydrologic factors controlling runoff generation and flooding are (1) drainage network morphometry, (2) hillslope soil infiltration, (3) geology related to structure, tectonics, and surface erodibility, (4) vegetation and land use, and (5) meteorological-climatic conditions (Patton, 1988). Drainage basin morphology, catchment size, and relief are important controls on flood hydrology such as concentration time, hydrograph shape, and flood peak (Edson, 1951; Rodriguez-Iturbe and Valdés, 1979; Gupta *et al*., 1980). For many decades these flood–geomorphological relationships have been found to be relatively valid at regional scales where hydroclimatology and geology control stream network development (Horton, 1945; Maxwell, 1960; Morisawa, 1962; Patton and Baker 1976; Patton, 1988; Knighton, 1998; Ward and Trimble, 2004).

The first attempt to combine drainage area and flood magnitude (peak discharge) was conceived by Dickens (1865) in India, and later by Jarvis (1936) in the USA. The equation shows an exponential relation ($Q_T = a.\ A^b$) between annual peak discharge (Q_T), estimated for a particular return period (T), and drainage area (A). The exponent b varies between 0.5 and 0.8 (Jarvis, 1936), or 0.5 to 0.9 (Thomas and Benson, 1970), depending on the region considered, and generally decreases as the flood return period increases. Although somewhat limited because of not considering the physical processes of runoff generation (Patton, 1988), a set of regional curves for different return periods can be constructed to reasonably approximate annual peak discharges. When fitted with paleoflood data the approach is well suited to questions concerning changes in flooding associated with projected climate change scenarios (Enzel *et al*., 1993), which may ultimately be utilized to identify an upper hydroclimatic limit in precipitation and peak discharge for a given drainage basin (Wolman and Costa, 1984).

An additional approach at the drainage basin scale examines the influence of drainage density on runoff generation and flood propagation (Horton, 1945; Gregory and Walling, 1973; Baker, 1976), because network geometric parameters condition runoff connectivity and travel distances. Different indices can be constructed from drainage density and morphometric characteristics (basin shape, area, stream length, and relief), and may be used for developing empirical equations to model stream flow (Mosley and McKerchar, 1993). The application is limited, however, because of a lack of extrapolation to different regions (Patton and Baker, 1976), and because of the usage of various techniques to define the extent of drainage networks (see Mosley and McKerchar, 1993). Additionally, drainage density develops over a much longer time period than the relatively short time periods of climate stability, such that relict drainage morphometry formed during older climatic regimes may not produce representative hydrogeomorphic indices (Patton, 1988). Nevertheless, the topologic characteristics of drainage networks have been utilized by modelers to identify a basin-scale transfer function to deal with inherent non-linearity, which represented a problem to the classic unit hydrograph (UH) approach developed by Sherman (1932) as well as Nash's (1957) instantaneous unit hydrograph (IUH). The geomorphological unit hydrograph (GUH) formulated by Rodriguez-Iturbe and Valdés (1979), later generalized by Gupta *et al*., (1980), attempts to relate the IUH of a catchment to the geometry of the stream network, so that relevant parameters of the IUH such as peak discharge, shape, and time to peak can be related to geomorphological drainage characteristics deduced from the Strahler (1957) stream order and Horton's (1945) "laws of drainage networks".

10.2.2 Flooding and flood hazards at the floodplain (local) scale

The consideration of discreet flood processes in relation to floodplain geomorphology results in several categories of floodplain styles (e.g. Nanson and Croke, 1992) of importance to flood hazard management. Along most fluvial systems floodplain styles range along a continuum upstream to downstream, from confined narrow high-energy floodplains to broad low-energy floodplains. Flood hazards and flooding are characterized by three main valley profiles representative of upstream (Fig.10.2.I), middle (Fig. 10.2.II), and downstream (Fig. 10.2.III) reaches of a typical fluvial system. These valley geometries have significance in terms of discharge-stage relationships, energy dissipation, flood processes, area of inundation, and flood occurrence, and represent varying hazards as related to human settlement and damages (Figure 10.2; Table 10.1).

The inundation of floodplain surfaces within confined narrow river valleys (cross-section I; Figure 10.2), particularly within small mixed bedrock–alluvial valleys, is

