Paul F. Hudson · Hans Middelkoop *Editors*

Geomorphic Approaches to Integrated Floodplain Management of Lowland Fluvial Systems in North America and Europe

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Springer

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Integrated Floodplain Management, Environmental Change, and Geomorphology: Problems and Prospects

Paul F. Hudson and Hans Middelkoop

Abstract Recognition of the failure of old perspectives on river management and the need to enhance environmental sustainability has stimulated a new approach to river management over the past couple of decades. The manner that river restoration and integrated management are implemented, however, requires a case study approach that takes into account the influence of historic human impacts to the system, especially engineering. The process of engineering frequently results in an embanked floodplain to reduce the impact of flooding. It is increasingly recognized that floodplain embankment, while usually effective at minimizing flood risk, results in a variety of adverse consequences to the functioning of the river and associated ecosystem health. New, geomorphic-based approaches, which take into account the different modes of adjustment under the framework of integrated management, are now largely seen as the way to move forward. Implementation of such an approach, however, requires a sophisticated understanding of the fluvial system.

Keywords Integrated floodplain management · Fluvial geomorphology · Embanked floodplains · Lowland rivers · Environmental change

1 Scope and Rationale

The purpose of this volume is to provide a comprehensive perspective on geomorphic approaches to the management of lowland alluvial rivers in North America and Europe. Lowland rivers constitute a distinctive type of fluvial system characterized by broad floodplains, complex flood regimes, and often have laterally active meandering channels. In North America and Europe, many lowland rivers have been heavily managed for flood control and navigation for decades or centuries, resulting

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in engineered channels and embanked floodplains with substantially altered sediment loads and geomorphic processes. Over the past decade, floodplain management of many lowland rivers has taken on new importance because of concerns about the potential for global environmental change to alter floodplain processes, necessitating revised management strategies that minimize flood risk while enhancing environmental attributes of floodplains influenced by local embankments and upstream dams. Although such floodplains are heavily modified, it remains essential to understand their controlling geomorphic processes to design effective plans for environmental management and restoration (Florsheim and Mount 2003; Singer and Aalto 2009), and to evaluate their longer-term impact on the fluvial system. Concurrently, the science of geomorphology is increasingly recognized as vital for designing effective management for dealing with different forms of global environmental change, thereby placing geomorphologists within a critical team of floodplain management specialists which also includes engineers, planners, and ecologists.

Integrated river management is commonly approached from the drainage basin perspective, which necessitates considering fundamental tenets of fluvial systems, specifically runoff and sediment sources, sediment transport, channel dynamics, and floodplain processes. The following chapters include case studies which emphasize the important role of geomorphology in river-floodplain management. These include case studies which consider the impact of different anthropogenic influences (dikes, dams, cutoffs…) to fluvial processes, as well as management and restoration approaches developed in response to both past and forecasted types of environmental change. European and North American alluvial rivers are of keen interest because of their long documented efforts at floodplain management and river engineering, an abundance of published literature available for syntheses, and because management agencies exists across governmental scales (e.g., local, state, federal). Additionally, because the timescales at which specific management styles have been implemented vary, there are important lessons to be learned by making a comparison across different river systems. Indeed, many ideas about river and floodplain management were exchanged between Europe and North America during the twentieth century (Reuss 2002; Hudson et al. 2008). Flood disasters over the past decade and a general concern about global environmental change suggests a vibrant exchange of ideas between Europe and North America concerning effective floodplain management strategies will continue well into the present century (e.g., US Congress 2005).

The issue of effective river and floodplain management is pressing along large alluvial rivers in North America and Europe, particularly in those regions with a high population density and economic activities (Kundzewicz et al. 2007). Such settings have a complex floodplain geomorphology and sedimentology, possibly influenced by ground subsidence and river avulsion processes (Stouthamer and Berendsen 2001; Aslan et al. 2005; Leigh 2008). These factors influence floodplain adjustment and increase flood risk but were often inadequately considered in the design of “traditional” flood control infrastructure (e.g., NRC 1995; ASCE 2007). Traditional flood control approaches utilized hard engineering to modify floodplain structure. Such approaches often did not consider the inherent dynamics of fluvial systems which drive abrupt changes over short timescales, the longer-term adjustments to regional controls (such as neotectonics), or the unintended consequences of floodplain engineering which unfold over longer timescales (Hesselink et al. 2003; Hudson et al. 2008; Singer and Aalto 2009). Additionally, these approaches are often focused on "local" management rather than considering the entirety of drainage basin controls. Modern—integrated—floodplain management is inherently more flexible and is designed to minimize flood risk, and at the same time to restore environmental attributes of embanked floodplains by "working with the river" (e.g., Ayres et al. 2014 for European river restoration).

Fluvial geomorphology provides an important conceptual framework and toolkit for design and implementation of river and floodplain management. Although reference to the importance of fluvial geomorphology to floodplain management can be found as far back as half a century, it did not strongly emerge until about the past 20 years within the United Kingdom and continental Europe (Downs et al. 1991; Middelkoop 1997; Middelkoop and Van Haselen 1999; WMO 2004). The inclusion of geomorphic approaches was formally advocated in the European Union's sweeping "Water Framework Directive" (European Council 2000). Scientific communities in North America have also recognized the importance of floodplain geomorphology to effective management strategies over the past couple of decades, but the importance of integrating geomorphic approaches to floodplain management may be characterized as "patchwork," occurring basin by basin, with individual states and "river authorities" (management districts) often adapting different approaches for different motivations (Ramin 2004). Indeed, within the USA, there exist strong regional contrasts in expenditures and management styles between the Mississippi basin, the west coast, and the Southern United States (Bernhardt et al. 2005).

Geomorphic approaches to floodplain management include diverse management plans that explicitly consider the physical processes and sedimentological and topographic frameworks in which modern processes function and engineering structures are emplaced (Hudson et al. 2008; Singer and Aalto 2009). Such approaches may include strategies such as dike (levee) realignment to increase the space for flood water retention (WMO 2004), channel planform and migration in relation to bank material (sedimentology), reconnection of meander bends or floodplain bottoms by levee breaches (Florsheim and Mount 2003), water resources and geomorphic processes (Asselman et al. 2003; NRC 2005; ASCE 2007), dike and flood control infrastructure with a knowledge of subsidence rates and neotectonics (Li et al. 2003; Dokka 2006; Törnqvist et al. 2008), and rates of floodplain sedimentation with management of floodplain water bodies (Middelkoop and Van Haselen 1999; Zeug and Winemiller 2009). These approaches require an understanding of the base-line physical processes for successful implementation.

There is much to be learned by examining different river basins across different physical landscapes and governmental settings. In this volume, we compile a range of case studies to consider the varying roles of geomorphology for river and floodplain restoration, and also to consider different approaches overseen by agencies charged with the task of designing effective strategies for floodplain management, and flood control.

2 Channel Dynamics

River management agencies have increasingly becoming aware of the linkages between channel dynamics and geomorphology as related to floodplain management. To date, most large-scale floodplain management plans, particularly for flood control, also include river channel management for bank stabilization and protection of flood control infrastructure. A common approach to flood control is river channelization (straightening) by artificial cutoffs of meander necks and sinuous reaches (Gregory 2006). Channel alignment and stabilization, however, is dependent upon knowledge of the sedimentary framework in which channels are active, specifically the channel-bed material (particle size) and bedload (volume) and the floodplain bank deposits (cohesive or noncohesive) (Frings et al. 2014). Additionally, channelization of sinuous reaches results in channel-bed incision, thereby decreasing the frequency of overbank events and sedimentation.

An important consideration is that channel bank protection infrastructure (groynes, revetments, etc.) was commonly designed for specific discharge regimes based on historic time-series data. Considerable modeling efforts have simulated changes in discharge regime (e.g., timing and magnitude of floods) in relation to regional climate change scenarios (e.g., IPCC 2007), but it is also essential to consider changes in rates of channel bank erosion and planform geometry as rivers adjust to changing discharge regimes. Most flood-control infrastructure was constructed without considering river channel avulsion processes. While perhaps requiring a century or so to occur, the initiation of a channel avulsion influences modern fluvial processes over decades, about the same timescale in which flood-control infrastructure is conceived and implemented. The slow, gradual process of channel switching changes discharge allocation and results in channel-bed aggradation that subsequently alters stage-discharge relations and flood regimes, which often requires further channel engineering as well as modification to flood-control infrastructure.

3 Embanked Floodplain Geomorphology, Flood Control, and Environmental Management

Flooding is one of the most significant ways in which climate change is manifest (AR5/IPCC 2014). Floods are natural events vital to river and floodplain geomorphic and ecosystem processes (NRC 2005). When humans are impacted, however, floods become “natural disasters” (White 1945; WMO 2004; Pinter 2005; Benito and Hudson 2010). Knowledge of fluvial processes and sedimentology is an important consideration in the design of flood control. For example, painful lessons were learned after the 2005 Hurricane Katrina disaster as regards the design and placement of dikes and flood walls in relation to subsurface sedimentology and changing topography. This is a critical issue to floodplain management and flood control, because as subsidence rates and climate change scenarios become integrated into flood forecasts it requires reengineering, which includes fortification and heightening or relocation of dike sections. An additional consideration concerns the linkages between sedimentology (historic floodplain geomorphology) and alluvial groundwater. This is vital as concerns the floodplain storage capacity for flood waters, but also because of controls on subsurface flow and dike seepage, which initiate sand boils (Davidson et al. 2013), as well as the management of groundwater resources.

Knowledge of embanked floodplain geomorphology is also vital to effective environmental management. A well-documented approach involves the removal of cohesive overbank sediments (clay—fine silt) for the creation of side channels and wetlands for environmental management and restoration. In densely populated regions, such as northern Europe, this becomes an essential approach because of limited space for dike relocation and the recognition of the need to adapt flood-control plans for climate change. Nevertheless, the removal of fine-grained top stratum deposits creates a risk of enhancing dike underseepage (Cobb et al. 1984) and should only be attempted with detailed knowledge of the underlying floodplain sedimentary architecture.

Large lowland river floodplains are mosaics of sedimentary deposits and topographic features created by various different geomorphic processes, which influences alluvial aquifers and surface flow paths of water, sediment, and nutrients (Nienhuis and Leuven 2001; Thoms 2003). Within embanked floodplains such processes represent fundamental controls on the dynamics and maintenance of ecosystems associated with floodplain water bodies such as oxbow lakes (Zeug and Winemiller 2009), but also artificially constructed water bodies such as dike breach ponds and borrow pits associated with the construction of flood-control dikes (Cobb et al. 1984; Jurada et al. 2004). Our understanding of overbank processes has advanced tremendously over the past couple of decades, particularly flood-pulse dynamics (Tockner et al. 2000), sedimentation (Day et al. 2008), channel-floodplain connectivity, as well as the exchange of nutrients and ecological processes. Integrating knowledge of these processes with floodplain management lead to more effective ecological management (NRC 2005). For example, the intentional breaching of levees to distribute sediment and nutrients has been found to be very effective at replenishing floodplain wetlands (Florsheim and Mount 2003), and is becoming a common option for integrated floodplain management.

This volume presents distinct approaches utilized for floodplain management of large alluvial rivers in Europe and North America, with particular focus to the role of geomorphology. The river basins examined in the subsequent 12 chapters (Fig. 1) provide a representative coverage of the drainage of North America and Europe, taking into account a range of climatic and physiographic provinces. The case studies are large basins and collectively drain a wide swath of North American and European landscapes, and as such can be viewed as representative of many other situations. The river basins include the (1) Sacramento (California, US), (2) San Joaquin (California), (3) Missouri (Missouri), (4) Red (Manitoba and Minnesota), (5) Mississippi (Louisiana), (6) Kissimmee (Florida), (7) Ebro (Spain), (8) Rhone (France), (9) Rhine (The Netherlands), (10) Danube (Romania), and (11) Volga (Russian Federation) Rivers. The case studies covered in this chapter span

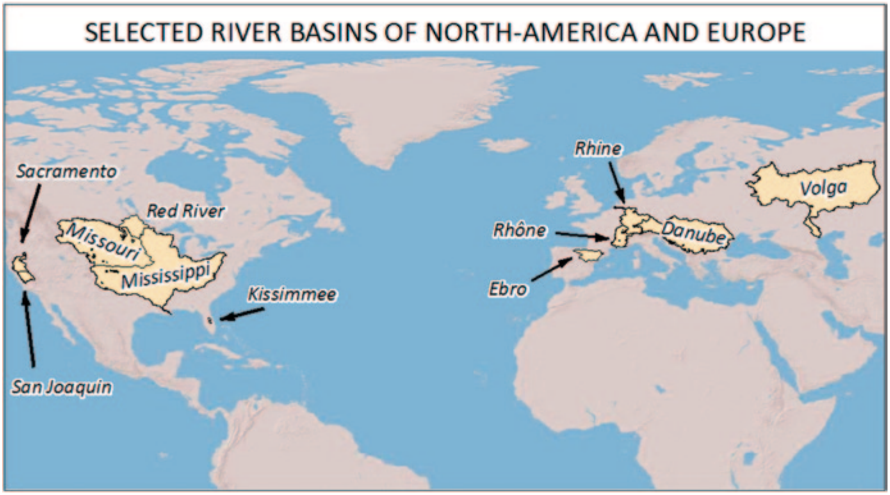

Fig. 1 Featured drainage basins of North America and Europe

a range of fluvial modes of adjustment, including sediment, channel, hydrologic regime, floodplains, as well as ecosystem and environmental associations.

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Sand and Gravel on the Move: Human Impacts on Bed-Material Load Along the Lower Rhine River

Roy M. Frings

Abstract Bed material controls the geometry and morphology of the channel bed as well as the suitability of the river to serve as habitat for aquatic organisms. Therefore, knowledge on bed-material load and the human impact thereon is essential for river managers and scientists. In this chapter, we present an overview of human impacts on bed-material load in the lower Rhine River and discuss its implications for river management. Although human activity did not significantly change the overall rate of bed-material load, it strongly changed the character of the transport: (1) the travel times of bed material decreased due to the prohibition of meander migration by bank protection, (2) the distribution of bed material over the Rhine delta changed due to the construction of barrages and the modification of river bifurcations, (3) a continuous exchange of bed material between the banks and the bed was initiated by shipping, and (4) the grain size of the bed material transport increased due to the effects of embankment, meander cut-offs, river narrowing, barrages, and sediment mining. The main morphological problem in large parts of the lower Rhine River is the erosion of bed material from the river bed. This process is probably induced by river narrowing, barrage construction, and sediment mining; and triggered by shipping and dredging. The ongoing bed erosion hinders navigation, infrastructure, ecology, and drinking water supply. River managers input large amounts of sediment to the river to supplement the natural bed-material load, to stabilize the river bed, and to prevent further erosion of bed sediments. At other locations, continuous dredging of bed sediment is necessary to allow year round navigability. In order to predict the morphological behavior of a river and to develop management strategies, the downstream fluxes of bed material (sand, gravel) through the river and the sources and sinks of this material must be understood. This requires bed-load and suspended-load measurements in combination with sediment budget analyses. The current trend among river managers to reduce the number of transport measurements in favor of relying upon echo soundings is of concern.

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1 Introduction

One of the classical concepts in fluvial geomorphologyis the division of a river's sediment load into wash load and bed-material load, which was introduced by Einstein et al. (1940) and reviewed by Frings et al. (2008). Wash load is the fine part of the sediment that, once entrained, is quickly "washed" down the river in suspension. It is not normally found in significant quantities in the river bed and only becomes deposited in slack water environments or on bar tops and floodplains. Bed material is the coarse portion of the sediment that forms the bed and lower banks of the channel. It may be transported as bed load, but much of the sediment is intermittently suspended, with its transport rate governed by the flow competence.

Whereas many studies have examined human impacts on wash load (e.g., Walling 2006; Syvitski and Milliman 2007), much less is known about human impacts on bed-material load, probably because quantification of bed-material transport is more difficult. Knowledge about human impacts on bed-material load, however, is essential from a morphological and an ecological viewpoint, because it is the bed material that determines the geometry and morphology of the river bed (Church 2006) as well as the suitability of the river bed (hyporheic zone) to serve as habitat for aquatic organisms (Boulton et al. 1998).

In this chapter, we present an overview of human impacts on bed-material load in the lower Rhine River and discuss its implications for river management. The bed material of the lower Rhine River predominantly consists of sand and gravel (grain size 0.063–125 mm), except for the very downstream estuarine area, where clay and silt become an important component of the bed material. In this chapter, we exclusively discuss the transport of sand and gravel, assuming all finer sediments (clay and silt) to be wash load.

After a brief description of the Rhine River, its natural and contemporary bed-material load are compared. Thereafter, the effects of embankment, meander cut-off, bifurcation modification, river narrowing, bank protection, barrage construction, shipping and dredging on bed-material load are evaluated. Finally, a description is provided of bed-material load management and monitoring strategies.

2 The Lower Rhine River

The Rhine River is the most important inland waterway in Europe and flows from the Swiss Alps through Switzerland, Germany and the Netherlands towards the North Sea (Fig. 1). Its drainage basin covers 185,000 km^2. The lower Rhine River

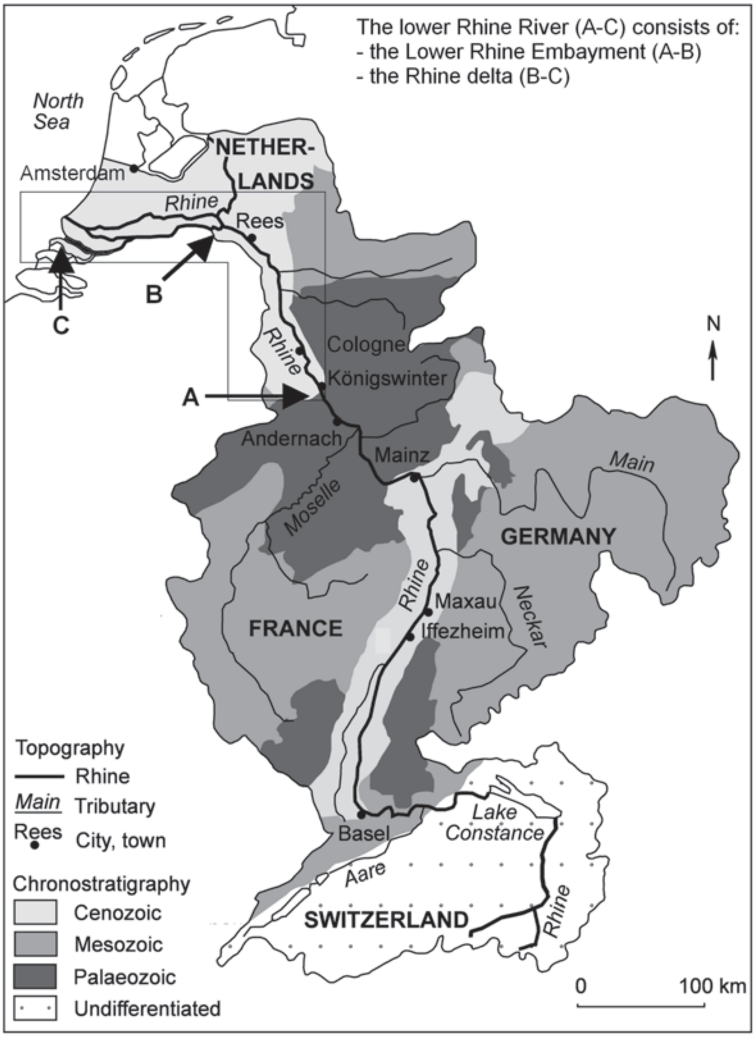

Fig. 1 Topography and geology of the Rhine basin (after Frings et al. 2014a). The study area is indicated by the box

(Fig. 2), in the focus of this study, consists of two segments. The upstream segment (area A-B in Fig. 1) runs from the village of Koenigswinter at the edge of the Rhenish Massif (Rhine-km 645) through the Lower Rhine Embayment towards the village of Millingen a/d Rijn near the German-Dutch border (Rhine-km 866), whereas the downstream segment (area B-C) runs from the German-Dutch border towards the North Sea (Rhine-km 1032). Typical river widths range from 230 to 330 m in the upstream segment and from 60 to 3150 m in the downstream segment, where the Rhine forms a delta with several large distributaries. The major distributary is the Waal, which transports two thirds of the total Rhine discharge. The lower Rhine

Fig. 2 The lower Rhine river (Waal Branch). (By Rijkswaterstaat/Joop van Houdt)

Table 1 Holocene and modern bed-material load in the lower Rhine River. See Fig. 1 for a definition of location A–C

Location	Bed-material load (Mt/a)	
	9000 − 100 BP	1991–2010 AD
A Upstream edge of Lower Rhine Embayment	0.55 ± 20 %	0.40 ± 40 %
B Upstream edge of Rhine delta	0.89 ± 20 %	0.66 ± 40 %
C Downstream edge of Rhine delta	0.00	0.00

has a rain-dominated discharge regime with maximum discharges in the winter (December–March). The mean discharge near the German-Dutch border (station Rees) between 1991 and 2010 was 2311 m^3/s, whereas the maximum discharge ever recorded was 12,200 m^3/s in 1926 (DGJ 1926).