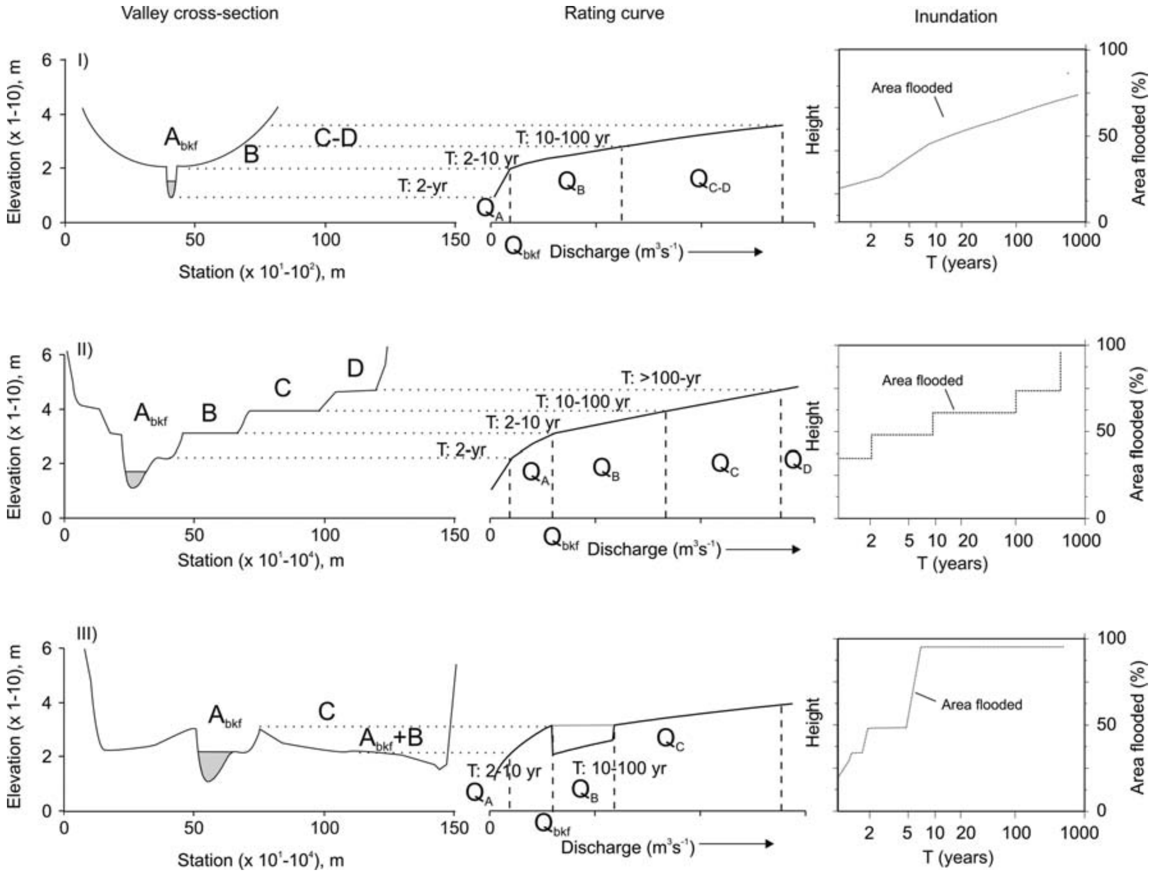

FIGURE 10.2. Models of floodplain morphology and flooding characteristics in the upstream (I), middle (II), and downstream (III) reaches of alluvial river valleys, including the general shape of rating curve and area inundated. The area of flood inundation follows the cross-sectional morphology, and can be linked to flood damages if a curve of exposure and property value is known.

primarily driven by high amounts of precipitation within the upper watershed. This setting may result in "flashy" events (short lag times) with large energy expenditure (unit stream power) on the floodplain surface (Nanson 1986; Grant and Swanson, 1995; Wohl, 2000). The flood process is simple overbank, and is not augmented by groundwater or surface conduits (e.g. crevasses, sloughs, paleochannels). Such settings may be readily identified by considering planform dimensions obtained from aerial photographs or topographic maps, and have ratios of channel width (W_C) to valley width (W_V), generally $< 0.5 W_C/W_V$ (Grant and Swanson, 1995). The floodplain geomorphology of such settings is generally reworked within a cycle of floodplain rejuvenation (Nanson, 1986), and thus provides discreet evidence for understanding flood hazard potential. Specific aspects of the floodplain geomorphology useful to understand the degree or stage of cyclic reworking include soil development (thickness and sequence of soil horizons), floodplain topography (relief and slope), and flood deposits (texture and thickness). Flood hazards are characterized by physical damage, such as undermining bridges and roads, washing away of human settlements, and destruction of the physical setting by altering the floodplain geomorphology (e.g. floodplain stripping).

Floodplains within middle reaches (cross-section II; Figure 10.2) are commonly composed of coarse-grained lateral accretion sediments (bottom stratum) covered by vertically accreted fine-grained flood sediments (top stratum) (Brakenridge, 1988; Bridge, 2003). Floodplain morphology exhibits different floodplain surfaces directly associated with different flood frequencies. While not all floodplain styles exhibit the same characteristics, similarities often exist in the types of specific channel and floodplain geomorphological units (flood zones A to D in Table 10.1; Ballais *et al.*, 2005). Channel bed unit (zone A; Table 10.1) includes channel lag, high-energy bar deposits, and low-stage slackwater facies (Brakenridge, 1988). Adjacent to the outer channel banks, the lower floodplain

TABLE 10.1 *Geomorphological description of flood hazard zones in relation to geomorphological units of a typical floodplain. Note that these zones may vary for specific fluvial systems, hydroclimatological conditions, and floodplain geometry. Flood zones are referred to Figure 10.2.*

Flood zone	Relative flood magnitude	Return frequency (years)	Geomorphological unit	Sedimentary facies	Dominant geomorphological processes	V m s^{-1}	Vulnerable land use/land cover	Perceived flood risk (relative to a human lifespan)
A	Q_A: minor flood	< 2	Channel	Channel lag, point bar, side bar, longitudinal bar, chute, low-stage slackwater facies (e.g. clay drapes)	Seasonal sediment flushing, coarse sediment mobility, incision, erosion–deposition zone	>2	In-channel infrastructure and economic activities (fishing, shipping). Highly dangerous to people	High risk: flooded every year
B	Q_B: moderate flood	2–10	Low floodplain	Lateral accretion, natural levee (sandy ripples and dunes adjacent to channel fining to silt laminations on natural levee flanks), high flow channel (floodway), crevasse splay, oxbow infilling, slackwater sedimentation in low depressions and backswamps	Channel migration and channel bar development, bank erosion, coarse floodplain aggradation. Irregular topography	>1	Riparian vegetation, gravel mining; agriculture and floodplain irrigation (in lesser developed nations). Dangerous to human life	Medium risk: seen 4–6 times
C	Q_C: large flood	10–100	High floodplain	Slackwater flood deposits on low Holocene terraces, significant backswamp sedimentation (fine sediments in slackwater ponded), and sloughs	Dominant vertical accretion, infilling of paleomeanders, activation of recently abandoned channels; channel avulsion; floodplain reworking	usually <1	Agriculture and floodplain irrigation, recreation areas, transportation infrastructure; rural and urban habitation (in lesser developed nations). Only dangerous to people when water depth >1 m	Low risk: 1–2 times
D	Q_D: extreme flood	>100	Low terrace/ highest floodplain	Slackwater flood deposits on older Quaternary terraces and high bedrock ledges; coarse overbank "stringers" on distal floodplains	Colluvial, tributary and alluvial fan accumulation; floodplain "stripping" (e.g. Nanson "cyclic disequilibrium model")	<1	Agriculture and irrigation, flood management infrastructure; urban areas with high population densities (developed nations). Not dangerous to human life	Very low risk: 0–1 times