3 Bed-Material Load

3.1 The Natural Context

Prior to human impacts (Holocene), the bed material of the lower Rhine River predominantly consisted of sand, with distinctive downstream fining. Gravel was a minor component of the overall bed material, typically varying between 0 and 10 % (e.g., Frings et al. 2009; Erkens et al. 2011).

An estimate of the bed-material load in the lower Rhine during the Holocene can be obtained from quaternary-geologic data (Table 1). Because the Rhine delta is known to have been a near-complete sediment trap for Rhine sediments during the Holocene (Beets and Van der Spek 2000), the bed-material load at the downstream boundary of the Rhine delta (location C in Fig. 1) must have equaled zero. The average bed-material load at the upstream boundary of the Rhine delta (location B) is estimated at 0.89 Mt/a, which is equal to the total Holocene accumulation of

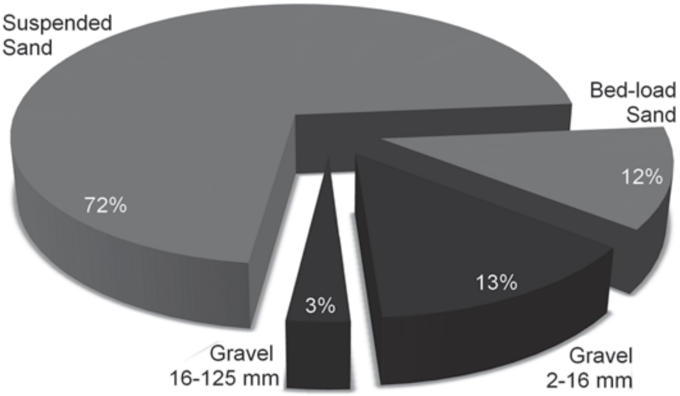

Fig. 3 The average composition of the sand and gravel load at the entrance of the Rhine delta (*Rhine km* 857.5 ~ Location B) between 1991 and 2010. (Frings et al. 2014b)

sand and gravel in the Rhine delta (4.68 $km^3 \pm 20\%$; Erkens et al. 2006) multiplied by the mineral density and solid fraction of the sediments (2600 kg/m^3 and 66 %, respectively; Frings et al. 2011a) and divided by the duration of deposition (9000 years; Gouw and Erkens 2007). Because the Lower Rhine Embayment is known to have been an area of incision during the Holocene, the bed-material load must have increased in downstream direction throughout the Lower Rhine Embayment. At the upstream boundary of the Lower Rhine Embayment (location A), the Holocene bed-material load is estimated at 0.55 Mt/a, which is equal to the bed-material load at the upstream boundary of the Rhine delta (0.89 Mt/a) minus the contribution of bed incision in the Lower Rhine Embayment (about 3.09 Gt in 9000 years, or 0.34 Mt/a; Erkens 2009, p. 189). The sand and gravel that entered the lower Rhine derived from fluvial erosion of the main-stem channel, as well as distant upstream tributaries (Rhenish Massif and Upper Rhine Graben).

3.2 *The Modern Status*

The current status (Period 1991–2010) of the lower Rhine River reveals a clear difference in the grain size of the channel bed between the upstream and downstream segments. The upstream segment (Lower Rhine Embayment, AB in Fig. 1) is characterized by a gravel bed, whereas the downstream segment (Rhine delta, BC) is characterized by a sand bed. The gravel content decreases along the lower Rhine from about 85 to 0 %. Typically, the grain size of the bed material in motion is much finer than the average grain size of the river bed (Frings and Kleinhans 2008; Frings et al. 2014b).

An estimate of the present-day bed-material load in the lower Rhine (Table 1) can be obtained from transport measurements. Recent studies reveal that, despite the locally high gravel fraction in the river bed, sand transport rates exceed gravel transport rates (Fig. 3) along the entire river. Most of the sand is transported in suspension; only a minor component travels as bed load (Fig. 3). The amount of bed-material load (sand and gravel) that presently enters the lower Rhine from upstream (location A in Fig. 1) equals ~0.40 Mt/a ± 40%. Within the Lower Rhine Embayment, the transport rate increases in the downstream direction, mainly because of bed incision (3 mm/a). At the transition towards the Rhine delta (location B in Fig. 1), the transport of sand and gravel equals ~0.66 Mt/a ± 40%. These values are based on hundreds of transport measurements over two decades from 1991 to 2010, and systematically analyzed by Frings et al. (2014b). Ten Brinke (2005) also provided an estimate of the bed-material load that is transferred from the Lower Rhine Embayment to the Rhine delta (location C), which resulted in a somewhat higher estimate (0.85 Mt/a ± 74%). Given the high uncertainty ranges, both estimates must be considered statistically indifferent. In the Rhine delta, bed-material load firstly increases because of bed incision, but eventually strongly decreases because of deposition (Ten Brinke 2005). As with the natural condition, no gravel and little sand from the Rhine River is transported into the North Sea, so the transport rate at location C approximately equals zero.

4 Human Impacts

4.1 Embankment

Widespread human activity in the Rhine basin started in the Neolithic age (~7500 BP), when valley slopes were deforested for agriculture. A little later, from the Iron Age onward, this was reflected by an increase in wash load (Erkens et al. 2006). Bed characteristics, channel morphology, and bed-material load, however, did not change until the Middle Ages, when inhabitants started with the construction of small flood protection works (Tümmers 1999). These first embankments were initially situated around villages, but by about 1100 AD embankments were constructed along the river for flood protection and land reclamation purposes (Van de Ven 1993). The construction of embankments started close to the sea, but gradually moved upstream. By 1350 AD, all major delta branches had been completely embanked (Berendsen and Stouthamer 2000). In the centuries thereafter, also the Rhine stretches in the Lower Rhine Embayment were completely embanked (Schmidt 2000). Between the embankment and the river channel, a floodplain ranging in width from tens to hundreds of meters remained active and was subjected to fluvial processes. Importantly, while the embankments prevented the discharge of flood water into the flood basins, the water depth and the bed shear stress (which is directly proportional to water depth) increased in the main channel during floods. The increased bed shear stress led to winnowing of fine grains from the river bed, supply of coarser bed material from upstream, and consequently resulted in a coarsening of the bed material (Fig. 4a) (Frings et al. 2009). Indeed, quaternary-geologic studies based on over 200,000 corings (Berendsen and Stouthamer 2001), show that channel-belt deposits of pre-embanked Rhine delta branches are nearly void of

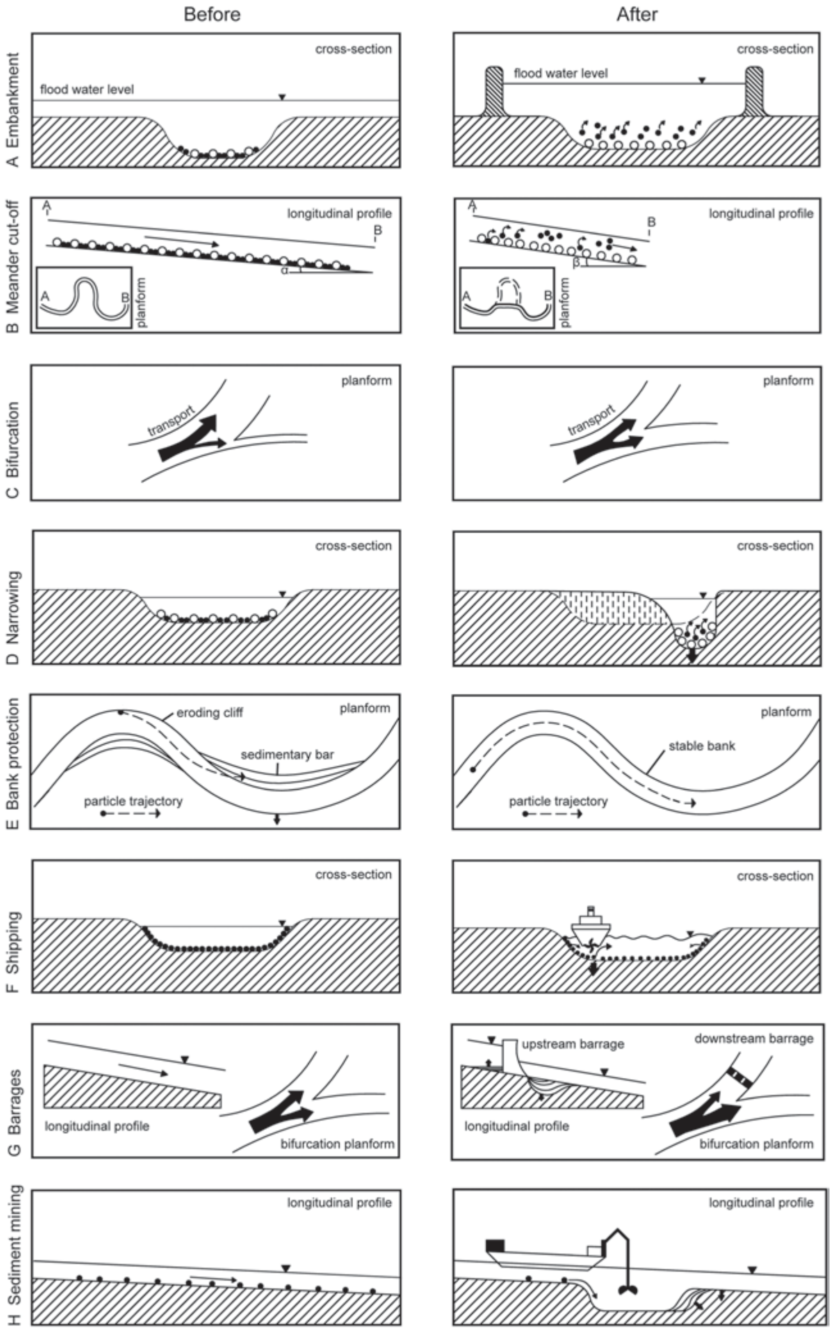

Fig. 4 Human impact on bed material **a** embankment, **b** meander cut-offs, **c** bifurcation modification, **d** river narrowing, **e** bank protection, **f** shipping, **g** barrage construction, **h** sediment mining

Table 2 Hydrodynamic and sedimentological changes in the downstream section of the Waal (thalweg)

Quantity	Unit	Before embankment (190 BC–1100 AD)	After embankment (1600–1870 AD)
Mean bed grain size[a]	(mm)	0.53	0.80
Water depth (10y flood)[a]	(m)	5.6	7.9
Bed shear stress(10y flood)[b]	(N/m^2)	5.5	7.7

[a] Data from Frings et al. (2009)

[b] Assuming a hydraulic gradient of 0.10 m/km

gravel, whereas channel-belt deposits of embanked Rhine branches contain significant amounts of gravel (cf. Sect. 3). In a case study focusing on the Waal, Frings et al. (2009) observed a 41 % increase in flood water depth and a 51 % increase in thalweg bed material size in the period of embankment (Table 2).

4.2 Meander Cut-off

Although the embankments prevented the hinterland from being flooded, the river remained free to shift its course between the embankments. Regularly, embankments were under threat of being eroded by rapidly migrating meander bends. To prevent this, several large meander bends were cut off in the centuries after embankment (in 1500, 1639, 1644, 1649, 1655, 1670, 1680, 1776, 1788, 1819 AD; Hoppe 1970; Berendsen and Stouthamer 2001). As a result, the river length decreased, thereby increasing the energy slope and the bed shear stress (which is proportional to the energy slope). The meander cut-offs thus influenced the bed-material load in a way similar to that of the embankment: i.e., coarsening the bed material (Fig. 4b). In the aforementioned case study, Frings et al. (2009) found the increase in energy slope to be only 20 % (from 0.10 to 0.12 m/km), suggesting the impact of meander cut-offs to be much less than the impact of embankment.

4.3 Bifurcation Modification

In the seventeenth and eighteenth century engineering works were carried out at the most upstream bifurcation of the Rhine delta to improve the discharge distribution over the Rhine branches, which had become unfavorable from a military and economic point of view (Van de Ven 1976). As a result, the Waal discharge reduced from over 90 % to about 67 % of the total Rhine discharge (Hesselink et al. 2006). The engineering works also caused a change in the distribution of bed material over the Rhine branches (Fig. 4c), which probably was different for coarse and fine grains (see e.g., Frings 2008). Although exact numbers are unavailable, it is to be expected that the bed-material supply to the Waal decreased in favor of the other delta branches.

4.4 River Narrowing

The first large-scale engineering works in the channel itself were carried out in the eighteenth century, following a disastrous flood in 1740 AD. To ensure a faster discharge of flood water, the river in the Lower Rhine Embayment was straightened, narrowed and forced into a single channel by connecting the numerous islands to the banks. Also, bank protections were constructed using revetments and groynes (Tümmers 1999). Because of the increasing importance of the Rhine for cargo transport after the onset of the Industrial Revolution, actions were taken to create a deeper channel suitable for navigation. Firstly in the Lower Rhine Embayment (early nineteenth century), later also in the Rhine delta (late nineteenth century), a regular array of groynes was built along the banks of the river (Topographische Inrigting 1873–1884; Jasmund 1901). The groynes influenced the channel processes such that the river narrowed, thereby increasing the shear stress on the river bed. Consequently, this resulted in a deepening of the channel by incision, temporary increasing bed-material load. The order of magnitude of the increase follows from historical river maps (Topographische Inrigting 1873–1884; Topografische Dienst 1915–1919). The data from the map surveys reveal that the average bed incision in the Waal during the period of river narrowing (1876–1916 AD) equaled 1.5 m (Van Heiningen 1991). Considering an average channel width of 260 m, a river length of about 90 km, a sediment porosity of 0.34 and a sediment density of 2600 kg/m^3, the annual loss of bed material must have been on the order of 1.5 Mt/a, more than twice the present-day bed-material load (Table 1). It should be noted, however, that a substantial portion of the sediment was not removed by fluvial processes, but instead by river dredging (Van Heiningen 1991).

River narrowing fundamentally changed the river system, probably more than any of the other human impacts. It resulted in a permanent increase in water depth, bed shear stress and transport capacity, to which the river reacted by recruiting sediment by erosion of bed material. In order to establish a new equilibrium, the river can try to reduce the bed shear stress again by decreasing either bed slope or flow depth. A sufficient reduction in bed slope requires several (tens of) meters of erosion at the upper boundary of the lower Rhine, whereas a reduction in flow depth requires significant bank erosion. Both mechanisms are unwanted and prevented by river managers. The other possibility for a river to attain equilibrium is to compensate the increased shear stress by increasing the critical bed shear stress for incipient motion by coarsening the river bed. This occurs during the process of bed erosion, because fine grains are easier to erode than coarse grains (Fig. 4d). Indeed, observations provide evidence for this process: the bed material coarsened over time (Frings et al. 2009) and today much of the lower Rhine bed surface is covered with a coarse armour layer (Frings et al. 2014b). In the transition reach between the Lower Rhine Embayment and the Rhine Delta (location B in Fig. 1), the armour layer has an unusual thickness of 0.9 m (Frings 2011).

4.5 Bank Protection

The engineering measures of the eighteenth and nineteenth century did not only result in a temporary increase in bed-material load and a coarsening of the bed, the bank protection measures also completely halted the process of meander migration. The natural Rhine River exhibited considerable lateral migration of meander bends, eroding bed material along concave meander banks and depositing sediment along adjacent downstream bars, resulting in lateral accretion of the convex point bars. The sand and gravel that entered the lower Rhine from upstream therefore were not simply transferred to the Rhine delta but were stored intermittently in the Lower Rhine Embayment. Because of the bank protection works, the process of intermittent sediment storage in the Lower Rhine Embayment ceased, thereby strongly increasing the travel velocity of bed material towards the delta (Fig. 4e).

A crude quantification of the magnitude of the effect can be made as follows. The total land area reworked by meander migration in the Lower Rhine Embayment during the Holocene equals 1028 km^2 (Erkens 2009, p. 184). Together with an average channel-belt thickness of 8 m, a porosity of 34 % and a mineral density of 2600 kg/m^3, the total mass of sediment reworked by meander migration equals 14,000 Mt. The average time for a sediment particle to reach the Rhine delta after entering the Lower Rhine Embayment is equal to the total mass of reworked sediments divided by the transport rate, or (14,000/0.55) 25,000 years. Today, most of the bed-material load is simply transported downstream through the channel. Given a river length of 225 km, an average river width of 280 m, a porosity of about 0.25 (Frings et al. 2011a), a bulk density of 2600 kg/m^3, an assumed average thickness of the mobile sediment layer of 0.2 m and a bed-material transport of 0.4 Mt/a (Table 1), the average time for a sediment particle travelling as bed load to reach the Rhine delta after entering the Lower Rhine Embayment becomes 62 years. Note that these values are averages. Fine sediment particles in suspension are transported much faster, and probably reach the Rhine delta within a few days (Frings et al. 2014), whereas very coarse particles (e.g., those with a diameter of 125 mm) may never reach the Rhine delta.

4.6 Shipping

Humans have been sailing the Rhine River since Prehistoric Age. In 47 AD, the Rhine became the northern boundary (limes) of the Roman Empire, and the river was intensively used for patrolling and transporting cargo (Nienhuis 2008, p. 33). Vessels sailing the Rhine became markedly larger after the invention of the steam engine in the Industrial Revolution. Today's Rhine vessels have lengths up to 200 m and typical drafts of 2.5–4.0 m. During low and mean discharges, often less than 25 cm of water remains between the vessels' draft and the river bed (Schroeder, WSV, pers. comm.). The enormous water displacement caused by these vessels, in combination with their propeller jets, causes local disruptions to the river bed, thereby setting sediment into motion. Camera observations from the Federal Institute of Hydrology in Germany reveal that if the gravelly armour layer on the river bed is disrupted by shipping, the sandy sediments underneath are washed away in suspension, thereby triggering bed erosion (Fig. 4f).

Shipping not only increases the downstream transport of bed-material load, it also results in an exchange of bed material between the sandy groyne field beaches alongside the river and the river bed (Fig. 4f) (Ten Brinke et al. 2004). At low to moderate discharges, shipping-induced currents erode sand from the groyne field beaches and carry it to the river bed. Although erosion rates are higher for loaded barge tows than for motorized vessels, the latter cause more erosion on a yearly base due to their higher frequency of passing. The amount of sand being eroded and transported to the river bed is a function of the underwater volume of the passing vessel. Heavily loaded vessels sailing along the south bank, from Rotterdam to Germany, cause much more erosion of the beaches than do empty or partially loaded returning vessels along the north bank. The investigations of Ten Brinke et al. (2004) reveal for the Waal that the transport of sand from the groyne fields to the main channel because of shipping more-or-less compensates the reverse transport of sand during floods.

4.7 Barrages

During the twentieth century, several barrages were built in the Rhine for hydropower generation and improvement of navigation. Most of them are situated far upstream of the lower Rhine. The Iffezheim barrage (completed in 1977), about 300 km upstream of the lower Rhine, is the last barrage in a long chain of barrages. Although exact numbers do not exist, it is certain that the barrages greatly reduced the supply of bed material to the downstream reach, leading to a sediment deficit and subsequent erosion of bed material, winnowing of fines and bed coarsening (Fig. 4g). Although these effects are strongest directly downstream of the dam, the sand deficit caused by the barrages is also likely to contribute to the erosion of bed material and bed coarsening in the lower Rhine.

The lower Rhine is largely free-flowing, and barrages are only located in the lowermost reaches. Between 1957 and 1971 three barrages (near the villages of Driel, Amerongen and Hagestein) were constructed in one of the delta distributary branches to improve navigability at low-flow conditions, whereas two other barrages were constructed in the Rhine estuary (the Haringvliet and Volkerak barrages) to protect the Netherlands against coastal storm surges. The barrages changed the distribution of the Rhine discharge over the three delta branches. Combined with the change of water distribution, the distribution of channel-bed material also changed (e.g., Frings and Kleinhans 2008, Fig. 4g).

In addition to the main-stem Rhine, its tributaries are also regulated with barrages. The largest tributary of the Rhine is the Moselle River, which joins the Rhine only 50 km upstream of the lower Rhine. Several barrages regulate its flow discharge, with the last one situated directly at the mouth of the Moselle. Although the Moselle barrages probably contribute to the sediment deficit of the Rhine, there are strong indications that parts of the bed load and suspended load are able to pass through the barrages during floods.

4.8 Sediment Mining

In the nineteenth and twentieth century, large amounts of sand and gravel were mined from the river bed of the lower Rhine River and sold to the building industry. Sediment mining increases the water depth, which was advantageous during the period of river training works because it helped to create a channel sufficiently deep for navigation (Van Heiningen 1991). Sediment mining also increased the bed shear stress, probably leading to a coarsening of the bed-material load similarly to the embankment, meander cut-offs and river narrowing. Sediment mining, however, also caused a bed-material load deficit downstream of the mining area, thereby leading to erosion of bed material (Fig. 4h). Some decades ago legislation was passed to offset this problem, making it illegal to extract bed material from the lower Rhine. An exception was made for the sedimentation zone in the downstream-most part of the lower Rhine.