surface is characterized by an irregular topography formed by frequent flooding (return periods 2–10 years) containing depositional (e.g. crevasse splay) and erosional landforms (high-flow channels) with medium to coarse sands, and occasional gravel (Table 10.1, zone B). This lower floodplain is usually covered by riparian vegetation, which significantly favors flood energy dissipation. The distal (lateral) floodplain contains morphological evidence of former river meanders, episodically inundated by extraordinary floods (10 to 100 year return period). Here, the sedimentology is composed of fine-grained sediments (silt and clay) infilling backswamps, paleomeanders (oxbow and oxbow lake environments), and backwater sloughs along valley margins (Table 10.1, zone C). The low relief and episodic flooding favors human activities (agriculture, roads, and mining), and settlements on the distal (upper) floodplain. The lower river terraces (late glacial) or the highest floodplain surface may be flooded by extreme floods (>100 to 500 year floods; zone D in Table 10.1), indicated by fine sands and silts on older alluvium and soils. On valley sides, the floodplain may contain additional alluvial and colluvial deposits from adjacent high surfaces, including slope and cone deposits, and alluvial fans.

Broad floodplains (cross-section III in Figure 10.2) within wide alluvial valleys or deltas, in contrast to confined narrow valleys, have a more complex floodplain geomorphology that requires consideration of local controls on floodplain inundation. Large floodplains, having low W_C/W_V ratios, are associated with long duration flooding with low unit stream power (Nanson and Croke, 1992; Ferguson and Brierly, 1999). Additionally, these settings generally have fine-grained cohesive floodplains and sufficient space to store older channel belts, as well as high degrees of lateral (hydrologic) connectivity (Mertes, 1997; Burt *et al.*, 2002; Poole *et al.*, 2002). Here, the floodplain sedimentology and topography represents an important control on flooding. In large lowland alluvial valleys (Figure 10.2.III), the meander belt (channel and active floodplain) is perched above the lower-lying floodplain bottoms, increasing the complexity of flood processes (Hudson and Colditz, 2003). During local-scale floods (return periods ~2–10 years), longitudinal flow paths are mainly confined by natural levees (flood zone B; Figure 10.2.III), although lateral flow paths may stagnate distant floodplain bottoms. Flooding of natural levees occurs less frequently than floodplain bottoms (return periods of ~10–100 years; Table 10.1, flood zone C), with a much lower duration, mainly associated with watershed-scale flood mechanisms (Hudson and Colditz, 2003). In combination with fine-grained cohesive top stratums, these settings can remain inundated for weeks and months after river stage has receded (Badji and Dautrebande, 1997; Hudson and Colditz, 2003), a severe limitation to many types of human activities and hazardous to floodplain agriculture. Older buried coarse-grained channel belts that intersect the active channel represent pathways for rapid groundwater flow (Sharp, 1988; Poole *et al.*, 2002), which can then inundate distant floodplain reaches, even beyond river dikes (levees). High surface connectivity represented by crevasses, sloughs, oxbow lakes, and abandoned channels can be "reoccupied" during a flood event and result in flooding and sediment dispersal in distant floodplain areas (Gomez *et al.*, 1997).

10.2.3 Flood hazard mapping

Flood hazard mapping is a fundamental tool for flood risk assessment and management, and the recognition of different fluvial styles suggests that multiple techniques are required (e.g. Dunne, 1988; Pelletier *et al.*, 2005). Flood hazard maps include the extent of flooding for a given flood recurrence interval, and other fundamental hydraulic information such as flood depth, velocity, and frequency of inundation (Wolman, 1971). Much research in this sector of the discipline is for applied study, funded by government agencies or insurance companies, and is commonly accompanied with flood risk maps that illustrate the area of inundation and the potential damage impact, including human risk, economic value, and impacts on environmental systems (Figure 10.1). The final aims of flood hazard mapping often include (1) support for flood management plans, (2) spatial land use and planning activities, (3) emergency and evacuation plans, and (4) increased public awareness of flood risks.

Traditional hydrological approaches concerning flood hazard analysis are based on the estimation of peak flood discharge (Q_2, Q_{10}, Q_{50}, and Q_{100}) and corresponding flood stage levels for events of various frequencies of occurrence or return periods (where Q_N represents N-year flood), for which associated estimated damages are established for each probability (flood risk map and model). Flood maps based on hydraulic-hydrologic modeling approaches are expensive and require long instrumental discharge or rainfall records, which makes it difficult to cover extensive areas of a state or nation. However, the concept of "acceptable risk" has become widely used, in which delineation of flood-prone areas is based on multicriteria including stream gauge records, geomorphological mapping of flood-related landforms, historical evidence (documentary), and occasional flood events (Figure 10.3). This philosophy underlies the European Council Flood Risk Directive 2007/60/EC (EC, 2007), under which flood hazard maps should distinguish three main flood zones, namely floods with low probability (extreme event scenarios), floods with medium probability (likely return period ≥100 years), and floods with high probability. Some European countries

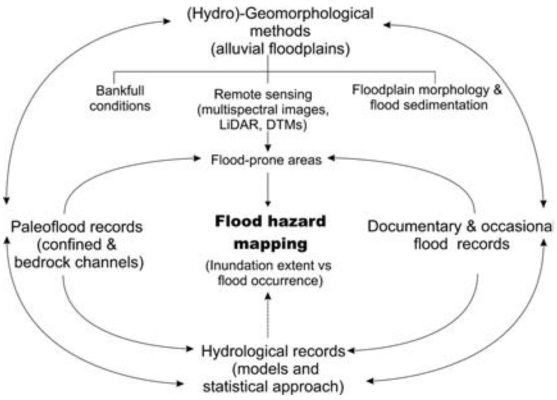

FIGURE 10.3. Integrated methodological approach for flood hazard mapping, based on hydrological, geomorphological, paleoflood, and historical records.

(e.g. France and Spain) recommend that geomorphological criteria be integrated with conventional flood hazard mapping approaches to fulfill the European Directive (DIREN-PACA., 2007; Díez-Herrero *et al*., 2008).