5 Management

5.1 Managing Bed-Material Load

The preceding sections show that human activity strongly affected bed-material load in the lower Rhine. Although it did not cause a significant change in the *rate* of transport (Sect. 3, Table 1), it certainly changed the *character* of transport: bed-material load became coarser and is transported faster, the distribution of bed-material load changed between the three major distributaries, and there is now a dynamic exchange between the river bed and groyne fields.

Although these changes affect the ecological, navigational, recreational, industrial, and agricultural functioning of the lower Rhine, they are presently not considered very problematic. The main morphological problem for river managers in large parts of the lower Rhine is the erosion of bed material, which hinders navigation, infrastructure, ecology, and drinking water supply (Gölz 1994). The severity of the problem may be illustrated by looking at the Lower Rhine Embayment. Large parts of this area have been subject to bed erosion; about 1.0 m since 1930 (Frings et al. 2014b). The present incision (Sect. 3.2) could be a continuation of the natural Holocene incision process (Sect. 3.1). Most likely, however, it is at least partially due to the human impacts previously listed, specifically the river narrowing, barrage construction, and sediment mining (see Frings et al. 2009, 2014b; Frings 2011).

Although all the constructional works have long been completed and sediment mining is now prohibited, the river has probably not yet fully adapted to these impacts. Degradation rates probably will decrease due to the coarsening of the bed surface, but bed material dynamics during floods remain high, such that the armour layer can be disrupted locally, enabling erosion of the underlying fine sediments. Human activities such as shipping and dredging also cause a disturbance to the river bed and may trigger erosion of bed sediments. Furthermore it is questionnable whether the river bed will ever become coarse enough to fully stop bed degradation.

The easiest way to stop channel-bed degradation is to increase river width, thereby reducing the water depth, bed shear stress and transport capacity. This seems infeasible as long as the Rhine serves as major navigation route between the Netherlands and Germany. River authorities, therefore, chose a different solution: Since 2000 river managers supply allochtonous sediments to river stretches that have a sediment deficit. This concerns relatively fine sediment (typically 4–32 mm) that is meant as substitute for natural bed load and serves to halt the general trend of bed degradation (Fig. 5b). Although costly, this management strategy appears to be successful, and in addition to the present feeding locations (all located in the Lower Rhine Embayment), feeding locations in the Rhine delta are also planned. In order to stabilize the bed in areas prone to local scouring, coarser allochtonous sediments (8–150 mm) are supplied to the river bed too (Fig. 5c). The total amount of sediment supplied to the river is enormous: between 1991 and 2010 8.4 million t of bed material were dumped into the Lower Rhine Embayment, which would (if the sediments had been evenly spread) correspond to a sediment layer of 8 cm thickness. A recent study on sediment fluxes in the lower Rhine (Frings et al. 2014b) has revealed that presently 32 % of the total bed-material input to the Lower Rhine Embayment comes from upstream. Another 35 % is related to erosion of bed material (incision), whereas the remaining 33 % is fed to the river by river managers (Fig. 6). Without sediment feeding, the proportion of bed-material load transport associated with bed incision would have been much higher, probably about 70 %.

The artificial supply of bed material to the river is not the only measure to guarantee year-round navigability in the lower Rhine River. In the very downstream part of the Rhine River, where the bed material that is eroded further upstream is deposited because of the decreasing velocity, dredgers operate all-year round to keep the river sufficiently deep for navigation. Dredging activities, however, are also needed in other river sections of the lower Rhine to remove all newly formed sedimentary deposits that hinder navigation. These sediments are re-allocated to the river elsewhere (Fig. 5a).

5.2 Monitoring Bed-Material Load

Monitoring bed-material load is difficult, because some of the bed material travels along the channel bed (bed load) whereas the remaining load is transported by suspension. Moreover, bed-material load varies strongly spatially and temporally, so that automated isolated point measurements are insufficient and monitoring

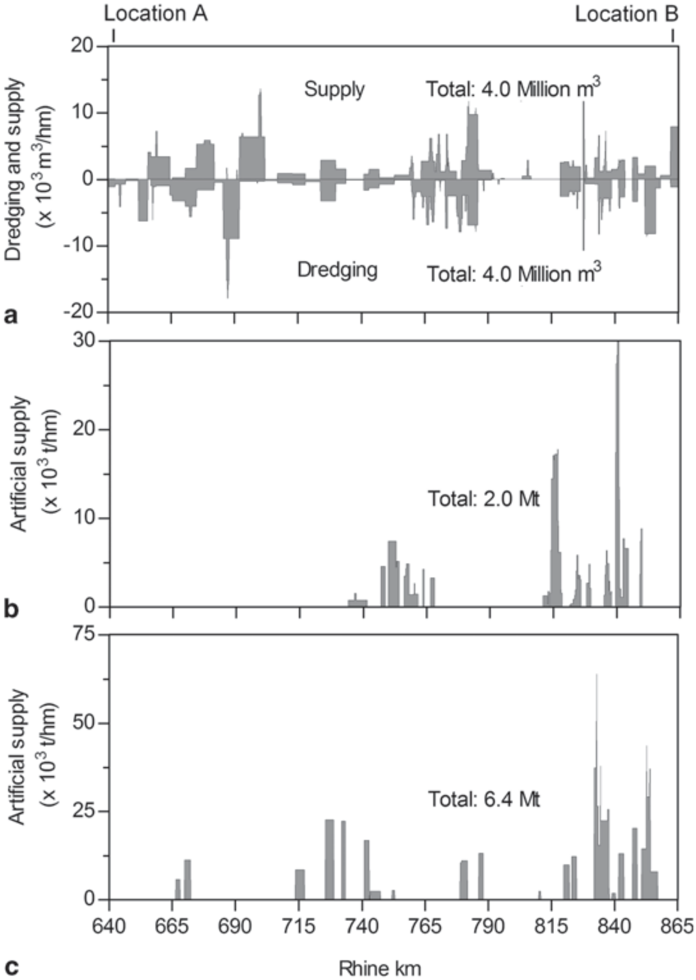

Fig. 5 Amounts of sediment dredged from the river bed or artificially supplied to the river between 1991 and 2010 in the lower Rhine Embayment: **a** dredging and re-allocation (supply) of dredged sediments, **b** artificial supply of fine gravel (typically 4–32 mm) as substitute for natural bed load, **c** artificial supply of coarse gravel and stones (8–150 mm) for bed stabilization purposes. (Frings et al. 2014b)

programs become prohibitively expensive. As a result, only a few river basins are equipped with a systematic program to monitor bed-material load. For the Rhine basin, a systematic monitoring program only exists for the German reaches.

River managers are increasingly relying upon accoustic echo soundings to obtain information related to morphological processes, such as bed incision. Echosoundings, however, do not provide answers to essential questions such as: “How much bed material is moving downstream?,” “Which grain size fractions are transported, eroded, or deposited?,” “How is the bed material transported (as bed load or suspended load)?,” “Where is the bed material transported by the river coming from

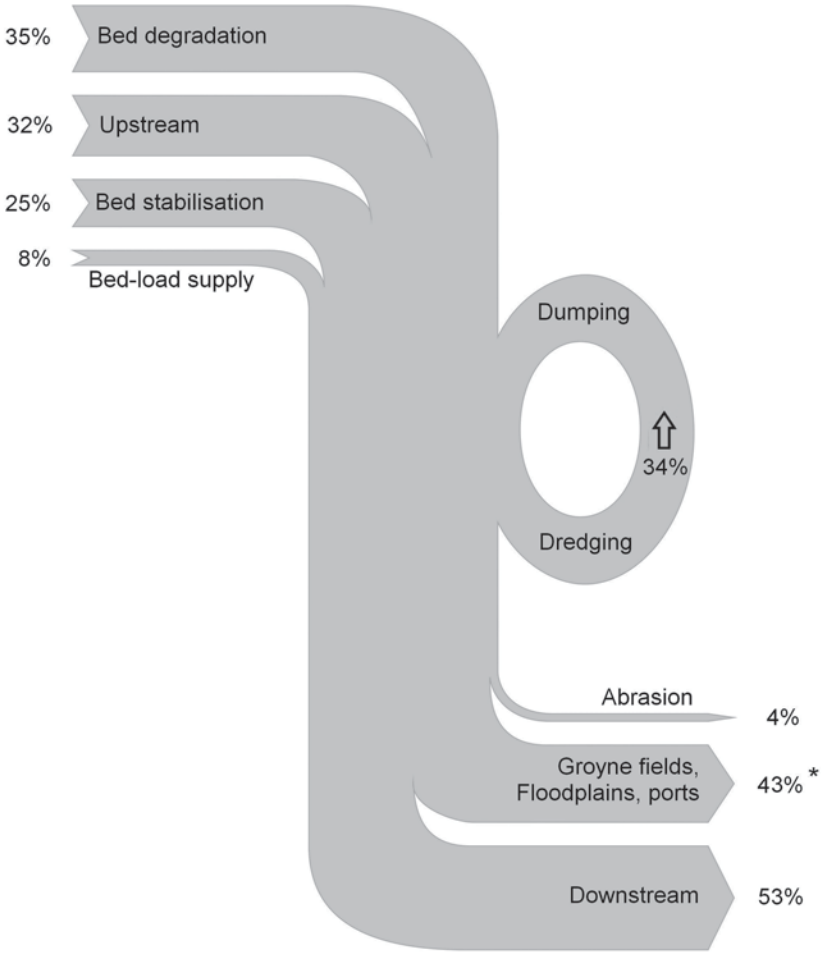

Fig. 6 Sediment budget for bed-material load (*gravel and sand*) for the lower Rhine Embayment (*Rhine km 640–865*) in the period 1991 to 2010. (Frings et al. 2014b). 100 % = 1.25 Mt/a; * estimated

or going to?," and "What's the fate of bed material that is artificially supplied by humans?." In order to provide an answer to these questions and to get a real understanding of a river system, detailed information is needed about the (1) downstream fluxes of bed-material load (sand, gravel) through the river and (2) sources and sinks of this bed material. Such information can only be obtained through measurements of actual bed load and suspended load, in combination with the construction of a sediment budget, the balance between the amount of sediment entering a study area, the amount of sediment leaving the study area and the (change in) sediment storage. Thus, whereas echosoundings are the best means to quantify bed-level changes, transport measurements and budget analyses are indispensable to understand the cause of these changes, their character, and the effect of possible counter measures.

The importance of transport measurements and budget analysis can easily be illustrated with data from the Rhine. For decades, it has been thought that especially gravel is eroded in the German part of the Rhine, whereas the erosion products were supposed to be transported downstream as bed load. Recently, however, analysis of bed-material load transport measurements has shown that a significant part of the eroded sediments consist of sand, whereas many of the erosion products are transported downstream in suspension (Frings et al. 2014a, 2014b), suggesting that sand can be much faster supplied towards the Rhine delta than is often assumed by river managers and geologists. A subsequent sediment budget analysis has shown that the amounts of bed-material load that are supplied to the lower Rhine Embayment by upstream supply, artificial supply or by bed incision are much larger than the amounts of bed-material load that enter the Rhine delta (Fig. 6). This suggests that floodplains, groyne fields or harbors along the lower Rhine constitute a major sink of sediment. Such information is crucial to improve sediment feeding strategies, dredging strategies, and numerical simulation models that are used to predict future morphological behavior.

6 Conclusions

The preceding sections illustrates that human activity had the following effects on bed-material load in the lower Rhine: (1) the travel times of bed material decreased due to the prohibition of meander migration by bank protection, (2) the distribution of bed material over the Rhine delta changed due to the construction of barrages and the modification of river bifurcations, (3) a continuous exchange of bed material between the banks and the bed was initiated by shipping, and (4) the grain size of the bed material increased due to the effects of embankment, meander cut-offs, river narrowing, barrages, and sediment mining.

The main morphological problem in large parts of the lower Rhine River is the erosion of bed material. This process is probably induced by river narrowing, barrage construction and sediment mining, and triggered by shipping and dredging. River managers feed large amounts of allochtonous sediments to the river to supplement the natural bed-material load to stabilize the bed and to stop bed incision. Other locations require continuous dredging to enable year-round navigability. To predict the morphological behavior of a river and to develop management strategies, the downstream fluxes of bed-material load (sand, gravel) through the river and the sources and sinks of this material must be understood. This requires detailed and systematic bed-load and suspended-load measurements in combination with sediment budget analyses, in addition to the regular bed level surveys.

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Channel Responses to Global Change and Local Impacts: Perspectives and Tools for Floodplain Management, Ebro River and Tributaries, NE Spain

Alfredo Ollero, Askoa Ibisate, David Granado and Rafael Real de Asua

Abstract In the last five decades, mountain and lowland rivers of the Iberian Peninsula have undergone noticeable hydrological and geomorphological change, in response to an overall reduction of discharge, floods and sediment supply. The causes are humaninduced land use change, the building of reservoirs and gradual climate change. In lowland river floodplains, further significant impact comes from human interventions in the channels, such as the building embankments, in-channel gravel extractions and artificial meander cut-off. The case of the middle Ebro River and its tributaries (Aragón, Gállego and Cinca rivers) is very well suited to exemplify and analyse these processes and impacts, with morphological changes (incision, narrowing, simplification) and progressive reduction of channel migration and reduced presence of sediment bars. River migration was reduced from 15 m/year to values from 0 to 5 m/year since mid-twentieth century. Floodplain natural areas were reduced 40 % on average since 1927. In recent years, we have begun to seek solutions to mitigate these fluvial problems. Most of them are focused on floodplain management through the Fluvial Territory approach. Here we present this approach, the basic tools for its demarcation and the results of some actions of fluvial restoration already implemented. Four case studies of embankments removal are presented. Flood peak reduction was detected and morphological effects are being monitored. These initial actions could lead to new river management practices with improved river dynamics.

Keywords Channel change · Human impacts · Floodplain management · Fluvial Territory · Ebro River

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1 Introduction

Fluvial geomorphology is a powerful science to identify, quantify and analyse disturbances to rivers and floodplains. The science also provides conceptual and analytical tools to interpret and evaluate causes of fluvial adjustments and to facilitate the design of mitigation strategies and management (e.g. Schumm 1969; Gregory 2006; Hudson et al. 2008; Zawiejska and Wyżga 2010; Buffington 2012). Identifying whether an observed change is a response to natural dynamics, local impacts or global change, however, is a complex task. Understanding the adjustment and providing effective management strategies requires detailed, complex and long-lasting measurements and analyses.

Over the last five decades, mountain and lowland rivers and floodplains of the Iberian Peninsula have undergone noticeable hydrological and geomorphological changes. These changes are a response to an overall reduction of discharge, floods and sediment supply (Conesa 1999). The main causes are land use change, reservoir building and far more gradual climate or global change (Blöschl et al. 2007; Hoffmann et al. 2010).

The objectives of this study are to provide an overview of some of the current problems for representative streams of the northeastern Iberian Peninsula, to examine various geomorphic and river management projects, to provide suggestions and management strategies for future projects especially as related to the concepts inherent to the Fluvial Territory approach.

2 Background: Iberian Rivers, global change and local impacts

Iberian rivers respond to different hydrological regimes. Except for rivers in the north, the rivers are influenced by mediterranean hydroclimatic patterns with dry, low flow summers, being differentiated by their basin elevation and characteristics. All river systems of the Iberian Peninsula show common hydrological changes over the last six decades, with the most important being the decrease of streamflows since 1950.

Many studies have focused on hydrologic responses to climate change and mainly to precipitation (Del Río et al. 2011). At a regional scale, the hydrologic effects of climate and vegetation cover in the Duero watershed (Morán et al. 2011) and in the Tajo and Guadiana watersheds (Kilsby et al. 2007; Mourato et al. 2010) showed a steep reduction in surface runoff. Similar decreased precipitation patterns have been detected in southern Iberian Peninsula (Ruiz et al. 2011) and on the Mediterranean Coast basins (González Hidalgo et al. 2009), revealing a 10% rainfall reduction. Lorenzo et al. (2012) showed a marked decrease in annual, winter and spring streamflows in most of the Iberian watersheds, especially southern basins. Analogous trends occur in streams in Southeastern France (Lespinas et al. 2010) and throughout Southern Europe (Lehner et al. 2006; Stahl et al. 2010). Progressive decline in the average streamflow, and frequency and magnitude of floods, can be observed in many rivers since the 1980s, due to the expansion of forests (a change from marginal agricultural use) (García-Ruiz et al. 2011). An increase between a 0.4 and 0.6 % per year in forested area is estimated for the Ter and Llobregat watersheds which derived in the loss of 21 % of water resources in 46 years (Gallart et al. 2011).

Changes in the seasonality of river regimes reveal a decrease of flows in winter and an increase in summer as a consequence of dam regulation and water management strategies (Gil-Olcina ed. 2004). More than 1200 large dams regulate Spanish rivers and are, therefore, subject to substantial alterations of their natural flow regimes. Of the total amount of water regulated by these reservoirs, 75 % is dedicated to irrigation (Fernández et al. 2012). Dams especially affect flow magnitude creating significant seasonal differences by decreasing winter releases to meet the demand of water in summer (Lorenzo et al. 2012). These permanent changes in the flow regime result in major morphological alterations linked to shifts in sedimentary dynamics and to changes in the composition, distribution and succession of riparian vegetation (Magdaleno and Fernández 2011).

From a hydromorphological perspective, the effects of dams and global change at the basin scale have been studied mainly in the NE Iberian Peninsula, and more specifically in the Ebro watershed. A number of studies have revealed considerable changes in the seasonality of the annual flow regime with steep reductions in minor flood events (Beguería et al. 2003; Batalla et al. 2004; Ibisate 2005; López Moreno et al. 2006, 2008). These changes have resulted in a reduction in both bedload and suspended sediment load (Batalla 2003; Day et al. 2006; Liquete et al. 2009; Batalla and Vericat 2011). As a result, many rivers are beginning to adjust their channel through vertical incision (Beguería et al. 2006; García Ruiz et al. 2010) or lateral adjustment (Acín 2004; Granado 2004).

Additionally, the intense use of riparian space and fluvial resources has led to local impacts on all Iberian streams (e.g. García Ruiz and Puigdefábregas 1985; Gómez and Martínez 1991; Hooke 2006; Boix-Fayos et al. 2007; Borja et al. 2009; Gonzalo et al. 2010; Ibisate et al. 2011). Public institutions, such as the Ministry of the Environment, Water Agencies, Regional Governments and Townships and environmental advocacy groups have recently shown an increasing interest on the subject (Sánchez-Fabre and Ollero 2010). Over the past decade numerous forums, conferences, technical workshops and studies have provided valuable contributions that offset the deficit of scientific publications. Some fluvial geomorphologists have been involved in this technical process of dialogue, training, participation and search for solutions. It is in this sphere where most of the fluvial-related problems derived from direct channel actions have been reported.

3 Channel Responses to Global Change and Local Impacts in the Middle Ebro River and Tributaries

3.1 Case Studies

The middle Ebro River and the lower reaches of its tributaries: Aragón, Gállego and Cinca Rivers were selected as case studies since the complexity of their problems and the detailed information available for analysis.

The Ebro is the largest Mediterranean river of the Iberian Peninsula, with a 84,393 km² basin and a channel length of 930 km. The middle Ebro River forms free meanders for 347 km (Fig. 1) and has a 739 km² floodplain, the most extensive of the Iberian Peninsula (Fig. 2). The average width of its floodplain is 3.2 km, reaching a maximum of 6 km (Table 1). Mean sinuosity index is 1.505, increasing to 1.608 in the central reach. The average channel slope is 0.67 m/km and the average width of the meander belt 812 m (Ollero 1992). Mean discharge at Zaragoza gauging station is 233 m³/s (1912–2008). The value of an Ebro River with free meanders and the importance of their geomorphic dynamics have been shown in various studies (Ollero 1992, 2010; Cabezas et al. 2009; Magdaleno et al. 2012).

The watershed of the Aragón River is 8537 km² and has 117.3 m³/s of average discharge at the confluence with the Ebro (Table 1). During the first half of the twentieth century, the lower Aragón presented a very active and wide wandering channel located in a floodplain with an average width of 2.65 km that widened noticeably at the confluence with the Arga River. The mean channel gradient is 1.12 m/km, and its current channel sinuosity values are 1.5 and 1.22 above and below the confluence with the Arga River, respectively.

The channel length of the Gállego River is 200 km and the watershed area 4031 km². In its most-downstream 20 km, it has developed an extensive braided channel that has been narrowing, with a current average sinuosity of 1.23, a mean channel gradient of 3.4 m/km, and a mean floodplain width of 1.6 km (Table 1).

The Cinca River has a length of 184 km and a basin of 9768 km². Its lower reach, starting from the confluence with its main tributary, the Ésera River, has an extensive braided planform (braided parameter 2.65 in 1927) of an average gradient of 2.5 m/km and a width ranged between 0.3 and 1.2 km. This study includes the lowest 30 km, from the confluence of Alcanadre River, where the average floodplain width is 1.46 km (Table 1).