Flood hazard maps based on a geomorphological approach utilize aerial photography or remote sensing imagery combined with field work to map flood-related landforms, sediments, and high-stage indicators (Baker *et al*., 1988; Garry and Graszk, 1999). A first approach to floodplain mapping is the identification of two assemblages of deposits and landforms: channel deposits (base flow and high-flow channels), and channel bank and overbank deposits (lower and upper floodplain surfaces). Flood hazard maps also commonly delineate a channel migration zone (CMZ), including recent channel activity and changes (migration) based on aerial photos and historical maps (e.g. Rapp and Abbe, 2003). Additional flood indicators refer to pedogenic conditions, such as soil development, stratification, and drainage (Smith and Boardman, 1989), and biological flood markers, including distinctive floodplain (riparian) vegetation assemblages, and specific vegetation types (e.g. indicator species) related to high-water conditions (e.g. Foxcroft *et al*., 2008). These physical and biological flood indicators can be combined with hydraulic-hydrological estimates and data from occasional historical flooding to provide relevant hydraulic data directly related to flood stage levels (e.g. water depths, flow velocity).

Recent advances in geospatial methodologies (e.g. French, 2003; NRC, 2007) and absolute dating techniques (Duller, 2004) substantially improve the reliability of geomorphological flood mapping. Common sources of geospatial data used in flood mapping include global positioning systems (GPS) (Hudson and Colditz, 2003), digital photogrammetry, and high-resolution ground and airborne remote sensing techniques (e.g. ALS, SAR, LiDAR) (Smith, 1997; NRC, 2007) to develop topographic products such as digital elevation models (DEMs). The use of airborne light detection and ranging (LiDAR) has tremendous potential for floodplain mapping because of the high vertical (~10 cm) and horizontal (1,000,000 points per km^2) resolution. LiDAR is an active sensory system mounted on an airborne platform that uses laser light to measure distances between the sensor on the airborne platform and points on the ground (or a building, tree, etc.). The data provide substantial details on flood-related landforms and can easily be integrated with traditional remote sensing (aerial photos and satellite imagery) (NRC, 2007). An additional major technological development to support flood geomorphology studies is numerical age dating of fluvial sediments (sand and silts) and organic materials. Radiocarbon dating of organics (e.g. seeds, charcoal, wood, peat, shells, bones, etc.) is a standard absolute dating tool employed for alluvial sediments (e.g. Baker *et al*., 1985). New developments in optically stimulated luminescence (OSL) dating (Duller, 2004), and new analytical protocols such as the single-aliquot regenerative-dose (SAR) for determining the equivalent dose (Murray and Wintle, 2000) provide very accurate numerical dating of alluvial sediments, with age uncertainties of 5–10%. Additionally, this approach yields accurate dates for deposits younger than 300 years, a period associated with considerable measurement error in radiocarbon dating (Duller, 2004).

10.2.4 Estimation of rare events using paleoflood hydrology

Significant advances in understanding flood hazards have been provided by using paleoflood hydrology to quantitatively estimate the magnitude and chronology of large floods over the past millennia. Paleoflood studies involve many different techniques relying on regime-based studies of discharge capacity (e.g. bankfull discharge) of alluvial channels (Williams, 1988) and sediment transport-flow competence analysis (Costa, 1983; Williams, 1988; Komar, 1989). The most developed approach, however, is based on flood stage indicators in stable bed-rock channels (Baker and Kochel, 1988; Baker, 2008).

Flow competence evaluations are based on selective-entrainment relationships (empirical and physically based equations), usually based on the largest clasts (Carling, 1983; Costa, 1983) providing mean-flow stress, velocity, and discharges per unit flow width. Deficiencies and constraints of this method are mainly related to inherent problems with entrainment equations, being largely inadequate to predict incipient motion because of issues related to grain sorting, vertical armoring, sediment packing, and mechanisms of grain pivoting versus sliding (Komar, 1989).

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The most successful paleoflood techniques are based on field reconnaissance of high water marks (HWM), slackwater flood deposits, and other paleostage indicators (SWD-PSI), which are combined with conventional indirect methods to estimate peak flood discharge magnitudes (Baker, 2008). Paleoflood hydrology has undergone a revolutionary development in the three decades since Kochel and Baker (1982) coined the term (see recent review by Baker, 2008). A major achievement is the establishment of a core array of standardized protocols for the collection of field data and quantitative techniques for estimating paleodischarge. Such procedures can now be included within standard statistical flood frequency analysis. Importantly, the procedures have gained scientific credibility and recognition as an effective tool for numerous applications in understanding flood occurrences and the evaluation of flood hazards (Baker *et al*., 2002; Saint-Laurent, 2004; Benito and Thorndycraft, 2005; Baker, 2008).

Sources of paleoflood data include geological and botanical indicators such as slackwater flood deposits at high rock ledges, silt lines and erosion lines along the river channel, terraces, and canyon walls (Baker and Kochel, 1988; Greenbaum *et al*., 2000). The methodological steps to conduct a paleoflood study include: (1) preliminary inventory of potential sites using aerial photographs, (2) field visit and survey for the identification and selection of flood indicators (flood deposits and marks), (3) stratigraphical description with emphasis on identifying flood units, (4) sample collection for age dating, (5) topographic survey of flood sites and river reaches, (6) hydraulic modeling and discharge estimation, (7) comparison with available historical data, and (8) flood frequency analysis.

Sedimentary environments associated with slackwater flood deposition include: (1) channel widening, (2) channel expansions, (3) channel bends, (4) obstacle shadows where flow separation causes eddies, (5) alcoves and caves in bedrock walls, (6) back-flooded tributary mouths and valleys, and (7) on top of high alluvial or bedrock surfaces that flank the channel (Baker and Kochel, 1988; House *et al*., 2002b, Benito *et al*., 2003a; Benito and Thorndycraft, 2005). In these environments, depositional landforms include thick, high-standing terraces or “benches”, and eddy bars. The flood benches are formed by vertical accretion of slackwater sediment layers deposited by successive floods, which constitute a rising threshold or local censoring level over time (Figure 10.4). Dating of sedimentary flood units (radiocarbon, OSL, Cs-137) provides an understanding of flood frequency, and for recent flooding enables the identification of human recorded events in cases where historical, instrumental, and paleofloods temporally overlap. In Europe, paleoflood hydrology has been combined with information about floods in the pre-instrumental period (last 500 years) from oral and documentary sources (Benito *et al*., 2003b; Thorndycraft *et al*., 2003; Werritty *et al*., 2006).