3.2 Data and Methods

A variety of hydrologic- and reservoir-related information was obtained from the Ebro Basin Agency. Direct in-channel impacts were identified on aerial photographs, through fieldwork, and by consulting their characteristics, size and date of completion in the archives and documentation of the Basin Agency. Gravel mining data were provided in the archives of the Ebro Basin Agency. The volume of aggregate extraction since 1960 were estimated and divided by the km of channel.

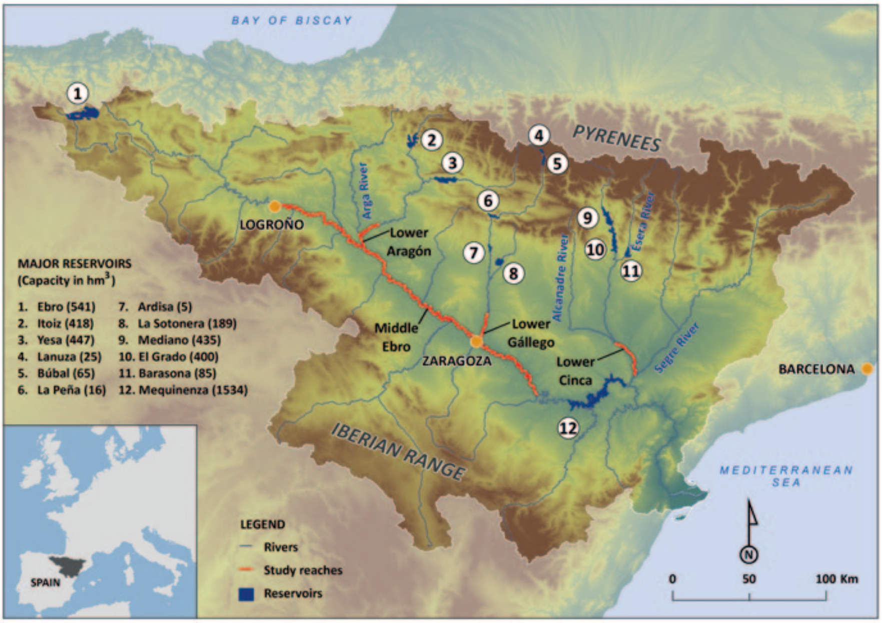

Fig. 1 Ebro basin, location of case studies and major reservoirs

Fig. 2 Ebro River upstream Zaragoza during the flood of April 2007

Channel and floodplain surfaces and evolution were measured and mapped comparing georeferenced aerial photographs and orthophotos, with the earliest dating to 1927. Channel migration was analysed following the methodology of Lagasse et al. (2004). The mobilized surfaces were calculated in hectares per km of channel, considering the change of the position of the active banks between two successive aerial photographs, and then obtaining the average annual change.

Table 1 Some hydromorphological data of the studied reaches

	Middle Ebro R.	Lower Aragón R.	Lower Gállego R.	Lower Cinca R.
Watershed area (km^2)	40434 (at Zaragoza)	8537 (at Ebro confl)	4031 (at Ebro confl)	9768 (at Segre confl)
Distance from source (km)	553 (to Zaragoza)	198 (to Ebro confl)	200 (to Ebro confl)	184 (to Segre confl)
Mean annual runoff hm^3	7348 (at Zaragoza)	3702 (at Ebro confl)	390 (at Ebro confl)	2503 (at Segre confl)
Mean channel slope (m/km)	0.67	1.12	3.40	2.50
Mean floodplain width (km)	3.20	2.65	1.60	1.46
Current average channel sinuosity	1.51	1.40	1.23	1.14

Field work was carried out in the most active sectors of each watercourse to evaluate progressive incision and other changes in morphology. Marks in fixed elements were placed to measure the changes detected between different sampling efforts. This deployed equipment and working protocol is used for subsequent monitoring. Additionally, previous public works documents were reviewed. Channel bed grain size and sediment bar armouring at different sampling points in the studied channels were analysed, yielding an armouring index average for every river through the relationship between the average size of surface and subsurface sediments. The degree of coverage and maturity of riparian vegetation seen on aerial photographs and in periodic fieldworks was also used as an indicator of river adjustments.

In the four locations where lateral embankments were removed, topographic and hydraulic measurements were developed to evaluate downstream peak flow reduction. The analysis of the change of the extent of the 10-year return-period flood in recent detailed cartography and orthophotos and with field reconnaissance was used.

The IHG hydrogeomorphical index (Ollero et al. 2011) was used to compare each reach degree of alteration. The IHG index evaluates nine parameters (Table 2) arranged in three groups: functional quality of the fluvial system, channel quality and riparian corridor quality. Each parameter has an initial score of 10, corresponding to the natural state and functionality of the system. Points are deducted from the initial value depending on the alteration given by impacts and pressures according to different criteria.

3.3 Global Change, Dams and Hydrological Alterations

As discussed in the background section, the Ebro watershed over the past decades has undergone changing patterns, including: (1) climatic change: since 1970 the average temperature has increased 1ºC and the precipitation has decreased by 7%

Table 2 Application of the IHG hydrogeomorphical index. Each parameter scored from 0 to 10. All the parameters altogether results in different hydromorphological situation: from 75 to 90 points very good, from 60 to 74 good, from 42 to 59 moderate, from 21 to 41, from 0 to 20 very bad

	Middle Ebro R.	Lower Aragón R.	Lower Gállego R.	Lower Cinca R.
Flow regime naturalness (a)	4	3	1	3
Sediment supply and mobility (b)	5	5	3	4
Floodplain functionality (c)	3	3	5	4
Functional quality (a + b+c)	*12 poor*	*11 poor*	*9 poor*	*11 poor*
Channel morphology and planform naturalness (d)	6	4	5	6
Riverbed continuity and naturalness of the longitudinal and vertical processes (e)	5	5	4	5
Riverbank naturalness and lateral mobility (f)	2	2	4	3
Channel quality (d + e+f)	*13 poor*	*11 poor*	*13 poor*	*14 moderate*
Longitudinal continuity of the riparian corridor (g)	5	5	4	5
Riparian corridor width (h)	4	4	4	4
Structure, naturalness and cross-sectional connectivity of the riparian corridor (i)	5	5	4	4
Riparian quality (g + h+i)	*14 moderate*	*14 moderate*	*12 poor*	*13 poor*
Hydrogeomorphological quality (total)	*39 poor*	*36 poor*	*34 poor*	*38 poor*

(Del Río et al. 2011), (2) changes in land use: abandonment of agricultural uses and reforestation in mountain areas between 1950 and 1980, 65 % of the slopes in the Pyrenees and the Iberian Range have been reforested (García-Ruiz and Lana-Renault 2011) –; (3) expansion of irrigation from 450,000 ha in 1950 to 820 000 ha in 2012 (Ebro Basin Agency 2011)—and increased water consumption in valley bottoms—the agricultural water use in the Ebro watershed is 15 times greater than the combined urban and industrial water use (Ebro Basin Agency 2011). Meanwhile, the increase in urban development and impervious areas is not significant to the present study.

These regional changes have exhibited themselves very clearly in the Ebro basin's hydrological cycle, with a significant reduction of flow in all watercourses and specifically in the case studies hereby presented. The average annual flows and maximum annual flows for four of the case studies are undergoing a decreasing trend. The regulation generated by reservoirs within the Ebro, Aragón, Gállego and Cinca basins (Table 3), have increased the effects of global change. Additionally, significant changes in flow regime, such as a substantial reduction in winter and spring flows, increase in summer flows and remarkable reductions in the number and volume of seasonal floods (Fig. 3, right), have occurred. Analysis of Ebro River streamflow data from 1960 to 2010 reveals a 50 % decrease in the maximum annual flow. The decrease is 70 % in the Cinca River.

The Gállego River is highly regulated, with a succession of dams in its upper reach and being subject to significant irrigation water draws in its middle and low reaches, especially since the construction in 1968 of the Sotonera reservoir. Nearly 71 % of the discharge is used for irrigation. The result is a highly disturbed discharge regime, with 81.5 % of annual runoff being impounded by dams, allowing only for minimal environmental flow. It is expected that the disturbance to the flow regime will increase in the future, since two new reservoirs have been approved by the Spanish government, namely Biscarrués and Almudévar with a storage capacity of 35 and 169 hm^3, respectively.

The Cinca River is also highly regulated with two reservoirs, namely Mediano (1974, 435 hm^3) and El Grado (1969, 400 hm^3) in its middle course. These reservoirs result in a tremendous amount of water withdrawal for irrigation, specifically 29.4 % of the entire discharge.

In the Aragón River, the Yesa reservoir with a capacity of 447 hm^3 became operational in 1960 enabling important water diversions for irrigation. Since then, the regulation is increasing (Itoiz reservoir 2003, 418 hm^3) and with the recent approval of an increase in the height of the Yesa dam to double the reservoir capacity. The degree of hydrological alteration of the Aragón is equivalent to that of Cinca, although its impact is reduced by receiving its less regulated main tributary, the Arga River, within the study area but near the confluence to the Ebro River.

The Ebro River is highly regulated in its headwaters by a large reservoir of 541 hm^3. Downstream the Ebro primarily receives flow from regulated tributaries, and substantial water withdrawal for irrigation are allowed. The values given in Table 3 correspond to the Ebro at the gauging station of Zaragoza, downstream of

Table 3 Hydrologic regulation data and sediment capture rates in reservoirs in the four case studies

	Middle Ebro R. (at Zaragoza)	Lower Aragón R. (at Ebro confl)	Lower Gállego R. (at Ebro confl)	Lower Cinca R. (at Segre confl)
Watershed area (km^2)	40434	8537	4031	9768
Annual water diversions for irrigation (hm^3)	2070 (73 % before 1960, 27 % since 1960)	732 (23 % before 1960, 77 % since 1960)	946 (43 % before 1968, 57 % since 1968)	1042 (56 % before 1970, 44 % since 1970)
Mean annual runoff hm^3	7348	3702	390	2503
% of natural annual runoff diverted for irrigation	22.0	16.5	70.8	29.4
Reservoir capacity (hm^3)	2192	993	332	1043
% of annual runoff impounded by dams	29.8	26.8	85.1	41.7
% deficit of sediments by dams	37.5	34.1	55.8	43.0

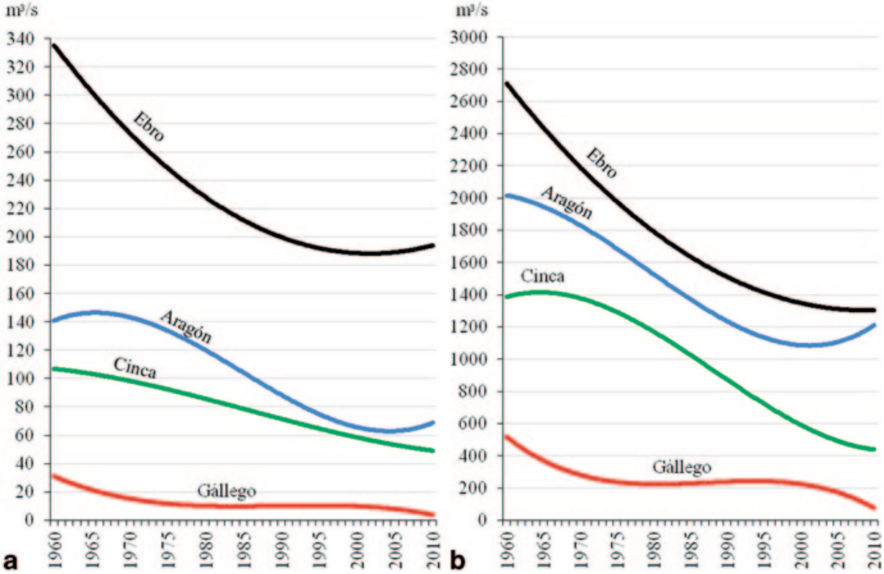

Fig. 3 Simplified trend lines (from 1960 to 2010) of mean annual discharge (*left*) and maximum annual flow (*right*).

Table 4 Direct in-channel impacts in the four case studies

		Middle Ebro R.	Lower Aragón R.	Lower Gállego R.	Lower Cinca R.
% of active banks with embankments		99.9	83.2	38.9	66.7
% continuity of levees		92.1	76.2	32.5	74.7
Gravel mining since 1960 (10^3 m^3/km)		7.5	11.2	73.3	14.6
% of natural areas in floodplain	1927	24.7	17.2	20.2	36.5
	1957	20.0	15.5	27.1	33.5
	1981	15.4	10.5	18.0	24.8
	2012	14.3	9.3	18.8	19.3

the confluence with the Aragón River and upstream of the Gállego River confluence. The effects of flow control in the Ebro River are much more important in its lower course, downstream of the confluences of the Cinca and Segre Rivers (Guillén and Palanques 2011; Sanz et al. 2001; Day et al. 2006; Vericat and Batalla 2006).

3.4 *Direct Channel Modifications*

The systematic construction of levees (flood control dikes), riprap and other defensive systems to prevent flooding and erosion began in the twentieth century, especially in reaction to large floods in 1959, 1960 and 1966 in the Aragón and the Ebro rivers (Ollero 2010). The process was completed in the early 1980s in the Ebro and the Aragón Rivers, and in the 1990s in the Cinca River following an extraordinary flood in 1982. The channel and floodplain of the Gállego River are less protected (with just a 32.5 % of the floodplain) compared to the other cases (Table 4).

The lower reaches of Aragón River have impacts that do not occur in the other rivers. In the 1980s, a short artificial meander cut was dug. In the 1990s, three small hydroelectric power stations were built, which resulted in a reduction in the length of three meanders. The downstream most 13 km of its tributary, the Arga River, was entirely channelised by meander cut-offs and the creation of an artificial channel. Work began in the 1960s within the area nearest to the confluence, and was completed in the 1980s (Acín et al. 2011).

Gravel mining occurred along all river reaches for provision to the construction industry (mainly between 1960 and 1990), but also in some cases to increase the channel capacity. It is noteworthy that the intensive extractions performed on the lower reaches of the Gállego River (73,300 m^3/km) in the 1960s and 1970s (Martín-Vide et al. 2010), were driven by the needs of construction because of population growth in Zaragoza.

Increasing water regulation and channel stabilization favoured anthropogenic human encroachment of the floodplain, gradually constricting the space of the natural river. Not developed floodplains were reduced to approximately half of their natural areas in 1927. This resulted in a 58 % reduction in the middle Ebro River, a 54 % reduction in the lower Aragón River and a 53 % reduction in the lower Cinca River. Currently, only 14.3 % of the middle Ebro, 9.3 % of the lower Aragón, 18.8 % of the lower Gállego and 19.3 % of the lower Cinca Rivers floodplain could be considered natural.

3.5 Channel Responses

As a result of the activities and the changes in the different watersheds previously noted, all the studied river courses have become stabilized. This has resulted in a narrower channel and riparian corridor, with channel-bed incision. The average channel width of the lower Gállego River, for example, reduced from 303 m to 60 m between 1957 and 2012. This resulted in changes to the general morphology of the channel or river style (Table 5), especially in the 1960s, 1970s and 1980s.

Bank protections (Fig. 4) and levees have stabilized the channels. The deceleration and near elimination of channel dynamics represent an important loss of natural heritage, especially considering the small number of dynamic river reaches which exhibit some geomorphic activity within the Iberian Peninsula. Since 1957, the mobility of Ebro River was progressively reduced, and the channel was stabilized in 1981. In the lower reaches of the Aragón and the Gállego Rivers changes continue with around 8 ha/km of sediment being mobilized between 1981 and 2012, an intensity of 5 m/year. Some fluvial activity does occur, and the lower Gállego River underwent a meander cutoff during a large flood in November 2003.

There has been a progressive and significant decrease of both the area covered by water and the gravel bars without plant colonization. As a result, the width of the riparian corridor has dramatically reduced in response to land use changes (Fig. 5).

Riparian colonization of alluvial bars in the study areas has been very intense since 1957, after the establishment of the main regulatory processes. With the reduction of flood frequency, the vegetation has rapidly achieved an excessive level of maturity. In 2012, 85 % of the vegetation within the channel of the Aragón River and 77 % of the Ebro River were classified as mature vegetation. The effect of this process is channel incision and a decline in the water tables of the alluvial aquifers. This can be seen at numerous sites along both rivers through an increase in dead trees and invasion of xeric and invasive vegetation species.

Channel incision has been very high in response to some human impacts, such as gravel extraction and the construction of small dams. Such changes, for example, resulted in incision of up to 6 m within 30 years along the lower Gállego River (Martín-Vide et al. 2010; Ferrer-Boix 2010). In other rivers examined in this study, there is much less channel incision. And, in the Ebro and the Cinca River sites of channel aggradation have been identified, which is considered to be a consequence of lateral channel constraints.

Table 5 Changes in the channel, riparian corridor and river style since 1927

		Middle Ebro R.	Lower Aragón R.	Lower Gállego R.	Lower Cinca R.
Mobilized surface (ha/km)	1927–1957	18.1	27.1	21.6	13.3
	1957–1981	3.6	14.5	17.2	14.5
	1981–2012	0.3	8.9	8.5	4.2
Change intensity (m/year)	1927–1957	12.2	15.0	8.8	7.3
	1957–1981	4.8	11.3	7.0	12.1
	1981–2012	0	5.2	5.0	2.9
% and type of vegetation in channel	1927–1957	8 % pioneer	12 % pioneer	2.5 % pioneer	4 % pioneer
	1957–1981	13 % pioneer + 13 % mature	16 % pioneer + 19 % mature	10 % pioneer + 2 % mature	24 % pioneer + 10 % mature
	1981–2012	15 % pioneer + 77 % mature	8 % pioneer + 85 % mature	35 % pioneer + 53 % mature	23 % pioneer + 65 % mature
Channel width (m)	1927	158.8	185.8	254.8	370.4
	1957	124.6	178.6	303.4	195.8
	1981	99.1	81.9	154.6	149.6
	2012	95.8	76.0	60.0	69.0
Riparian corridor width (m)	1927	363.2	491.8	425.8	451.7
	1957	294.5	444.2	436.5	414.4
	1981	227.6	257.3	290.5	307.0
	2012	219.1	266.3	302.5	238.1
Channel-bed incision (m)		+ 0.5 to − 2.2	0 to − 2.4	0 to − 6.0	+0.2 to − 1.6
Armouring index		1.4	1.5	2.6	1.8
Change of river style from 1950 to 2012		Wandering to meandering	Wandering to meandering	Braided to wandering to sinuous	Braided to wandering

Fig. 4 Embankment built in 2009 (lower Gállego River)

Following these responses, the four studied channels have undergone considerable changes in river style, which in general has been towards a trend of a more stable river patterns. In 1950, for example, the Ebro and Aragón Rivers (and very clearly in a 1927 photograph) had wandering channel patterns with a distinctive main channel of high sinuosity (around 1.4), many islands, extensive secondary arms and barren sediment bars. The process of change has resulted in a simple meandering pattern with a sinuosity of 1.5 and a single channel, resulting in some relict islands to be colonized by vegetation. The current active Ebro River has a meandering stream that lacks geomorphic dynamics, and instead is subject to the influence exerted by the embankments. In the case of the Cinca River, the higher slope and sediment load were responsible for an extended braided channel until 1950, which in the past half century has been transformed into a wandering stream with a main channel of increasing sinuosity, currently around 1.3. The lower reach of the Gállego River has undergone the greatest change, adjusting towards simplification. The river has evolved from a braided channel up to the 1960s to a wandering pattern until the 1990s. In the last decades, incision has led to a single, deep and very simple channel with low sinuosity (1.2). This is the consequence of considerable hydrologic alteration, despite that the Gállego River is less managed and has a dynamic channel.

4 Discussion, Management Targets and Proposals

4.1 Diagnostic

The processes of river adjustment are similar to those noted and analysed in other Iberian and European rivers. These systems display generalized trends towards stabilization, narrowing, incision and simplification of fluvial style for several decades (e.g. Bravard et al. 1997; Liébault and Piégay 2002; Surian and Rinaldi 2003; Uribelarrea 2008; Piégay et al. 2009; Surian et al. 2009) as a result of reduced sediment loads.