The stage associated with the different paleoflood units (paleostages) can be readily converted into discharge values using widely accepted hydraulic procedures (e.g. Jarrett, 1987; O’Connor and Webb, 1988). In fact, this conversion is an inverse problem, with the flood discharge obtained by trial and error using a hydraulic model to compare the observed river stage with simulated stage levels. The calculated discharges are minimum discharge values, since the water depth at the site of deposition is unknown (Figure 10.4). These models assume a fixed bed, hence the importance of application on bedrock channels.

Paleoflood hydrology techniques provide an accurate catalogue of flood discharges and their age dating. This paleoflood record can be combined with gauge station data for the estimation of the statistical moments. The basic hypothesis in the statistical modeling of paleoflood information is that all floods exceeding a certain water level or magnitude (threshold of discharge) have been registered through sedimentary records and/or other paleostage indicators (Stedinger and Cohn, 1986). In hydrology, flood observations reported as having occurred above some threshold are known as censored data sets (Leese, 1973). Paleoflood information is considered data censored above a threshold (Figure 10.4) and it is assumed that the number of k observations exceeding an arbitrary discharge threshold (X_T) in M years is known, similar to partial-duration series (Stedinger and Cohn, 1986; Francés *et al*., 1994). The value of the peak discharge for the paleofloods above X_T may be known or unknown. Paleoflood data are organized according to different fixed threshold levels over particular periods of time exceeded by flood waters. Estimated flood discharges obtained from the minimum high-water paleoflood indicators and maximum bounds (non-exceeded threshold sense, Levish *et al*., 1997) can be introduced as minimum and maximum discharge values (Figure 10.4). Estimation of statistical parameters of flood distribution functions (e.g. Gumbel, LP3, Generalized Extreme Value) are calculated using maximum likelihood estimators (Leese, 1973; Stedinger and Cohn, 1986), the expected moment algorithm (Cohn *et al*., 1997), and fully Bayesian approach (O’Connell *et al*., 2002; Reis and Stedinger, 2005). This provides a practical framework for incorporating imprecise and categorical data as an alternative to the weighted moment method (U.S. Water Resources Council, 1982).

The fields of application of paleoflood hydrology include (Benito and Thorndycraft, 2005): (1) flood risk assessment (Baker *et al*., 1988; House *et al*., 2002b; Thorndycraft *et al*., 2003; Benito and Thorndycraft, 2004), (2) determination of the maximum limit of flood magnitude (Enzel *et al*., 1993) and non-exceedence as a check of the probable maximum flood

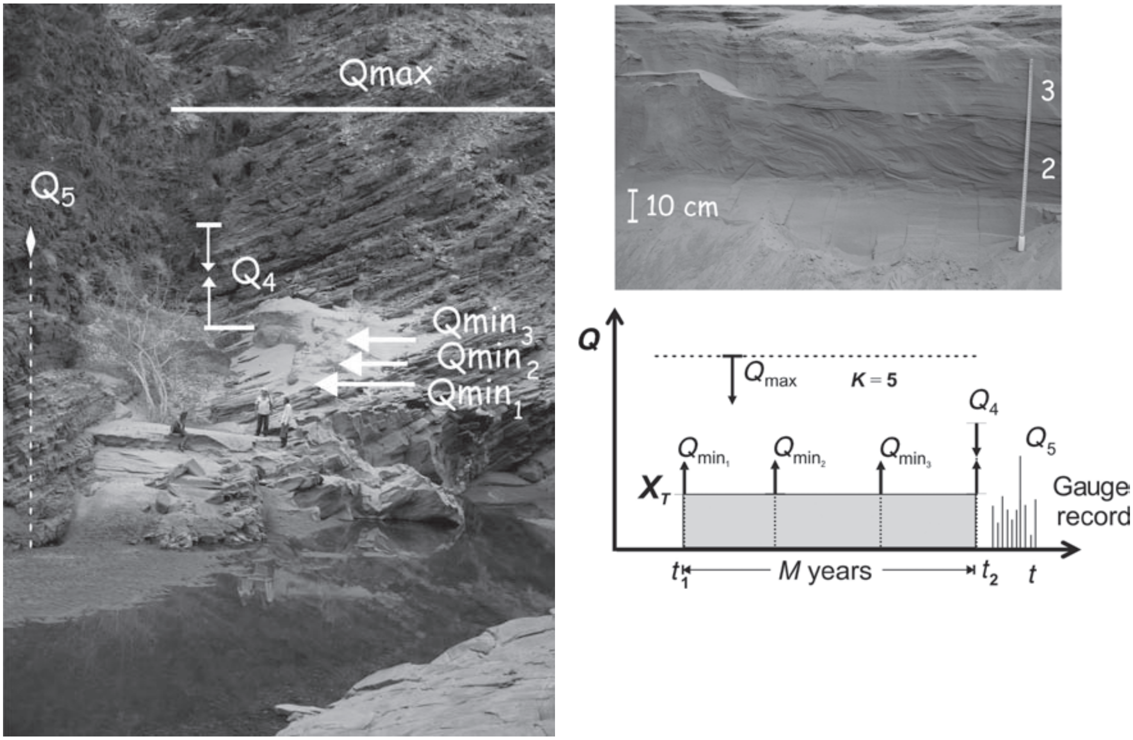

FIGURE 10.4. Slackwater flood deposits of the Kuiseb River (Namibia) with indication of paleostages associated with multiple flood events. The paleoflood records are censored data sets above a threshold and it is assumed that the number of *k* observations ($k = 5$) exceeding an arbitrary threshold (X_T) in *M* years is known.

(PMF) and safety risk analysis of critical facilities (e.g. dams and wastewater facilities and power plants; Levish *et al*., 1997; Benito *et al*., 2006; Greenbaum, 2007), (3) a better understanding of long-term flood–climate relationships (Ely, 1997; Knox, 2000; Thorndycraft and Benito, 2006; Benito *et al*., 2008), and (4) assessing sustainability of water resources in dryland environments where floods are an important source of water to alluvial aquifers (Greenbaum *et al*., 2002; Grodek *et al*., 2007). An alternative to the analysis of slackwater flood deposition methodology was developed by the U.S. Bureau of Reclamation to be applied to dam safety purposes based on paleostage exceedance information and paleohydrologic bounds (Levish *et al*., 1997; England *et al*., 2006). A paleohydrologic bound is physically located on a terrace or abandoned floodplain surface, at a high elevation, on which a paleostage has not been exceeded sufficiently to modify its surface (non-exceedance threshold) during a time interval obtained from age dating of soils and of scarce flood deposits.

10.3 Flood hazards in the context of global climate change

Historical and projected global climate change has raised concerns about flooding and flood hazards (Kundzewicz and Schellnhuber, 2004). Climate change projections, however, are generally within the range of climate change that occurred over the middle and late Holocene (Knox, 2000). Paleoflood records have revealed the sensitivity of flood magnitude and frequency to subtle alterations in atmospheric circulation (Knox, 1993; Ely, 1997), which have also been observed during the instrumental period because of climatic forcing (Knox, 2000; Redmond *et al*., 2002). Shifts in climate may have a greater impact on the estimation of large flood quantiles (50-year flood and higher), which have been found to be highly sensitive to climate variability (Knox, 2000). Analysis of gauge records has shown that hydroclimatic homogeneity may have only occurred for 30-year intervals during the twentieth century (Webb and Betancourt, 1992). This must be considered in flood frequency analysis (Baker *et al*., 2002), and has significant implications for the design of more effective approaches to flood management.

Paleoflood records provide rigorous data for understanding how future climatic variations might influence flood magnitude and frequency (Knox, 2000; Knox and Daniels, 2002; Macklin *et al*., 2006; Starkel *et al*., 2006). The aim of these studies is not necessarily to provide analogues of future flood–climate episodes but to analyze flood response to climate shifts. Paleoflood records from slackwater flood deposits of Spanish rivers show distinct flood periods at 1000–600 BC, AD 900–1100, AD 1450–1500 and AD 1600–1900 (Thorndycraft and Benito, 2006; Benito *et al*., 2008). Some of these flood periods are consistent with those found in other European countries, and in the SW United States (Ely, 1997). The direction of climatic shift is not unequivocal, with flood episodes related to cold (wet) conditions (phases 1000–600 BC, AD 1450–1500 and AD 1600–1900), while others were related to greater hydroclimatic variance (warming-dry periods: phase AD 900–1100). Anomalous magnitudes of recent floods, such as the 2002 flood of the Gardon River (France), the largest on record since 1890, occurred more frequently during the Little Ice Age (Sheffer *et al*., 2008), a period characterized in the Mediterranean by extreme variability in episodes of flood and drought (Barriendos and Martín Vide, 1998). Floodplain stratigraphy in the upper Mississippi (Knox and Daniels, 2002) has also provided excellent proxy records to characterize long-term changes in the flood frequency and magnitude, showing a clustering of small floods between 5,000 and 3,300 years BP, and a general increase in flood magnitude after 1,000 years BP, particularly between about 700 and 500 years BP. However, floodplain aggradation requires sufficient sediment yield and overbank flows, hence some recent aggradation episodes may respond more strongly to major environmental impacts in the basin (deforestation, land-use changes) than to specific climate change signals (Benito *et al*., 2008).

10.4 Geomorphological adjustment to flood management

Flood hazard management most commonly involves a variety of approaches coordinated across a range of government agencies and stakeholders (WMO, 2004; Hudson *et al*., 2008). Common goals of flood management are (1) reduction in the area of inundation to increase habitable lands, (2)

TABLE 10.2. *Common options associated with flood control*

Approach	Intention (rationale)	Unintended geomorphological response
	Floodplain modifications	
Dikes (levees) and flood walls	Reduce area of inundation (creation of embanked floodplain)	Change in floodplain hydrology, generally higher flood stages and rates of flood sedimentation; reduction of floodwater storage capacity; infilling of floodplain water bodies and wetlands; dike breach ponds; enhanced seepage and sand boils behind dikes; floodplain "borrow pits"
Drainage canals and relief wells	Remove waters attributed to rising groundwater and dike seepage	Oxidation of floodplain soils; ground subsidence and change in local drainage
Pumping	Remove waters attributed to rising groundwater and dike seepage	Oxidation of floodplain soils; ground subsidence and change in local drainage
Floodways	Bypass corridors and detention to store floodwaters; lower flood stage	Variable sedimentation and scour within flood diversion corridor and basins
	Channel modifications	
Straightening (cutoffs)	Lower flood stage and increase flood conveyance; reduce flood frequency; reduction in channel length, increase in channel gradient	Knickpoint formation, channel incision and bank erosion; downstream channel bed aggradation; creation of new floodplain oxbow lakes
Bank protection (revetment and rip-rap)	Manage bank erosion, protection of dikes	Reduction of channel sediment loads; possible channel bed scour
Groynes (wing dikes)	Align river channel, reduce channel width by selective aggradation of bed material	Increase in roughness at high water, possible increase in flood stages
Dredging	Removal of local bed material associated with shoaling	Localized channel bed change and formation of dredge spoil bars

reduction in flood stage and peak discharge, and (3) reduction in flood duration. Modern flood management strategies generally involve a variety of approaches to physically modify the floodplain and channel (Table 10.2). Fundamental engineering modifications to the floodplain include dikes (levees) to reduce the area of inundation, drainage canals and pumping to remove excessive water, and floodways to reduce downstream flood stages. Channel engineering procedures include straightening to increase flood conveyance, including channel reshaping, canalization, and enlargement, bank protection to reduce erosion, groynes (wing dikes) to reduce channel width, and dredging to manage channel bed aggradation. Although these techniques are extensively utilized all over the world, their effectiveness is highly dependent upon a detailed understanding of modern hydrological and geomorphological processes as well as the Quaternary sedimentological framework of the associated fluvial system (Winkley, 1994; Smith and Winkley, 1996; ASCE, 2007; Hudson *et al*., 2008). Over the past decade there has been increased attention concerning the unintended geomorphological and environmental consequences associated with conventional flood management options (Smith and Winkley, 1996; Hesslink *et al*., 2003; Pinter *et al*., 2006, 2008; Hudson *et al*., 2008).