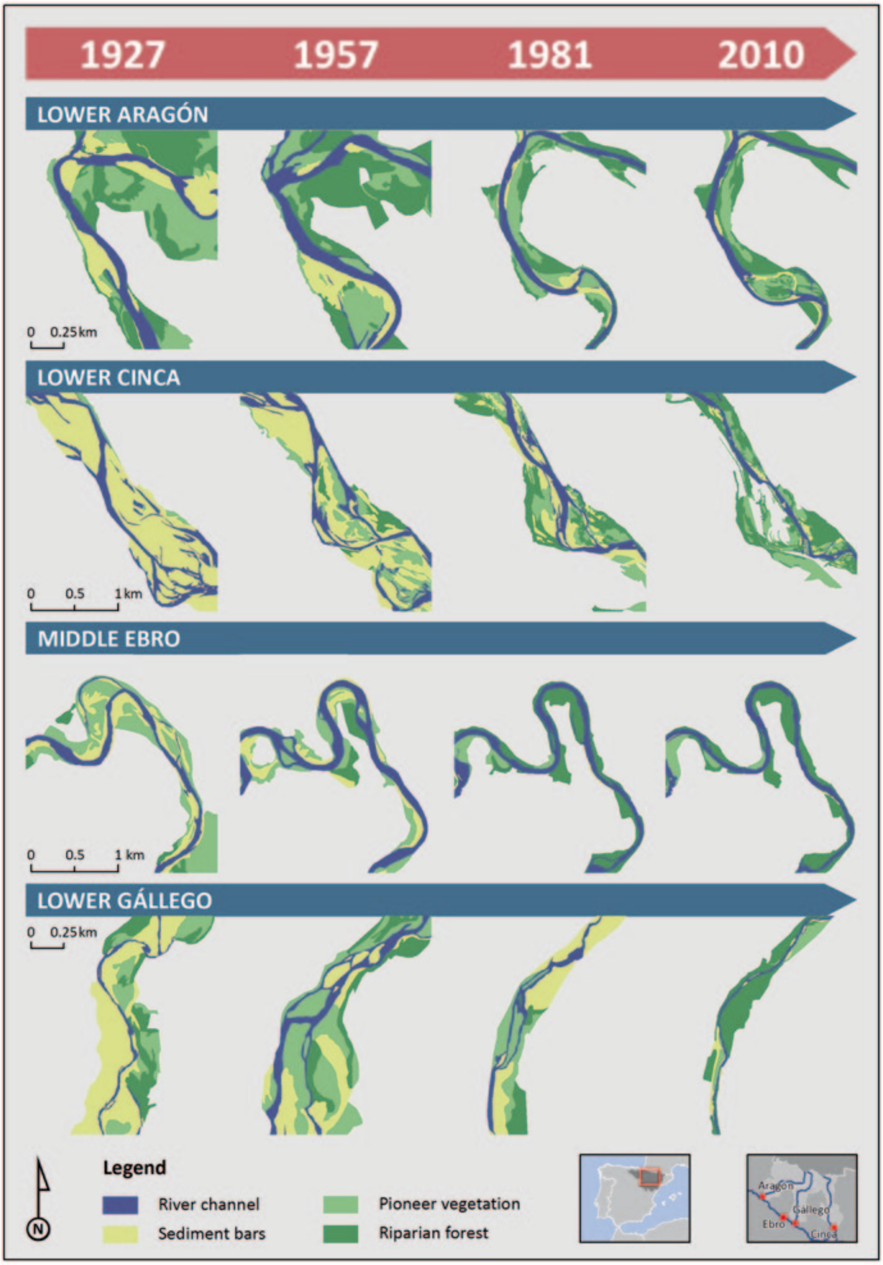

Fig. 5 Changes in channel and floodplain in representative reaches of each case study

In the cases presented here, changes in trends are similar since they belong to the same climatic zone and have undergone similar land use change processes. In this case, the key is the reduction of flow and sediments in recent decades, with similar mean values to other watersheds of the Iberian Peninsula (Lorenzo et al. 2012).

The four drainage basins were strongly impacted by the construction of reservoirs. The greater disturbance, in the Gállego River, has comprised a more rapid and intense transformation of its fluvial style compared to the other examples, as well as higher levels of armouring. Incision is also much greater in the Gállego, although it is not only an effect of the reservoirs but also of the significant extraction of aggregates.

In addition to basin-scale disturbances, local impacts are also widespread. The Gállego is the channel with fewer embankments and therefore maintains higher local channel dynamics, which would likely have been greater without the vertical incision. Bank protection has been effective in the Ebro and Aragón Rivers, such that lateral channel dynamics is quite limited. As a result, these courses are also initiating vertical incision, as well as the decline of riparian bank vegetation.

The application of the hydrogeomorphical index IHG (Ollero et al. 2011) to the four case studies completes the diagnosis (Table 5). The reaches examined in the present study reveal a poor hydrogeomorphical quality. The Gállego has the lowest composite value, due to the seriousness of its hydrologic and sedimentary problems. The Ebro River is favoured by slightly less river regulation and has channel banks in relatively good shape.

The geomorphologic response to watershed- and local-scale change will continue in the coming decades. Moreover, climate change projections for the next century forecast a decrease in precipitation and higher evapotranspiration, induced by higher temperatures (Lorenzo et al. 2012). These are projected to result in further flow reductions. In addition, reservoirs cannot be eliminated and will likely display a short-term increase in the Aragón and Gállego Rivers, impacting those rivers as well as Ebro. Given this inevitable situation, river managers should focus on improvement efforts to reduce local pressures and on the hydrogeomorphical rehabilitation of the lower reaches of the rivers.

4.2 From Geomorphology to Management

Environmental management of river systems is needed, including the identification and conservation of reaches in good conditions, the restoration of all recoverable reaches and the rehabilitation of damaged river reaches. The management should be planned together with floodplain risk management. Fluvial geomorphology provides working and monitoring methods for these purposes. At the same time, geomorphology has an intrinsic value of its own and becomes a key issue in restoration efforts, as recovering channels to a geomorphologically active and a free state implies improving the whole river ecosystem, with all its complexity. Stream restoration and appropriate management of floodprone areas require conserving natural hydrological conditions and free space to rework for the river.

Given that these are floodplain streams, it is necessary for the environmental management system to be combined with a floodplain risk management. The main solution proposed is the creation of a space for the river or *Fluvial Territory*. But this measure should come with others: flood water management from dams, sediment delivery, removal of bank defences, elimination of channeling and reconnection of disconnected meanders.

4.3 The Fluvial Territory Approach

Allocating a dedicated space for the river is a key solution to protect natural dynamics, to improve fluvial ecosystems, to manage floodplains and to minimize risk (Dister et al. 1990; Bazin and Gautier 1996; Piégay et al. 1996; Cals and van Drimmelen 2000; Ureña and Ollero 2001; Buijse et al. 2005; Pottier et al. 2005; Rohde et al. 2006; Kondolf 2012). In Spain, the National Strategy for River Restoration agreed to name such space the *Fluvial Territory* (Ollero and Romeo, coord. 2007).

The *Fluvial Territory* is defined as the landscape area controlled by a fluvial system. It includes the river bed, the riparian corridor and the floodplain, the latter either partially or completely. It is a geomorphological and ecological zone of activity with maximum efficiency and complexity as a natural system. The *Fluvial Territory* is a zone to be reclaimed for sustainable river management, but its reclamation often conflicts with socio-economic interests located along the fluvial system. Public or private ownership could be allowed in the *Fluvial Territory* with strong land use controls, such as regulations or prohibitions of different activities, including new developments and gravel extractions. The *Fluvial Territory* must be wide, continuous, and subject to flooding and erosion. Ripraps and levees must be removed or set back. To create and manage the *Fluvial Territory*, the concept needs to be included in planning regulations along river areas.

The *Fluvial Territory* contributes to naturalize the channel and to diversify the geomorphological environments, so it increases the ecological diversity in channels and riversides as encouraged by the European Habitats Directive (1992/43/EU). In lowland riversit favours lateral geomorphological dynamics, which enrich the complexity of the alluvial substrate. It establishes the vertical dynamics, slowing down the typical incision processes of regulated rivers with constricted channels. The *Fluvial Territory* preserves the functions, interactions, dynamics, continuity and connectivity of fluvial ecosystems within the requirements of the *ecological good status* of the Water Directive (2000/60/EU). *Fluvial Territory* is a tool to reduce floods naturally, moderating peak flows by allowing overflow, and a way to slow down the flood wave which mitigates the risk and results in savings in defences and compensations. It is, in fact, a new defence system following European Floods Directive (2007/60/EU) suggestions, a resiliency strategy (Vis et al. ed. 2001) opposite to the traditional resistance strategies (levees, dredging, embankments, etc.). The *Fluvial Territory* reduces flooding problems by reducing exposure, thereby creating sustainability when facing risk situations (Blackwell and Maltby 2006; Ollero and Elso 2007). This proposal enables the floodprone areas to have multifunctional uses. Human activities can be developed as long as they are compatible with the flood or they are insured. It is better to combine diverse activities in the same territory than to compartmentalize spaces, so that the exerted pressures are less intense and more easily recovered (Sparks and Braden 2007).The *Fluvial Territory* has been designed to be delimited by geomorphological, ecological and historical (channel evolution) criteria. The classification system has transitory boundaries that are periodically revised in order to be continually adapted to its own fluvial dynamics (Ureña and Ollero 2001). The delineation process has been the subject of considerable research (e.g. Malavoi et al. 1998, 2002; Piégay et al. 2005; Ollero et al. 2009) is explained in Fig. 6.

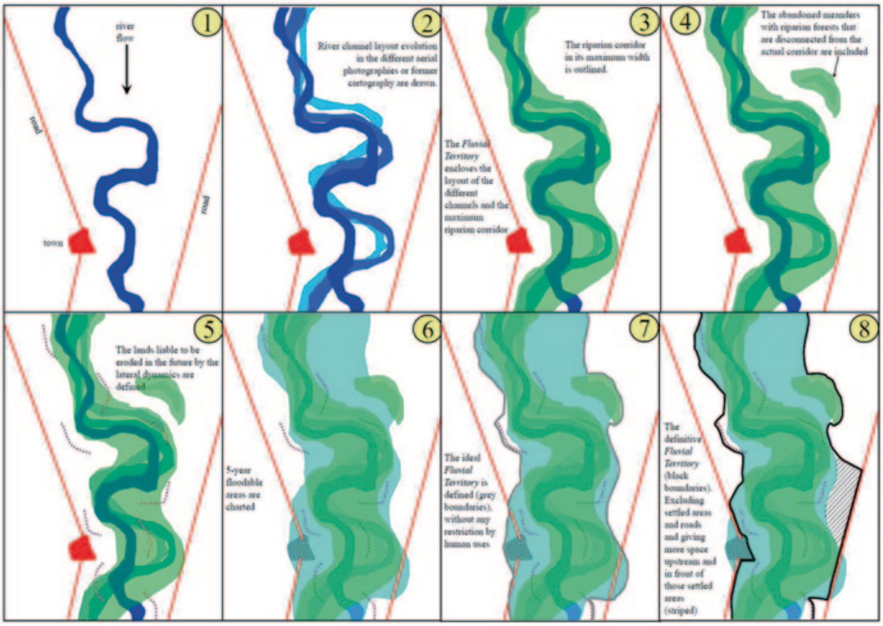

Fig. 6 Methodology of delimitation (*eight steps*) of the *Fluvial Territory*, based on Malavoi et al. 1998, 2002; Piégay et al. 2005 and Ollero et al. 2009

Property conflicts, multiple uses, the complex compatibility of different interests, inherited situations, and the challenge of integrating the measure with flow management and other environmental measures reveals the complexity arising with the application of the *Fluvial Territory* (Ollero et al. 2009). The chance of its implementation in Spain is minimal, as it has not been taken into account in political and administrative levels. Because of its difficulty in application and management, it is not appreciated as a solution for environmental and risk management issues. The National Strategy of River Restoration was launched in 2007 involves the Spanish central government, with some success at being able to awake social awareness on the subject. In 2009, the *Iberian Centre of Fluvial Restoration* was established and integrated in the *European Centre for River Restoration,* which gathers professionals and working initiatives to support the *Fluvial Territory* as a fundamental approach.

4.4 Fluvial Territory Proposals and Embankment Removal in the Case Studies

In the Middle Ebro River and in some of its main tributaries different studies and proposals have been developed to implement the *Fluvial Territory*. A first outline was proposed in the free meandering reach of middle Ebro River upstream of the city of Zaragoza (Ollero 1992). This idea has not been yet put into practice but it

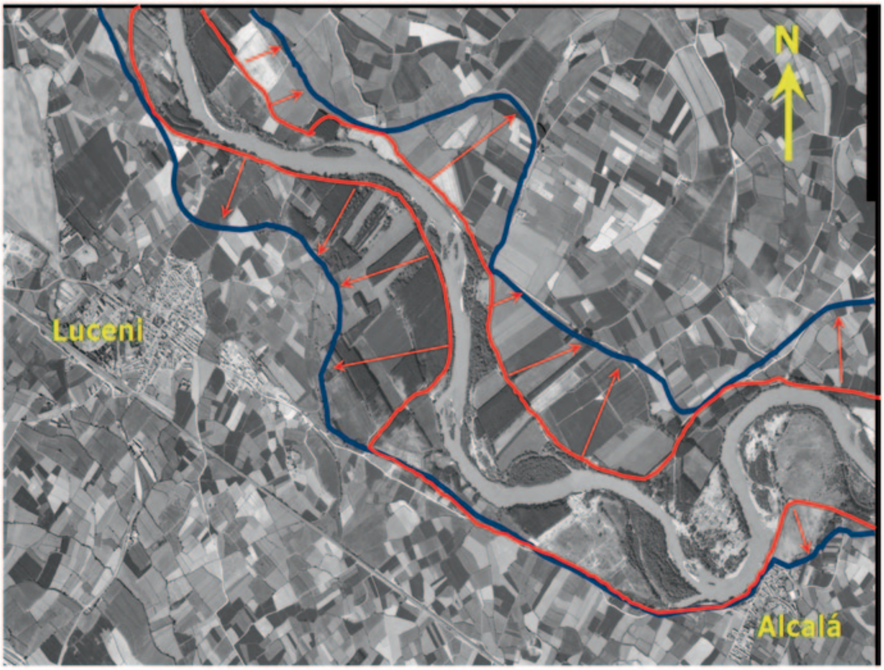

Fig. 7 *Fluvial Territory* in a reach of Ebro River upstream Zaragoza (Ollero 2010). Moving back of lateral defences is proposed. This proposal has not been put into practice

has been discussed continually. The Environmental Plan of the Ebro River, prepared after the 2003 February flood, was funded by the regional Government of Aragón, which proposed a continuous *Fluvial Territory* for the reach located in Aragón. In this proposal, the river space would include a total surface of 13,035 ha (6705 ha of crops), with an average width of 1184 m, that is, a 30 % of the total surface of the floodplain. The implementation of this territory would entail moving the defences away an average of 350 m on each margin (example in Fig. 7).

Recently, some initiatives have accepted controlled flooding of rural fluvial spaces. The Ebro Basin Agency set up a technical commission where two options were discussed: (1) make the dikes with floodgates permeable, getting controlled 53 hm^3 flooding areas, equivalent to a 10-year flood, upstream Zaragoza, and (2) the removal of levees establishing a new line of continuous levees on the 25-year flood boundaries. The Basin Agency approved the option to control the flooding, to keep the banks stable and current property and land use boundaries. However, this measure does not provide any environmental benefit to the fluvial system, as it continues to be restricted by bank defences and consolidates the legal loophole which resulted in human occupation of the fluvial space in the last 50 years. Consequently, there is still a need for middle Ebro River *Fluvial Territory*.

Implementation of the *Fluvial Territory* and a recommended width were proposed in projects undertaken in different tributaries of the Ebro River—lower

Fig. 8 The four cases showing recent embankments removal: Tudela (Ebro River), Caparroso (Aragón River), Zaragoza (Gallego River), Fraga (Cinca River)

reaches of the Arga and Aragón Rivers (Díaz et al. 2002), middle Cinca (Ollero et al. 2001), Zadorra River (Ibisate 2004), lower Gállego (Ollero and Martín-Vide ed. 2005), lower Cinca River (Acín et al. 2006). For different administrative reasons most of these proposals were not implemented.

There are four cases, one in each of the sections of study, in which embankments have been locally removed (Fig. 8). An important line of work is to moni-

Fig. 9 Aragón River showing the inundation after levee removal from the January 2010 flood near Caparroso

tor the hydromorphological effects of the embankment removal within these four reaches: Tudela (Ebro River), Caparroso (Aragón River), Zaragoza (Gallego River) and Fraga (Cinca River).

In the middle reach of Ebro River, 2 km upstream of the town of Tudela (Fig. 8), a levee was removed which provided 110 ha of space back to the river. Municipally owned until 2003, the area was thereafter cultivated with rice. In 2005, the defence was removed, and the space was subsequently inundated by the floods of April 2007 and June 2008. No morphological change occurred in the channel, while riparian vegetation colonized portions of the meander lobe. For a 10-year flood, the area's storage capacity would be 1.4 hm^3, reducing the peak flow at Tudela by 3.6 % and lowering the water surface elevation by 12 cm.

In the *Management Plan for the Site of Community Importance ES2200035 Lower Reaches of Aragón and Arga Rivers*, a Natura 2000 area, the *Fluvial Territory* was proposed as one of the key planning elements for biodiversity conservation (Díaz et al. 2002). In the LIFE project *Ecosystemic Management of Rivers with European Mink-GERVE*, the establishment of the *Fluvial Territory* in some pilot areas was carried through the removal of levees or ripraps, allowing the recovering of natural floodplains in some sites. In 2008, levees were removed from a short reach in the Arga River and a 1300 m reach in the Aragón River near Caparroso. The *Fluvial Territory* gained was 12.5 ha (Fig. 8) which can hold 0.18 hm^3 for a 10-year flood. The flow reduction capacity is very low, but as the January 2010 flood reveals (Fig. 9), the new space allows high-flow inundation to reduce pressure from the opposite bank where the town of Caparroso is located. The channel has not significantly adjusted since the defence was removed.

A 660 m segment of an old ditch along the right bank of the Gállego River near Zaragoza was removed in 2007. The river reacted quickly, initiating a meander, causing a rapid erosion of 20 m on the right bank and generating two new alluvial bars 190 m and 164 m long and 20 m wide (Fig. 8).

As a result of the serious flooding in the city of Fraga, a *Fluvial Territory* zone was proposed for the lower reach of the Cinca River, by removing the defences upstream of Fraga. The site comprises 1621 ha with an average width of 620 m. In 2009, in one of the main actions from the National Strategy of River Restoration, a damaged levee adjacent to the river was removed over a distance of 7350 m, while a second defence further away from the river was strengthened (Fig. 8). The added territory amounted to 350 ha, having a flood storage capacity of 2.2 hm^3 for a 10-year flood, reducing the peak flow rate by 7.4 % and the level of flow by 24 cm at the city of Fraga. Since restoration there has not been any channel adjustment or flooding.

Except for the Gállego River, the recovery of the geomorphological dynamics is ineffective. Changes are expected in the coming years to be assessed with a continuous monitoring and especially after some flood events.

5 Conclusions

This study conducted a geomorphological analysis of four alluvial channels in the middle reaches of the Ebro basin considered to be representative examples of the problems faced by many Iberian and European streams.

Global change, dam-building and various local human activities have induced different geomorphological responses from these rivers, such as channel stabilization, channel and riparian corridor constriction, channel-bed incision and substantial changes in river style. This has resulted in very clear processes of simplification over the past six decades, since about the 1950s. Differences in the intensity of these responses for the four case studies, however, enable a comparison of hydromorphologic trends.

This study has shown the important role of fluvial geomorphology in identifying stream-related problems and their causes, in measuring and analyzing the intensity of their effects, in defining future trends of these effects and in arriving at solutions through research.

The optimal solutions are based on river restoration techniques and must be hydrogeomorphological in nature, using flow, floods and sediment transport recovery and providing streams with sufficient space to recover their dynamics. The river space or *Fluvial Territory* is scientifically based and technically feasible. It should be incorporated as a fundamental management objective in environmental reclamation and in flood-risk mitigation, and as a key element in the improvement and restoration of lowland alluvial rivers. It would be of interest to apply it to hold the decline of European streams and to integrate floodplain management in land planning. This challenge is in itself urgent because the implementation of river restoration measures is complex and slow as compared to the processes and time scales for channel stabilization and vertical adjustment.

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Impact Scales of Fluvial Response to Management along the Sacramento River, California, USA: Transience Versus Persistence

Michael Bliss Singer

> *'We…have acquiesced to the destruction and degradation of our rivers, in part because we have insufficient knowledge of the characteristics of rivers and the effects of our actions that alter their form and process.' (Leopold 1994)*

Abstract Most large rivers in industrialized nations are managed carefully to maximize their benefits (e.g., water supply, hydroelectricity), while limiting their hazards (e.g., floods). Management strategies employed in lowland river systems such as large dams, levees, and bypasses affect flow regimes, sediment supply to channels, and the net flux of sediment through river reaches fairly soon after construction. Therefore, equilibrium approaches to fluvial geomorphology are typically inadequate to characterize the effects of anthropogenic activity on management timescales (10–102 years). Each human alteration to the fluvial system has an 'impact scale' in time and space, and these impacts may manifest as persistent (steady, localized influence) or transient (dying away with distance and/or time) landscape responses. The cumulative effects of transient and persistent fluvial responses influence flood risk, the state of aquatic and riparian habitat, and the fate and transport of contaminants. Whereas some persistent impacts are straightforward to anticipate (e.g., reduced flood peaks), transient impacts may result from emergent behavior in fluvial systems and are not easily predicted. This chapter outlines the differences between these divergent landscape responses to perturbations in managed fluvial systems using examples from the Sacramento River in California. The discussion focuses on: (1) persistent local signals of altered flow regimes below large dams that attenuate in lowland valleys, (2) transient longitudinal sediment redistribution due to changes in sediment supply by dams, (3) transience in the magnitude and frequency of flow over flood control weirs into flood bypasses, and (4) persistent overbank sedimentation in localities that favor the export of sediment from chan-

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nels to floodplains. The chapter shows that persistent and transient fluvial processes coexist and interact in large, lowland river basins subject to anthropogenic perturbations in a manner that can produce unanticipated outcomes that are relevant to aquatic and riparian ecosystems, river management, as well as to human communities living in lowland floodplains. It suggests the need for more careful examination of the impact scales of river management to clarify trajectories of landform evolution.