The construction of earthen dikes (levees) is the oldest approach to managing flood hazards, having been done along many of the world's great rivers, such as the Nile, Tigris-Euphrates, Yangtze, Danube, and Rhine, for hundreds and even thousands of years (Van Veen, 1962; Butzer, 1976). When properly designed, river dikes can be highly effective in minimizing flood risk, enabling large populations to safely reside adjacent to major river systems (NRC, 1995). Dike construction, however, abruptly alters fundamental floodplain processes and floodplain geomorphology (Middelkoop, 1997; Hesselink *et al*., 2003; Glynn and Kuszmaul, 2004; Hudson *et al*., 2008). The embanked floodplain (river side of the dikes) is significantly narrower than the natural floodplain, which changes flood hydrology and sedimentation processes (Figure 10.5). The narrower floodplain results in higher flood stage levels and greater floodplain shear stress. Floodplain sections landward (behind the dikes) are effectively removed from most active overbank fluvial processes. However, serious flood hazards remain because of groundwater inundation (NRC, 1995; Li *et al*., 1996). This is because the higher embanked flood stages change the alluvial groundwater hydrology, enhancing dike under-seepage and resulting in an increase in the frequency of emergent sand boils that can destabilize dikes (Li *et al*., 1996; Glynn and Kuszmaul, 2004). This is particularly problematic when dikes and floodwalls are constructed atop unsuitable sedimentary deposits such as permeable sands and organic rich clays (US-ACE, 1998; Glynn and Kuszmaul, 2004), increasing the risk associated with floodplain economic activities and urban populations (NRC, 1995; Pinter, 2005; ASCE, 2007). Despite relief wells and drainage channels along 150 km of the Lower Mississippi River, for example, the 2008 spring flood resulted in the formation of 40 sand boils and landward inundation of over 40,000 hectares.

The modification of floodplain processes associated with dike construction changes the floodplain geomorphology. The change in flood hydrology and hydraulics alters flood sedimentation processes, disrupting the classical fining sequence (e.g. Kesel *et al*., 1974; Pizzuto, 1987), and resulting in greater variability in overbank sedimentation rates and texture (Middelkoop, 1997; Hesselink *et al*., 2003). Over long time periods this results in an anthropogenic style of floodplain architecture (Hesselink *et al*., 2003). Accelerated floodplain aggradation infills oxbow lakes and floodplain depressions, reducing the capacity of the floodplain to store flood waters, resulting in higher flood stages (Middelkoop and Van Haselen, 1999; Silva *et al*., 2001; Glynn and Kuszmaul, 2004). Over longer periods the construction of dikes is associated with the formation of unique anthropogenic floodplain water bodies, dike breach ponds and

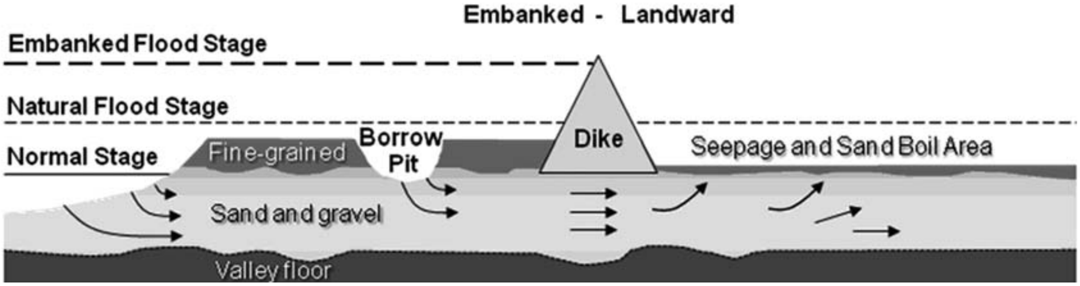

FIGURE 10.5. Embanked floodplain hydrology of a large alluvial river. Groundwater flow depicted at flood stage with high hydraulic head. Note thicker overbank (fine-grained) deposits associated with higher rates of embanked sedimentation because of dikes trapping flood sediments. Borrow pit formation is associated with dike (levee) construction.

borrow pits (US-ACE, 1998; Hudson *et al*., 2008). Further, the groundwater inundation of landward floodplain reaches requires a network of pumps and canals for floodplain drainage, which fundamentally initiates a sequence of human response and geomorphological adjustment. Over long periods floodplain drainage results in oxidation of hydric floodplain soils and ground subsidence. The lower surface is thereby more susceptible to groundwater inundation and flooding, which requires further land drainage and represents a greater flood hazard in the event of dike breach events (Van Veen, 1962; van de Ven, 1993). In addition to dikes and floodplain drainage, flood management often includes a significant amount of channel engineering to increase flood conveyance and to reduce flood stage and duration. The most significant type of channel modification is straightening by meander neck cutoffs (Hudson *et al*., 2008), which reduces channel length and increases channel gradient (Winkley, 1994). Channel cutoffs result in the formation of a channel knickpoint, which incises and subsequently migrates upstream (Yodis and Kesel, 1992; Toth *et al*., 1993; Winkley, 1994; Smith and Winkley, 1996; Shankman and Smith, 2004; Harmar *et al*., 2005; Hudson and Kesel, 2006; Simon and Rinaldi, 2006). The incision is generally effective at initially lowering flood stages, but over time flood stages may increase in height (Smith and Winkley, 1996; Wasklewicz *et al*., 2005). Where multiple cutoffs are located along a valley reach, knickpoints initiate a distinctive sequence of geomorphological responses that require further engineering solutions to maintain a stable channel and to minimize flood risk (Hudson *et al*., 2008).