Keywords Hydrology · Sediment transport · Levees · Flood control · Crevasse splay · Floods · Climate change

1 Introduction

1.1 Background

Rivers are fundamentally variable in space and time, and this has profound implications for existing theory in fluvial geomorphology. The theoretical framework in fluvial geomorphology is largely built upon limited observations from a range of fluvial systems with varying internal dynamics and external forcing, and which are often formalized through equilibrium-based principles imported from other disciplines. Since river management strategies generally rely on such equilibrium theoretical paradigms, river management may be limited in efficacy and sustainability. Spatiotemporal variability in geomorphic processes and fluvial forms over decadal timescales affects the ‘impact scales’ (spatial and temporal) of major river management projects. For example, upstream dam construction affects downstream hydrographs and sediment supply, which produce localized effects, but may also interact to create unanticipated emergent river behavior from 10s to 100s of river kilometers away from the dam site, over years to centuries with potential impacts to flood risk, habitats, etc. Likewise, along-channel embankments designed to increase channel conveyance capacity, a fundamental component of flood control systems, may affect longitudinal sediment budgets on various spatial and temporal scales and thus undermine the efficacy of engineered levees and floodways. Furthermore, interaction between external forcing (e.g., climate changes) and internal dynamics in fluvial processes may produce spatial patterns and temporal evolution of river channel boundaries and floodplain topography. These morphological changes will in turn affect engineering works constructed along large rivers, existing habitat availability and quality, as well as large-scale river rehabilitation efforts, which are increasingly implemented to counter the unforeseen negative consequences of past river engineering. However, there are great challenges to predicting the impact scales of river management. Multifaceted perspectives on existing fluvial datasets are needed to tie river management of large rivers systems to the trajectories of evolution (in time and space).

Geomorphology over the last several decades has applied quantitative principles, some developed in other disciplines, to studies of river behavior and form including the physical expenditure of energy (e.g., minimum variance (Langbein and Leopold 1966; Scheidegger and Langbein 1966)), self-similarity hypotheses (i.e., there is inherent fractal organization of drainage basins (Rodriguez-Iturbe et al. 1994; Stølum 1996)), 'ergodic' principles (e.g., space-for-time substitutions that allow for inventories of existing fluvial landforms (Paine 1985; Scheidegger and Langbein 1966), and 'geomorphic transport laws' (e.g., stream power incision (Dietrich et al. 2003). Most of these methods/concepts assume equilibrium in fluvial systems, which is rarely satisfied over human timescales (1–100 years), especially in large river basins subject to spatial variability in geology, tectonics, and climate (Dunne et al. 1998; Fischer 1994; Hack 1960; Howard 1965; Montgomery 1999; Roe et al. 2002; Slater and Singer In Press; Stark et al. 2010), and where external perturbations such as anthropogenic activity and climate change may affect fluvial system forcing in unexpected ways.

Over these human timescales, large river systems may be more realistically viewed within the construct of dynamic equilibrium (Hack 1960), where there is (are): (1) inherent transience of fluvial forms, (2) trajectories of fluvial form evolution, (3) a spatial range of landscape sensitivity (Brunsden and Thornes 1979), and (4) where differences in relief and form may be explained in terms of their spatial relationships rather than of monotonic evolutionary development (Hack 1960). In their review, Brunsden and Thornes (1979) outline the basis for transience in landscape evolution. They suggest that characteristic landforms in a drainage basin are created under constant forcing and that external perturbations may create transient behavior. The manifestation of this transience is likely to be temporally and spatially complex and may lead to diversity of landforms. Indeed various landform outcomes have been produced by driving landscape evolution models with stochastic climate variables (Tucker and Bras 2000) and by driving sediment flux models stochastically based on probability distributions of geomorphic processes themselves (Benda and Dunne 1997a, b). It has also been shown in large continental datasets that exhibit higher rates of landform change (bed elevation) in regions with more variable hydrology (Slater and Singer 2013). Brunsden and Thornes (1979) suggest that landscape stability or equilibrium of landforms is a function of the temporal and spatial distributions of the resisting and perturbing forces, which are unlikely to be well balanced on management timescales.

In this context, probability distributions of measurable fluvial system forms and fluxes could yield insight into the range of physical processes and their resultant forms over a period of decades. This is especially possible in basins endowed with excellent historical datasets on streamflow, sediment transport, storage, and topography. We might benefit from contextualizing 'mean' behavior exhibited in such datasets within more complete information on entire data distributions, especially the 'tails', which may actually have disproportionate control on the manifestations produced by the spatial and temporal integrals of fluvial processes. Furthermore, we may be able to better distinguish between fluvial forms and processes that are persistent over the relevant time scale versus those that are transient, or passing by in space or away with time. Such perspectives will provide stronger frameworks for anticipation and prediction of fluvial adjustment to perturbations, as well as defining the space and time scales over which such adjustments to management and restoration should be expected. In essence, we may view the river in terms of impact scales and the persistent and transient responses that may result from external or internal perturbations (changes in forcing) to governing physical processes, especially in managed settings where constraints are discontinuous in space and time. In this chapter, evidence for persistent and transient large river adjustment in a system that has been the object of major engineering works for nearly 100 years and, similar to many other large rivers, is currently targeted for major river rehabilitation efforts designed to ameliorate some of the negative consequences of these are presented.

1.2 Spatial and Temporal Perspectives

An individual observer traveling upstream or downstream a particular river may witness dramatic spatial differences in fundamental river characteristics (e.g., width–depth ratio, slope, sinuosity, grain size, or floodplain vegetation), many of which may exhibit abrupt transitions rather than smooth monotonic gradients. Thus, the choice of study site(s) is likely to have important implications for the interpretations of fluvial forms and processes. Likewise, when the observer returns to the same location on the river, changes in river form and functioning that occurred in the interim, may be visible and measurable, depending on the timescale of adjustment and the magnitude of the local divergences (e.g., in sediment flux). For example, an upstream dam installation or widespread deforestation in the contributing drainage basin may impact streamflow distributions and sediment supply, leading to modifications of fluvial forms at the observer's location. It is also possible that such upstream changes are propagating downstream and may not yet have reached the observer's location, potentially producing an incomplete understanding of the impending consequences of the upstream perturbations. Further, there is potential for the effects of the upstream disturbance to dissipate longitudinally, such that the observer's location is buffered from the impact of the upstream event.

Thus, problems in fluvial geomorphology must clearly be undertaken explicitly in four dimensions (i.e., planform, topography, and time), where the appropriate spatial and temporal scales must be carefully chosen to tackle the scope of a particular question. This selection of scales, especially in response to management, will determine whether a particular variable is independent or dependent to the system evolution and the trajectory of adjustments (Hudson et al. 2008; Schumm and Lichty 1965). Spatial biases may be minimized by developing synoptic vantage points from which to view the river, wherein spatial variability can be characterized by one of an increasing number of remote sensing methods (e.g., Gilvear and Bryant 2005; Kilham et al. 2012), by generalizing synchronous data from a network of monitoring stations (e.g., Singer 2007; Singer and Aalto 2009), by combining detailed contemporary field sampling with historical data and process modeling (e.g., Singer 2010; Singer et al. 2013a; Singer and Michaelides 2014) and/or by using geochronology to develop spatial links between synchronous geomorphic events (Aalto et al. 2003; Gomez et al. 1998; Walling 1999). So, for at least an instant in time (and indeed over temporal domains of aerial photography and satellite observations), we have suitable methods to describe and quantify how different parts of fluvial system compare and contrast in terms of measurable properties.

Temporal variability presents more complex challenges, primarily due to the short history of detailed, quantitative direct human observation of river systems. However, there are notable examples of long historical records of streamflow in particular regions, for example, that have fomented understanding of the controls of synoptic teleconnections (Andrews et al. 2004; Eltahir 1996) or the decadal influence of impoundments on streamflow (Magilligan and Nislow 2001; Singer 2007). Similarly, sedimentary records have been exploited in forensic geomorphic analyses (Daniels 2008; Knox 1987), although recent research has suggested potential biases in sediment records based on the overlaps in frequency of sediment delivery, hiatuses, and preservation (Jerolmack and Paola 2010; Jerolmack and Sadler 2007; Sadler 1981; Schumer et al. 2011; Schumer and Jerolmack 2009). The subject becomes increasingly complicated when we address the combined effects of spatial and temporal variability in fluvial systems. In the above example, the observer could develop a range of perspectives on the downstream impacts arising from the upstream perturbation. Spatially, this will depend on the location and the resolution of measurements. Temporally, it will depend on the frequency of visitation and the duration of the observer's career in field research. Of course, this field perspective can be aided by datasets that span great areas of a basin over decades to centuries. Fortunately, such intensive data collection is often undertaken in large river basins, where detailed understanding is required for river management that has economic dimensions (water supply, electricity generation) and implications for infrastructure and public safety (flood risk). In such basins, much can be ascertained about the external forcing and internal dynamics, by looking at these spatially extensive and long data records in creative ways. This chapter will discuss a body of work on one such river that provides a window into persistent controls and transient fluvial adjustment to perturbations. River responses to large dams and to engineered flood control levees are addressed, and a context of the river's functioning and form that may yield new, generalizable understanding of large, managed river systems is provided.

The broader goal of this discussion is to provide clearer context for management and rehabilitation of large, embanked river systems, within an understanding of large-scale environmental changes (climatic and anthropogenic). These large fluvial systems typically bisect major population centers and zones of intensive agriculture, and they support major industrial activity (e.g., power generation). As regional climate changes and these rivers and floodplains become increasingly modified by humans, the effects of these shifts in forcing variables get expressed in ways that are inherently unpredictable by conventional perspectives and models. This contribution highlights some of the less well appreciated aspects of river corridor evolution. It is hoped that the examples presented here provide a window into the potential challenges of predicting response to river management under unsteady forcing.

2 Sacramento River

2.1 Background

The Sacramento River of Northern California (Fig. 1) is the state's largest river and one of the major rivers in the American West. It supplies water to millions of California residents (many of them outside the basin boundaries) and contains some of the last great lowland habitats for fish and waterfowl within the Central Valley (Sommer et al. 2001a). Flooding in the basin is dominated by large, winter frontal storms that produce intense rainfall basinwide, albeit mostly concentrated in the mountains (Jones et al. 1972; Singer and Dunne 2004a; Thompson 1960), and snowmelt provides a smaller and diminishing source of water in spring (Knowles et al. 2006). The river flows through the 96 km wide, 418 km long Sacramento Valley, a broad, alluvial, structurally controlled lowland basin between the Sierra Nevada Mountains and the Coast Range on a bed of mixed gravel and sand (Bryan 1923; Harwood and Helley 1987; Singer 2008a). Where the river enters the synclinal trough known as the Central Valley, it assumes the character of an alluvial channel, alternating between active meandering, anastomosing, and straight sections, building bars on a discontinuously armored bed (Singer 2008a; Singer 2010). The channel lies between intermittent natural levees that demarcate a relatively high floodplain composed of fine sands, silts, and clays (Brice 1977; Singer and Aalto 2009; Water Engineering & Technology 1990), which is vegetated by a mix of riparian forest that has been extensively converted to agricultural land over the last century, but is now being restored (Fremier 2003; Golet et al. 2006; Greco and Plant 2003; Micheli et al. 2004). This forest in the riparian corridor interacts with the channel in ways that may influence bank erosion and thus lateral migration rates (Micheli and Kirchner 2002; Tal and Paola 2007), although sediment supply and local floodplain materials and local engineered hard points may be of more importance (Constantine 2006; Constantine et al. 2009; Dunne et al. In Review; Hudson and Kesel 2000; Michalková et al. 2011), particularly in rivers such as the Sacramento where tree roots do not generally penetrate deeply into high banks and therefore provide little protection against erosion of the bank toe. In such systems, entrainment of large woody debris may merely be a by-product of pore pressure failure of banks (Simon et al. 2000). Bank erosion rates in the historical period average 7.7 m y^{-1} (Larsen et al. 2006a), about 6 % of which is comprised of chute cutoff (Micheli and Larsen 2011).

2.2 Controls on River Behavior

As is the case with many large alluvial river systems (Dunne et al. 1998; Schumm and Winkley 1994), the trunk streams of the Sacramento Valley are naturally affected by valley tectonics and geology, as well as by the valley's sedimentary history. River position within the valley is generally controlled by valley tilting, faulting

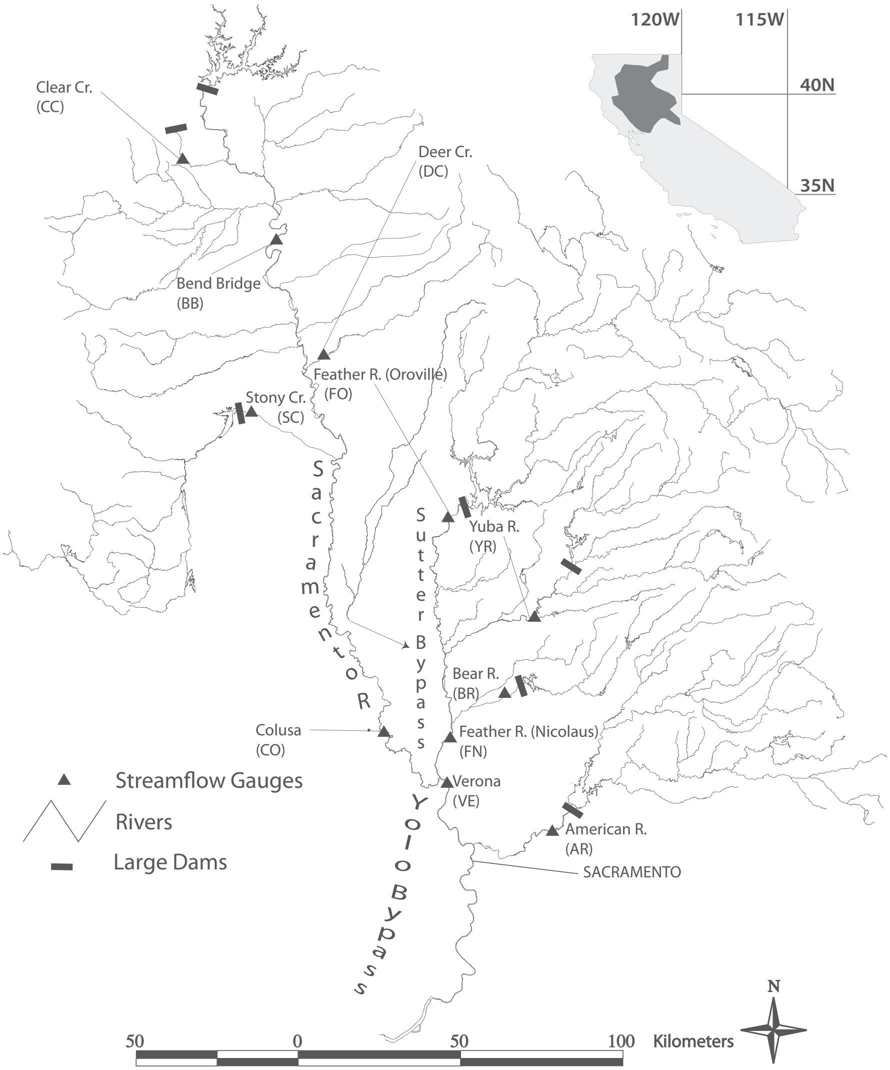

Fig. 1 Map of study area showing major streams, gauging stations, and dams in the Sacramento Valley. Adapted from (Singer 2007)

and folding, resistant outcrops and intrusive rocks, and large Pleistocene alluvial fans (Fischer 1994; Harwood and Helley 1987; Water Engineering & Technology 1990). For example, the alignment of the Sacramento River is affected by the buried Colusa Dome beneath the city of Colusa, composed of relatively resistant uplifted Cretaceous rocks (Harwood and Helley 1987), which causes a major eastward deflection of the river course. This condition results in a decrease in downstream channel capacity, from 7000 $m^3 s^{-1}$ upstream of Colusa to 2000 $m^3 s^{-1}$ downstream, and sequestration of water and sediment in the reach of the Sacramento Valley upstream of the deflection (Singer 2007; Singer and Dunne 2001, 2004b). The reduction in downstream channel capacity during floods causes backwaters to form in the Lower Sacramento and Feather Rivers, the latter of which joins the Sacramento near Verona, 100 km downstream of Colusa. Similarly, the ancestral Pleistocene fan of Cache Creek, a west-side tributary of the Sacramento, apparently pushed the river northeastward downstream of Knights Landing in the vicinity of Fremont Weir so that its course to Verona trends west-east, instead of in the direction of the prevailing north-south valley slope. Within the confines of such geologic, tectonic, and sedimentary controls, the trunk streams meander over aggraded beds. The rivers construct natural levees. by frequent flooding into relatively low natural flood basins that occupy the majority of the land area in the Sacramento Valley (Bryan 1923; Gilbert 1917; Kelley 1998), modulated by the influence of major runoff-producing cyclonic frontal storms and high postglaciation sediment supply.

Under presettlement conditions flow and sediment into the valley was generated in mountainous headwaters (Porterfield 1980). In the lowland valley streamflow and associated sediment discharge into flood basins from the main channels tended to occur at low points along the levee, and where levee materials were inadequate to prevent crevasse formation. Such exit locations, often at the entrance to sloughs (Kelley 1966), were typically coincident with tectonic and geologic controls that forced repeated occupation of flow through levee weak points. Flooding would thus fill the contiguous flood basins, resulting in the development of a seasonally persistent ‘inland sea’ that is well documented elsewhere (Kelley 1998). While valley flooding is essentially a seasonal phenomenon, its depth and areal extent are maximized during extreme floods. Based on flood history in the Sacramento River (US Army Corps of Engineers 1998), large, basin-filling floods have occurred in 17 % of the years between 1878 and 2001 and likely occurred at a similar frequency prior to flood records (Singer et al. 2008), and these seem to be accentuated by ‘atmospheric rivers’ (Dettinger 2011), or synoptic events often driven by ocean-atmosphere teleconnections (Hirschboeck 1988) that produce widespread flooding (Singer and Dunne 2004a). Since the subsiding (Fischer 1994; Ikehara 1994) land surface outboard of the natural levee is lower in elevation than floodplains along the river corridor, sediment carried primarily in suspension was transported by advection out of the channel through these exit loci into the bounding natural flood basins (Singer and Aalto 2009). The resulting pattern of sediment accumulation near the channel margins has been documented as alluvial splays, natural levees along the Sacramento River, as well as accumulation in oxbow lakes (Constantine et al. 2010; Robertson 1987; Singer and Aalto 2009) in patterns similar to other fluvial systems (Bridge 2003; Hudson and Heitmuller 2003).

The various natural controls described above typically produce persistent impacts on the fluvial system at various locations through the basin. For example, at locations where the river interacts with geologic outcrops or tectonic tilting, river channel slope and geometry may be affected (Singer and Dunne 2001), with implications for reach-scale fluvial system behavior. River management strategies are superimposed on the natural environment, such that some of the effects of these structural controls are still apparent and influence management operations (Singer et al. 2008).

2.3 Management Context

The basin has been subjected to a range of management actions, including dams, levees, bank protection, and mining operations, which have affected the geomorphic character of the river and its floodplain. In the 150 years since the discovery of gold in the Sierra Nevada, the Sacramento River valley has been transformed by extremely productive agriculture and human settlement and thus by radical flood control policies intended to ensure the survival of these floodplain activities (Kelley 1998). Hydraulic mining in the Sierra produced huge masses of sediment that clogged up lowland water courses and increased already high-flood risk within the Sacramento Valley. This resulted in lawsuits and ultimately the US government created an integrated flood control plan. This flood control system was designed to convey water and sediment as efficiently as possible through the main stem Sacramento River using straightened channels and high levees built upon protected river banks to prevent overbank flooding and bank erosion, and subsequent lateral channel migration. Since it was acknowledged that the Sacramento River would never have the capacity to carry its entire flood flow (Singer et al. 2008), the system was designed with 'pressure release valves' where flood waters overflow into two major flood bypasses, Sutter and Yolo, via a system of weirs which were constructed to convey water into existing lowland flood basins (Figs. 1 and 2). These floodways divert water in high flows and provide multiuse zones of agriculture and habitat in drier seasons (Singer and Dunne 2001; Sommer et al. 2001a; Sommer et al. 2001b).

Thus, the water courses of the Sacramento Valley are managed through a sequential flood control plan that began in the early twentieth Century to provide flood protection to its low-lying population centers (e.g., Sacramento) and to maximize land for agricultural reclamation. The Sacramento River drains 68,000 km^2 and is controlled by seven large dams (storage $>1\times10^8$ m^3, Fig. 1) that are operated for various combinations of hydroelectricity, water supply, flood control, irrigation, and recreation (Singer 2007). Dams were installed between 1940 and 1970 in the uplands to augment the existing flood control system, for power generation, and to provide water for various downstream uses. Many of the largest dams are located in the foothills of mountain ranges (elevation <600 mASL) and were primarily designed to dampen the largest winter flood peaks and store spring snowmelt runoff for summer irrigation in the valley (Singer 2007).

2.4 River Rehabilitation

In the nearly 100 years since the flood control plan began to be implemented, many important impacts to the Sacramento fluvial system have been documented, including altered flow regimes (Singer 2007), degradation of aquatic habitats (Kondolf 1995), loss of riparian forests (Thompson 1961) and floodplain functioning, contamination of waterways, floodplains, and ecosystems (Conaway et al. 2007; Domagalski 2001; Hornberger et al. 1999; Springborn et al. 2011), and impairment

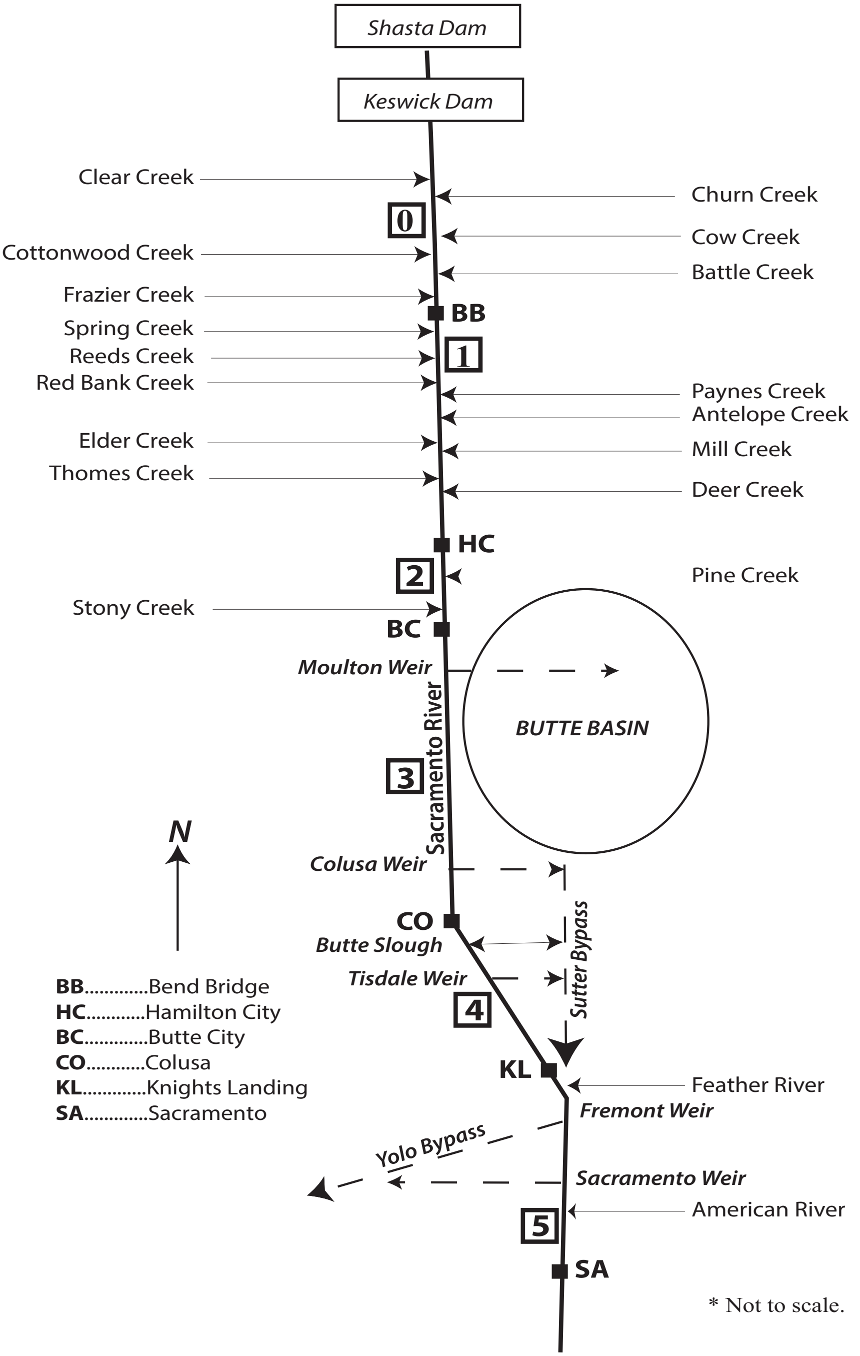

Fig. 2 Schematic map of flood control system indicating primary gauging stations on the main-stem Sacramento River and its tributaries, and where flow is diverted into flood bypasses. Adapted from Singer and Dunne (2001)

and risks to the flood control system itself (Mount and Twiss 2005; Singer et al. 2008). In response, the Sacramento River and its floodplain have been targeted for major river rehabilitation designed to restore the appearance and functioning of the river system (Golet et al. 2006; Larsen et al. 2006b, 2007; Singer and Dunne 2006). Apart from widespread re-plumbing of the river system, which included construction of a peripheral canal to safely divert water around the delta into the State Water Project upstream of the salt wedge that threatens water quality, and bolstering of early twentieth century levees, many of which have become porous and susceptible to failure by earthquakes (Mount and Twiss 2005), several restoration strategies have been proposed that address ecological functioning.

First, to ameliorate the impact of impoundments on the flow regime, flow alteration below major dams has been suggested to better represent natural flow and inundation regimes (Junk et al. 1989; Poff et al. 1997) and this has been attempted for limited periods below some dams (e.g., Glen Canyon Dam-Colorado R. and Shasta Dam-Sacramento R.). Ultimately, a complete and adaptive flow regime must be developed that compromises between ecological needs (Kondolf and Wilcock 1996; Richter and Richter 2000; Richter and Thomas 2007) and intended dam purposes (e.g., hydroelectricity generation, irrigation, flood control), and which must treat the nonstationarity in climatic drivers that may affect the magnitude, timing, and spatial location of streamflow generation. Ultimately a complete and spatial understanding of streamflow alteration and relevant impacts to ecosystems is required to improve design (Richter et al. 1998; Richter et al. 1996; Singer 2007).

To mitigate the negative impacts of flood control levees (embankments) that have constrained bank erosion and river migration, levee setbacks have been proposed (Laddish 1997; Larsen et al. 2006b; Singer and Dunne 2006) to increase the width of the riparian corridor and to allow for natural processes of bank erosion and bar construction (Constantine et al. 2009; Dunne et al. In Review), to recruit coarse sediment from floodplains to channels to fortify anadramous spawning habitat (Kondolf and Wolman 1993; Moir and Pasternack 2010), to increase area of flood retention, and to replenish fine sediments and associated nutrients to and from bounding floodplains (Tockner et al. 1999). Finally, to replenish sediment supplies that have been disrupted and/or diminished by dams, gravel-mining operations, and bank protection, sediment (typically spawning gravel) augmentation has been proposed and attempted on a limited basis in the Sacramento, Merced, and Yuba Rivers to restore natural geomorphic processes and in-stream habitat.

3 Adjustment to Dams

There has been much discussion in the scientific literature about the influence of dams on streamflow regimes (Dynesius and Nilsson 1994; Magilligan and Nislow 2001, 2005; Richter et al. 1996; Singer 2007) and on sediment dynamics and river morphology (Andrews 1986; Gregory and Park 1974; Schmidt and Wilcock 2008; Singer 2008a; Singer 2010; Williams and Wolman 1984). Outstanding issues in-

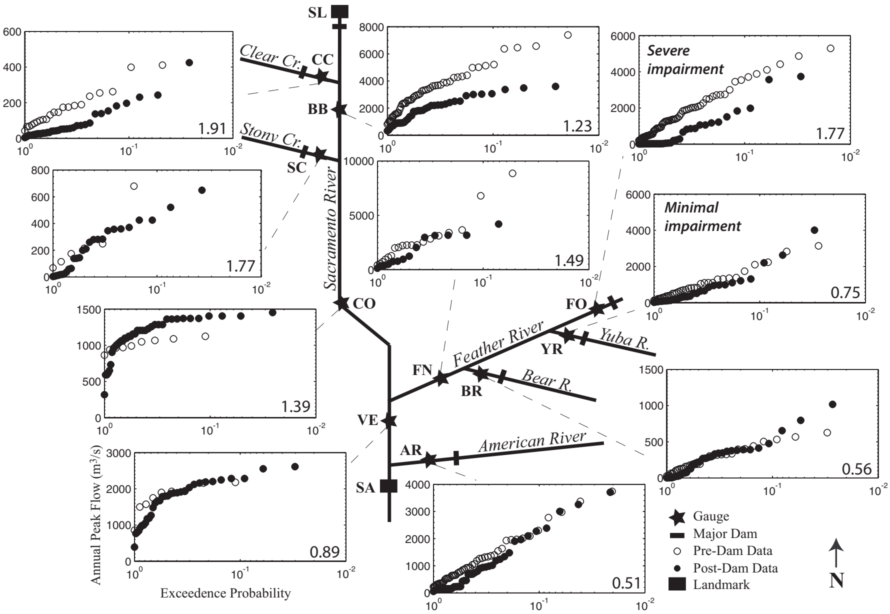

Fig. 3 Streamflow implications of dams. Each panel shows the empirical flood frequency curve (annual streamflow peak) for the indicated gauging station. The value of the impoundment runoff index (IRI) is listed in the lower right-hand corner of each panel; higher values indicate higher level of flow impairment. Station codes are listed in Fig. 1. Adapted from Singer (2007)

clude how individual dams or cascading sequences of dams affect various hydrograph characteristics (which have varying relevance to downstream flood retention and ecology) and the supply of sediment to valley floors. Important measures of the hydrograph that may be affected by dams include flood peak, time-to-peak (rising limb of the hydrograph), drawdown time (falling limb), and annual flood volume. The various dams of the Sacramento Valley, constructed over several decades in the foothills on the periphery of the valley, have had important impacts to fluvial system functioning.

3.1 Dam Impacts on Streamflow

Impoundment by dams allows for a range of flexible release strategies to benefit one or more of several management objectives (water supply, hydroelectricity generation, flood control, etc.). A straightforward measure of such flexibility is the impoundment runoff index (IRI), defined as the ratio of reservoir capacity to median annual flood runoff volume (Singer 2007), a slight modification from the definition in Batalla et al. (2004). This index crudely identifies to what degree downstream streamflow has been altered by dams (Fig. 3). Dams that have high storage capacity relative to annual flood volume (i.e., high IRI) are likely to cut off flood peaks and store them for subsequent release following flood termination (e.g., site codes BB, CC, FO, Fig. 3). Such practice may also reduce time-to-peak and drawdown time, lower annual flood volume, and increase flood interarrival times (Table 1) because small and moderate sized floods are completely cut out of the hydrologic record. Dams with low IRI, on the other hand, do not have adequate storage capacity to completely cut off flood peaks. To control floods, they must instead be operated to lengthen the rising (early release) and falling (late release) limbs of the hydrograph (e.g., sites BR, YR, AR, Fig. 3). Generally, the hydrograph is extended on both limbs (increasing time-to-peak and drawdown time), but there are some late release dams (SC), which lengthen the falling limb without affecting the rising limb.

Detailed analysis over space (many stations around the basin) and time (several decades of daily records) allows for insight into local and downstream impacts of such impoundments. Such an approach provides more direct assessment of historical hydrology and the complex role of many dams with different operating rules than using one of a number of basin-scale hydrologic models (e.g., Lettenmaier and Gan (1990)). It is clear from this analysis in the Sacramento basin that large dams generally have a persistent, localized impact on streamflows, especially annual peaks (indeed, many are designed for flood control), but the whole basin view reveals that the impact of these dams typically dissipates with increasing distance downstream through the fluvial network (Fig. 3) into the lowland valley (Singer 2007). This is because dams are only capable of controlling high flows locally, but since they are located along the basin periphery, there are often large downstream contributing areas that add flow to lowland channels and provide floodplain storage of overbank flows. These factors can diminish the persistent impact of dams in this basin, rendering it localized.

3.2 Evaluating Impacts of Altered Streamflows

The above empirical analysis leaves open the question of prediction—what should we expect the future evolution of streamflow to look like in the context of these dams and associated with projected climate changes? One alternative is to use the wealth of historical records for the basin in a creative way to glean more information on potential decadal adjustments to perturbations and/or modifications of the fluvial system. A stochastic flood-event generator was used that combines flood flow from important tributaries in the basin and routes the combined flows through the mainstem. The philosophy is that the largest source of uncertainty is due to the variability in flow, rather than to the temporal variability in local hydrologic and geomorphic processes (Benda and Dunne 1997a, b). Each 30-year simulation, constructed of semi-randomly selected flood events from the major tributaries based on empirical analysis of synchronous flood event correlation across the basin, produces a distinct flood frequency curve at any point along the mainstem. Analysis of an ensemble of 50 simulations allows for characterization of expected average system behavior, as well as the potential range (tails of

Table 1 Table of hydrograph characteristics (flood peak, flood trough, flood volume, time to peak, drawdown time, and interarrival time) showing the significant directionality of change for the median of each flood frequency distribution based on the Kolmogorov-Smirnoff statistic. Adapted from Singer (2007)

Station	Peak	Trough	Volume	Time to Peak	Drawdown	Interarrival
CC	↓	↑	↓			
BB	↓	↑			↑	↓
DC						
SC		↓			↑	
CO						
FO	↓	↓	↓	↓	↓	↑
YR		↑				
BR		↑		↑	↑	
FN		↑				
VE		↑				
AR	↓	↑		↑	↑	↑

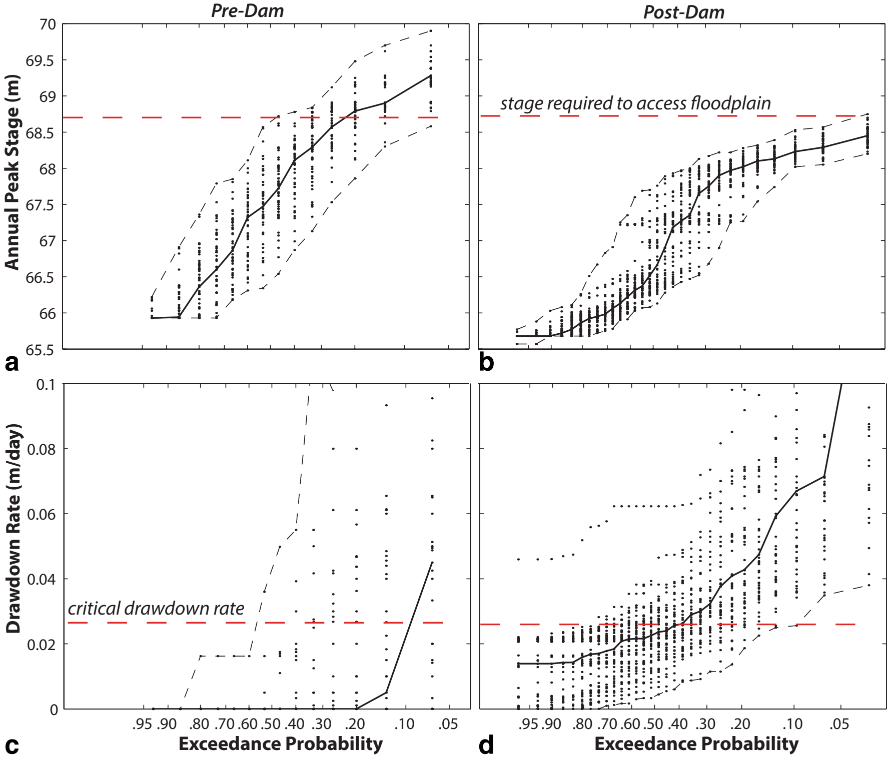

Fig. 4 Influence of dams on floodplain inundation and water table decline. **a** pre-dam hydrological simulations. *Red dashed line* depicts stage required to inundate the floodplain and thereby provide suitable recruitment habitat for cottonwood seedlings. Median of 30 simulations is indicated by bold black line and dashed black lines represent the upper and lower bounds of all simulations; **b** post-dam simulations of peak stage; **c** pre-dam simulations of water table decline. *Red dashed line* indicates threshold rate of water table decline above which cottonwood seedlings will not get established (Mahoney and Rood 1998); and **d** post-dam simulations of water table decline. Adapted from Singer and Dunne (2004a)

the distribution) based on hydrologic uncertainty due to various combinations of tributary inputs to the mainstem. A set of hydrologic simulations (Fig. 4) indicates how ensembles of information may be used to assess hydrologic restoration strategies in river corridors (i.e., re-creation of natural flow regimes). The results present a hypothetical analysis of a local cottonwood forest restoration effort on the floodplain. According to prior work, cottonwood forests develop only if two conditions are satisfied: (1) floodplains are wet during seedling release, requiring flow stage to exceed a threshold (68.7 mASL in this case), and (2) seedling roots must remain in contact with the water table, requiring a rate of water table decline less than 2.5 cm/day (Mahoney and Rood 1998). The analysis shows that in the era before the construction of Shasta Dam, the primary large dam on the Sacramento River, both conditions were satisfied the majority of time. The floodplain is wet in most years and the drawdown rate only exceeds the critical threshold ~ 10 % of the time (Fig. 4a & 4c). However, since dam construction, flow stage has not exceeded the threshold, so the floodplain is essentially stranded from the channel (Fig. 4b), and the water table declines faster than 2.5 cm/day about 40 % of the time (Fig. 4d). These are consequences of dam operation that will dramatically impact the hydrology in the riparian corridor, which has knock-on effects for any proposed restoration effort intended to expand forests in the riparian corridor and for trees that are already established (Singer et al. 2013b; Singer et al. 2014).

The response of stream hydrology to dam installation and operation is nonlinear and dependent on various factors. Thus, analysis of the distribution of flows, including various hydrograph characteristics such as flood peaks and hydrograph shape, provides more complete information on the direct downstream hydrologic impact and also indicates how these characteristics will be affected with increasing distances downstream of the dam perturbation (Singer 2007). When considered within a stochastic analysis framework, these empirical records for a basin can provide analytical support for assessing river rehabilitation strategies (Singer and Dunne 2004a, b; Singer and Dunne 2006). The impact of dams on hydrology may be considered to be persistent. Whereas the operation rules may change through time based on the water allocation needs, etc., the nature of such changes average out over the long term and become dampened by the localized impact of the dam on streamflow alteration, which remains relatively constant and can be tracked as it dissipates downstream.

3.2.1 Dam Impacts on Sediment Flux and Storage

What about dam impacts on sediment transfer and channel characteristics? These are usually discussed in terms of the local 'hungry water' effect, wherein clear water discharged below dams has high transport capacity and therefore entrains disproportionately high sediment loads, producing river incision. However, such incision generally produces localized river armoring that limits the extent of vertical incision. However, there is much less certainty about the downstream translation of the dam signature on sediment dynamics, although some basic metrics on sediment deficit have been proposed (Schmidt and Wilcock 2008). A straightforward indicator of the role of dams in disrupting sediment passage is a longitudinal grain size distribution (GSD) in the channel, which can be thought of as the first degree of freedom the river has to adjust to perturbations (Church 2006). This may be assessed through the analysis of bed-material sediment, which reflects the integration of geomorphic processes operating on the bed. Another obvious candidate variable is downstream topography, which reflects the sediment mass balance (e.g., through the evolution of fluvial landforms; Singer and Michaelides 2014).