Flood management infrastructure is designed for discharge–stage relationships having a specific recurrence interval, such as the “100-year flood” (NRC, 2007). A number of allogenic factors, however, can result in changes to the external boundary conditions, thereby increasing flood risk. Specifically, these include ground subsidence, neotectonics, climate change, and, at the coast, sea level rise. Ground subsidence and downwarping along fault zones is important along large alluvial valleys and delta plains, such as the Lower Mississippi and Rhine systems (Schumm, 1986; Dixon *et al*., 2006). Within several decades vertical displacements of 2–3 mm per year can significantly lower dike levels, such that lower magnitude floods present greater flood hazards (Dixon *et al*., 2006). Much flood management infrastructure represents a safety concern because of being decades old and in need of maintenance and upgrading, and may be inappropriately designed for our contemporary understanding of flood dynamics and floodplain geomorphology (e.g. Nanson, 1986; Mertes, 1997), ongoing human-induced environmental change (Gregory, 2006), or to the hydrologic implications of various climate change scenarios (Kundzewicz and Schellnhuber, 2004; IPCC, 2007; NRC, 2007). Indeed, the management of flood hazards is a pressing societal concern, and requires a comprehensive perspective over long time-scales to understand flooding in response to varying climate–land cover scenarios.

10.5 Flood hazard management: an integrated approach

The concentration of human settlements and economic activities along river systems demands that scientists and government agencies develop new effective measures to manage flood hazards. This is required because: (1) the increasing global population and associated economic activities will remain dependent upon floodplain lands and resources; (2) an appreciation exists for documented historical and late Quaternary global hydroclimatic change, and concerns over projections of future change beyond the boundary conditions that flood management infrastructure was designed for; and (3) in many instances the old hard engineering approach triggered socially unacceptable environmental change, and in some instances initiated a sequence of geomorphological responses that increased human vulnerability to flooding (Hudson *et al*., 2008). The confluence of these concerns represents the stimulus for a paradigm shift in the management of flood hazards, towards an approach increasingly referred to as “integrated flood management” (WMO, 2004).

As with traditional forms of flood management, the primary goal of integrated flood management (IFM) is to minimize loss of life (Silva *et al*., 2001; WMO, 2004). A major philosophical difference with traditional engineering flood control, however, is that IFM views flooding as a positive attribute of the fluvial system because of its importance to geomorphological and ecological processes (e.g. NRC, 2005), and as such is inherently more environmental. While IFM does not seek to constrain human activities on floodplains that could have adverse economic activities, it does embrace a longer-term perspective of the fluvial system, and prioritizes floodplain land use that does not have adverse environmental impacts (WMO, 2004). Fundamental tenets of IFM commonly include the following: (1) Flood control should be interdisciplinary to understand the myriad of geomorphological, hydrological, ecological, and social processes occurring within a floodplain. (2) Floodplain land use should be ranked by economic measures, and prioritized by its environmental impact. (3) Local stakeholder concerns should be integrated into the decision-making process, such that flood management options are in better accord with community priorities and values. (4) Government agencies

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should adopt a flexible approach to implementing flood control, such that new knowledge can be integrated into the program. (5) Monitoring is fundamental to IFM, and should be implemented before, during, and after specific flood control measures are implemented, and particularly after large flood events. Monitoring should include an array of ecological, hydrological, and geomorphological processes (WMO, 2004).

IFM represents a collection of ideals more than an exact flood control plan. Because flood control is implemented by large government agencies it is difficult to abruptly change philosophical approaches, or expend the financial resources to replace existing flood control infrastructure. Thus, while IFM represents a paradigm shift in thinking, the actual implementation of IFM is more nuanced, and highly dependent upon financial, political, cultural, and physical conditions within the nation of implementation. Nevertheless, the fundamental tenets outlined above are championed by international organizations, such as the European Union (EC, 2000) and the United Nations World Meteorological Organization (WMO, 2004). IFM is particularly important for developing nations because they are considered more vulnerable to flood hazards associated with climate change than developed nations (e.g. Kundzewicz and Schellnhuber, 2004; IPCC, 2007). In 2000 the European Parliament passed the Water Framework Directive (WFD) (EC, 2000), which explicitly attempts to implement an IFM approach through a series of policies with measurable goals and timetables. An excellent example is the "Room for the River" plan developed for the lower Rhine in the Netherlands (Middelkoop and Van Haselen, 1999; Silva *et al*., 2001). The Room for the River flood management plan was developed in response to large flood events in 1993 and 1995, public dissatisfaction with the environmental impact of traditional flood management, and a strong awareness of the threat of climate change to lowland floodplains. The Room for the River program is currently being implemented and explicitly takes into account new ideas in floodplain sciences (geomorphological, hydrological, and ecological) and climate change projections.

10.6 Conclusions

Fluvial geomorphology is vital for attaining a comprehensive understanding of flood hazards. For decades fluvial geomorphologists have worked to better understand the timing, controls, and historical changes in flooding and floodplains. With the development of new techniques and advances in digital remote sensing, GIS, and geophysical data, fluvial geomorphology is poised to make substantial contributions to the science of flood hazard management.

This chapter has reviewed a number of important concepts and approaches within fluvial geomorphology relevant to the topic of flood hazard management. The major points include: (1) Fluvial geomorphology has made important contributions to the spatial analysis of flooding, at watershed to local scales, whereby flood processes and flood hazards vary along a continuum with systematic downstream changes in floodplain styles. (2) Traditional hard engineering approaches to flood control have, in many instances, led to adverse geomorphological impacts that triggered unintended geomorphological and environmental changes that undermine existing flood control efforts. (3) Flood management will remain an important societal issue, although individual river basins should strive to attain "integrated flood management" (IFM) to address different types of local-scale environmental change, and for adapting to different environmental change scenarios. (4) Paleoflood data can be quantitatively employed in rigorous models to significantly extend the flood record. Further, the use of paleoflood data implies that, in many instances, different climate change scenarios are inherently integrated into the data set used to design flood control infrastructure. Thus, in an era of global climate change the use of paleoflood data is especially appropriate, and can be integrated into an IFM approach.

Flood hazards have been a mainstay of society since humans first settled upon the banks of the Tigris–Euphrates and Nile Rivers. The crux of the issue is how to assure personal and economic safety from flooding, while maintaining the geomorphological and environmental integrity of the fluvial system. In the context of a changing global environment and a tremendous increase in global population, flood hazard management will long remain an important societal issue and a vital scientific topic, and is best served by explicitly considering fundamental concepts and approaches within the science of fluvial geomorphology.

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