The longitudinal GSD along the Sacramento River has been analyzed based on subaqueous, boat-based (Singer 2008b) samples of channel bed sediments at > 100 cross sections (several samples per cross section) spanning ~ 400 river kilometers (Singer 2008a) (Fig. 5). This work showed that whereas the gravel-to-sand transi-

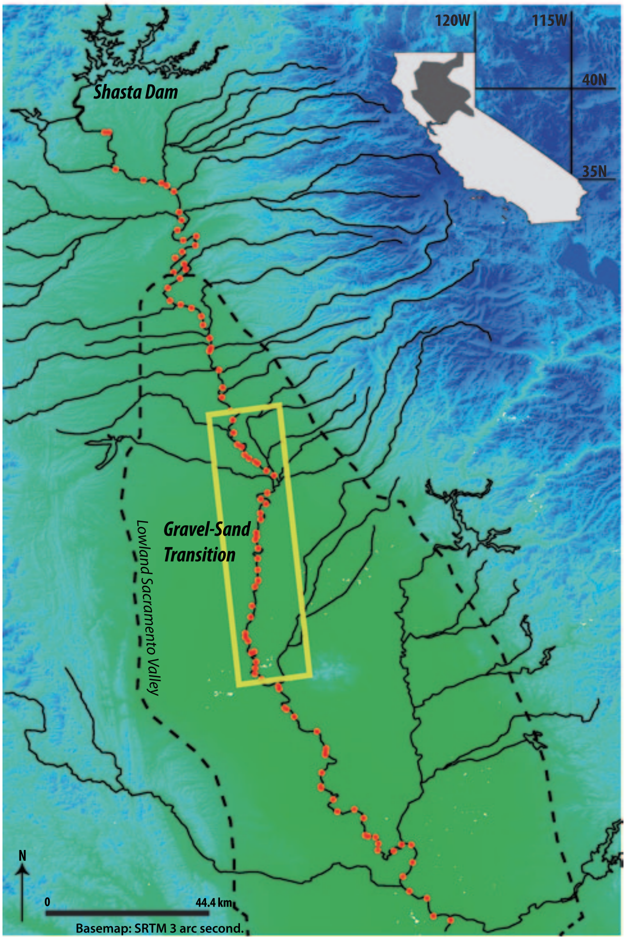

Fig. 5 Map of bed-material sampling locations obtained by boat via Cooper Scooper (Singer 2008b) along the Sacramento River. The yellow box highlights the protracted gravel-sand transition within the lowland Sacramento Valley, which is hypothesized to emerge as a redistribution of sediment from below Shasta Dam to downstream lowland sites of deposition. Tributaries play a small role in affecting Sacramento bed-material grain size because of the great distances they travel across the lowlands within the synclinal trough of the Sacramento Valley

tion in rivers (i.e., the point at which the median grain size changes from gravel to sand) is generally abrupt (Ferguson et al. 1996; Ferguson 2003; Sambrook Smith and Ferguson 1995), its expression in the bed of Sacramento River is protracted over ~ 125 km, as the median grain size (d_{50}) oscillates between coarse and fine sections (Figs. 5 & 6). This gray area in Fig. 6 corresponds to a region of the river where the values of sorting (a measure of GSD spread) are highest, suggesting a broad range of grain sizes are accumulating in this zone, where shear stress oscillates and declines (Fig. 6). This previously unknown phenomenon was interpreted

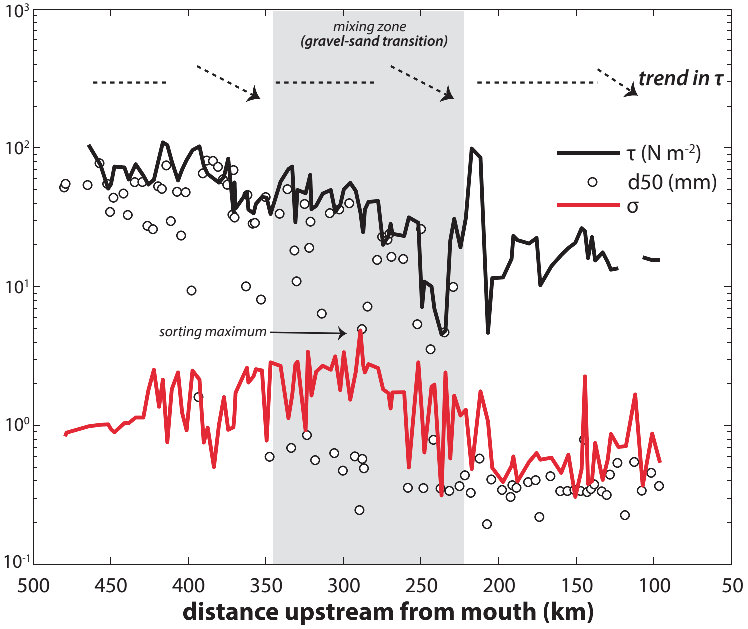

Fig. 6 Grain size characteristics (d_{50} and sorting coefficient, σ) and shear stress (τ) v. distance. Local (*reach-scale*) trends in τ are indicated at the top. Maximum sorting (*most poorly sorted*) part of the river system is located within the shaded gray area, the protracted gravel-sand transition shown in Fig. 4. Here median grain size fluctuates rapidly from sand to gravel associated with a suppressed decline in shear stress. Adapted from (Singer 2010)

as a response to sediment trapping by upstream dams and 'hungry water' vertical winnowing downstream of dams, which is known to affect downstream GSDs (Dietrich et al. 1989). These processes lead to a stranding of river bars, such that they are no longer engaged in active sediment transport (Lisle et al. 1993), thus leaving coarse bars as relict features in the landscape, reflective of a former balance between sediment transport and GSD (Singer 2008a; Singer 2008b). Consequently, bar GSDs become much coarser than channel ones (Fig. 7a). Concomitantly, distributions become truncated (narrower) in upstream coarse sections and extended (broader) in downstream fine sections (Fig. 7b), as fines are displaced from upstream to downstream. This can be thought of as a field elaboration of a phenomenon observed in laboratory flumes whereby pulsed sediment transport develops in 'transitional' reaches due to selective availability of bed material (Iseya and Ikeda 1987). Morphologically, the redistribution of sediments manifests in localized deposition, reflected as a hump in the longitudinal profile that can be observed in bed slope and curvature (Fig. 8a, 8b), in a region that is already characterized by a reduction in width that probably reflects the loss of gravel bars (Fig. 8c). The hydraulics suggest that dimensionless shear stress (or dimensionless Shields number) is suppressed in this zone of the river (Fig. 8d), such that both grain size populations (fine and coarse) may be nearly equally transported within the gravel-sand transition (Singer 2010).

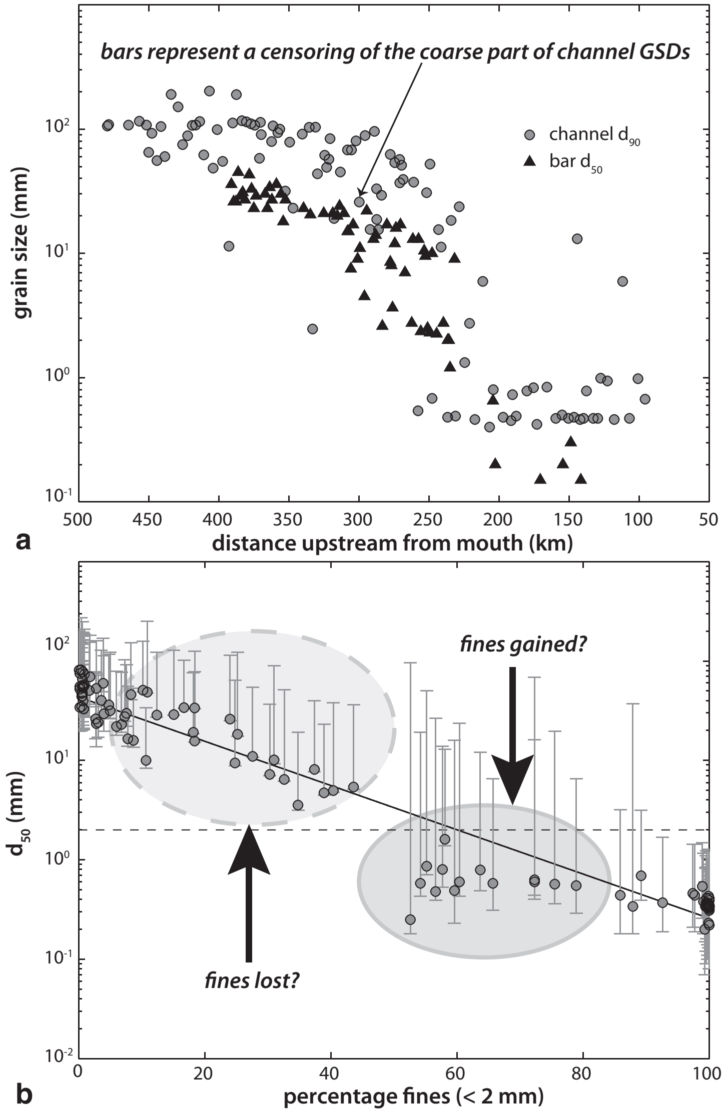

Fig. 7 Grain sizes and hypothesized changes **a** v. distance downstream for channel and bar samples and **b** grain size distributions v. percentage of fines in the sample. Grain sizes shown in **a** indicate that the bars are very coarse compared with the channel (i.e., the median size in the bar is equivalent to the 90th percentile of the channel), indicating they may be relict landforms no longer participating in active sediment transport. The error bars in **b** represent the 10th and 90th percentiles of each measured grain size distribution. Ovals represent opposite trending distributions wherein grain sizes are hypothesized to be truncated at the upper or lower ends due to a transient adjustment to upstream dams trapping gravel. The data demonstrate that in coarse river cross sections (*largely upstream*), d50 is very close to d10 (*bottom error bar*), but that there are nearly no fines in these locations. Also, in sections dominated by fines (where the distribution is composed of >50% fines), d50 is near the bottom of the distribution. These findings can be interpreted as a winnowing of coarse beds and fining of mixed beds (containing gravel and fines). Adapted from (Singer 2008a)

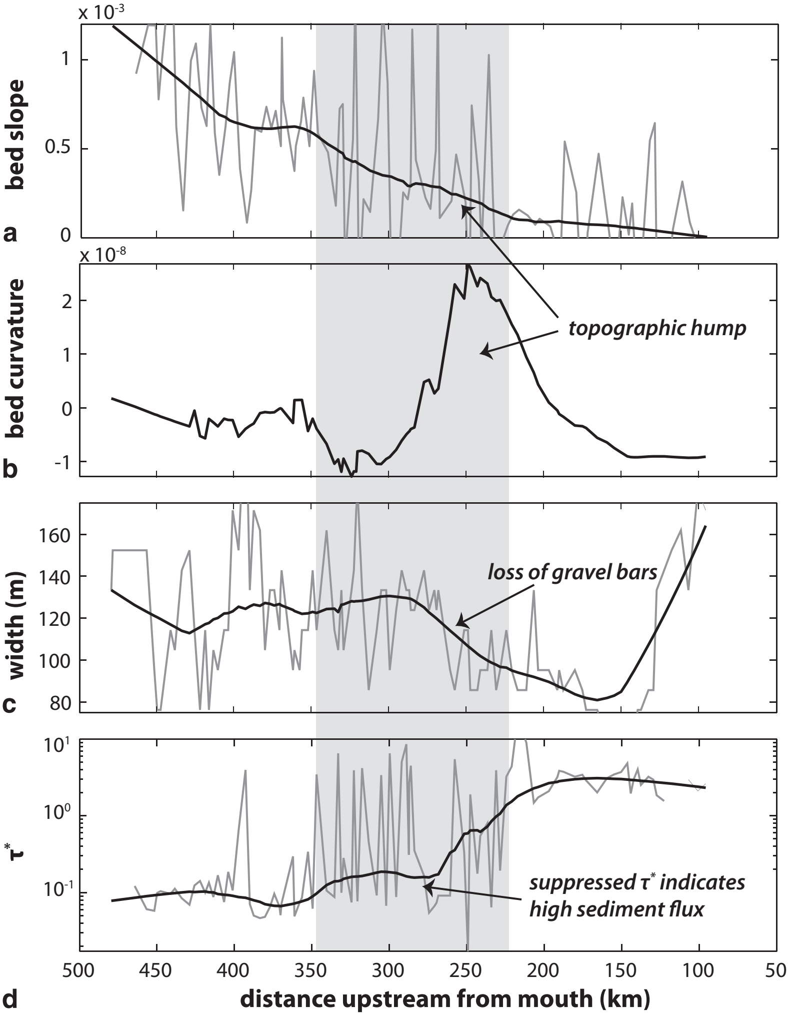

Fig. 8 Morphologic and hydraulic characteristics. **a** bed slope, **b** bed curvature, **c** channel width, **d** Shields number. Original topographic data were extracted/computed from 0.6 m bathymetric data for the Sacramento River. Shields number was computed using a the depth-slope product from hydraulic model output (HEC-RAS) and measured grain sizes from a field campaign that sampled riverbeds ~ 125 cross sections along the Sacramento by boat and a fit-for-purpose sampling device (Singer 2008b). Smoothed curves were obtained using robust LOWESS (0.25 span). These data support the hypothesis that the protracted gravel-sand transition is an emergent phenomenon that will re-coalesce into a more abrupt form at a point upstream, once the dam-related sediment redistribution ceases. Adapted from (Singer 2010)

These processes have extended the gravel-sand transition upstream and lengthened it from ~40 to ~125 km. However, this is not expected to last because if low gravel supply from upstream persists, the fines delivered from upstream will replace the remaining gravels and will smooth the long profile (removing the topographic hump). Ultimately, the fines accumulating will migrate downstream and further encroach on the predominantly gravel reach until the two fine regions are linked and the long profile is smoothed, facilitating transport that re-segregates gravel and fines longitudinally. At this point, the gravel-sand transition will have shifted upstream by 10s of kilometers, though its precise delineations and the timing of its coalescence are subject to speculation. In other words, the longitudinal GSD undergoes a transient response to upstream anthropogenic activity, largely due to gravel trapping by dams. However, the length scale of this sedimentary impact is not easily predicted because of the transient nature of this process.

Importantly, there is a clear distinction between hydrologic and sedimentary responses/adjustments to upstream dams. Although anthropogenic perturbations are often thought to function in tandem, the adjustments of hydrology and sediment dynamics outlined here appear to be disconnected from each other. The hydrologic impacts are localized and persistent, while sediment response is transient and nonlocal (e.g., the response translates downstream). Sediment transport theory typically treats sediment entrainment as a local process dependent only local hydraulics and sedimentary characteristics (i.e., all sediment transported are locally derived). However, the example provided here suggests that nonlocal aspects of sediment supply to any particular location (Stark et al. 2009) may be fundamental to thresholds for local transport, as well to the development of sedimentary conditions and morphology.

4 Adjustment to Levee-bypass System

The influence of flood control levees or embankments on hydrology and sediment transport in large river systems is a topic that has received far less attention in the literature than adjustment to dams, in spite of the ubiquitous nature of these features in lowland floodplains. Some notable research has investigated the impact of such lateral controls on river incision, grain size, and the net transfer of sediment through the channel and into floodplains (Asselman 1999; Hobo et al. 2010; Kesel and Yodis 1992; Simon and Rinaldi 2006; Steiger et al. 1998; Wyzga 2001), while other work has investigated the impact of removing these channel constraints on bank erosion rates, river migration, and sediment mass balances (Laddish 1997; Larsen et al. 2006b; Singer and Dunne 2006). Clearly flood control levees, especially when built upon channel banks, affect river depth and slope and thereby influence local hydraulics and sediment transport—knowledge that was not lost on the engineers who have built irrigation canals around the world for centuries. However, it is less well understood how fluvial adjustment to embankments persists through time and whether it affects fluvial functioning consistently in space (given similar boundary conditions).

Along the Sacramento River, flood control levees are nearly continuous, although they are set back in particular reaches. These structural controls, even when set back, have been shown to impact river alignment and longitudinal sediment budgets (Singer and Dunne 2001), but it is important to place these lateral controls within the broader context of natural geomorphic controls in the Central Valley.

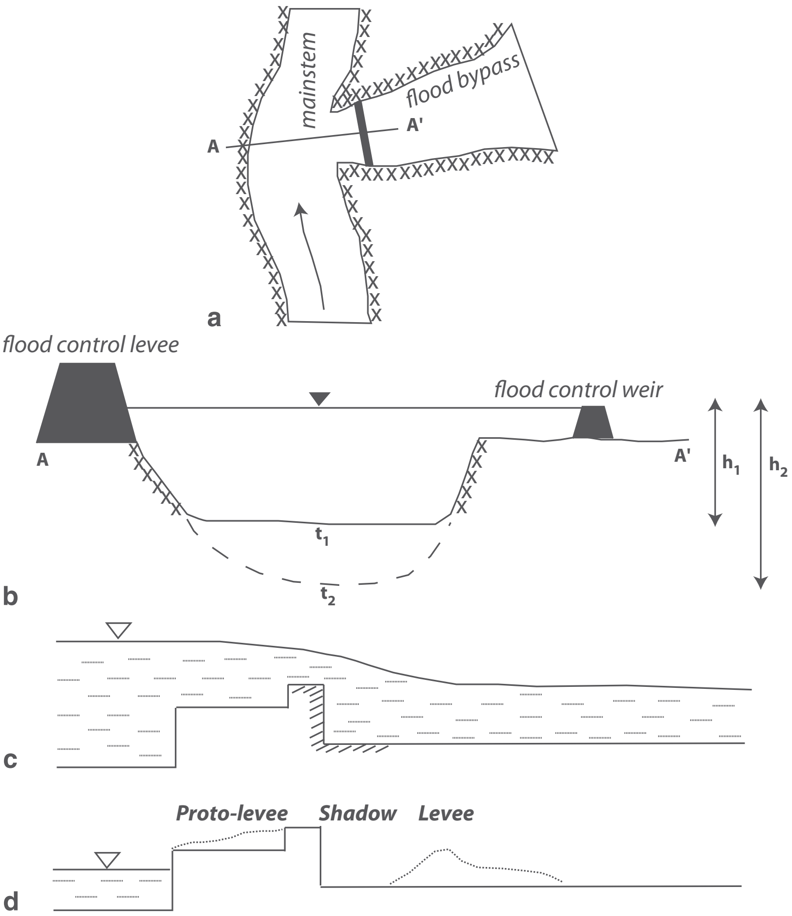

Fig. 9 Bypass schematic showing the operation of the flood-bypass system. **a** planform view, **b** cross-sectional view showing how changes to channel bed elevation affect flow over the weir, **c** the weir being overtopped during a flood; and **d** the sediment deposits produced by the passing flood, which affect subsequent flow over the weir. Adapted from Singer and Dunne (2006) and Singer and Aalto (2009)

Neotectonic structures and Pleistocene sedimentary features impact river alignment and the net transfer of water and sediment along the Sacramento River (Singer et al. 2008). Thus, the flood control system, as designed, inherits the long-term legacy of these features, in some cases by design, and this imposes persistent, localized behavior on the fluvial system.

The setup of the typical weir and bypass unit is depicted in Fig. 9. Weirs are generally passive structures that get overtopped during flooding. As flow accumulates in the main channel and reaches the overtopping threshold, it passes into the adjoining bypass through which it is conveyed much farther down the valley (Fig. 9a, 9b). If the boundary conditions change in the region of the channel/floodplain near the flood control weir, via adjustments in channel bed elevation Fig. 9b and/or sediment accumulation in the floodplain (Fig. 9c), the relationship between flow in the channel and flood spilling over the weir will be affected. Under typical operating conditions, flow over the bypasses during floods dramatically reduces the flood wave in the mainstem Sacramento River. This is depicted in Fig. 10, which shows the influence of flood flow over Colusa and Fremont Weirs during a major event in 1964 in reducing mainstem flood peaks at the gauging stations of Colusa and Verona just downstream of these respective weirs (Fig. 10a, 10b). However, detailed analysis of historical flood records at each of these stations (including the spill over the weirs) shows that these two weirs (two of the most critical for the functioning of the flood control system) have become progressively impaired. Over several decades the discharge over both weirs decreased compared with that in the main channel (Fig. 11).

The partitioning of water in the fluvial system, which is variable through time with implications for contaminant transport (Springborn et al. 2011), may evolve in a manner that negatively impacts the flood control system. But how does this occur? Detailed analysis of hydrologic records and floodplain sedimentation via sediment traps, ^{210}Pb geochronology, and topography, reveals the importance of sediment infilling at the margins of the bypass system (Singer and Aalto 2009; Singer et al. 2008; Fig. 9c), as the primary cause of flood weir impairment. As increasing sediment is deposited in the vicinity of the weir, for example, as a levee building process (Singer and Aalto 2009), it progressively limits accommodation space for subsequent floods. However, this process is not stationary; although the locations of sediment arrival into floodplains/bypasses seem to remain consistent (they are largely a function of the natural geomorphic functioning of the system (Singer et al. 2008)), sediment deposition near the weir depends on supply generated from upstream and the arriving sediment must reach a critical volume before it impairs weir/bypass functioning. Subsequently, sediment is occasionally evacuated by management authorities, leading to decreased impairment of the weir (e.g., sediment removal occurred before the 2004 time slice near Fremont Weir in Fig. 11b). It is clear that the interaction between sediment arrival and hydrologic impairment of weirs and bypasses is transient and therefore must be carefully monitored to avoid major problems in the flood control system.

5 Discussion/Conclusion

The examples provided here emphasize the need to address spatial and temporal perspectives in fluvial datasets in order to improve understanding of the impact scales and trajectory of fluvial adjustment to management perturbations. Although persistence of fluvial response to management is more obvious and predictable, transience is an important consideration, especially over human timescales when adjustment to perturbations may extend beyond human lifetimes. Many challenges exist in grasping the nature of fluvial response in large river systems because local perturbations may have nonlocal manifestations. Likewise, adjustments to such perturbations may translate through the fluvial system and not be measurable until

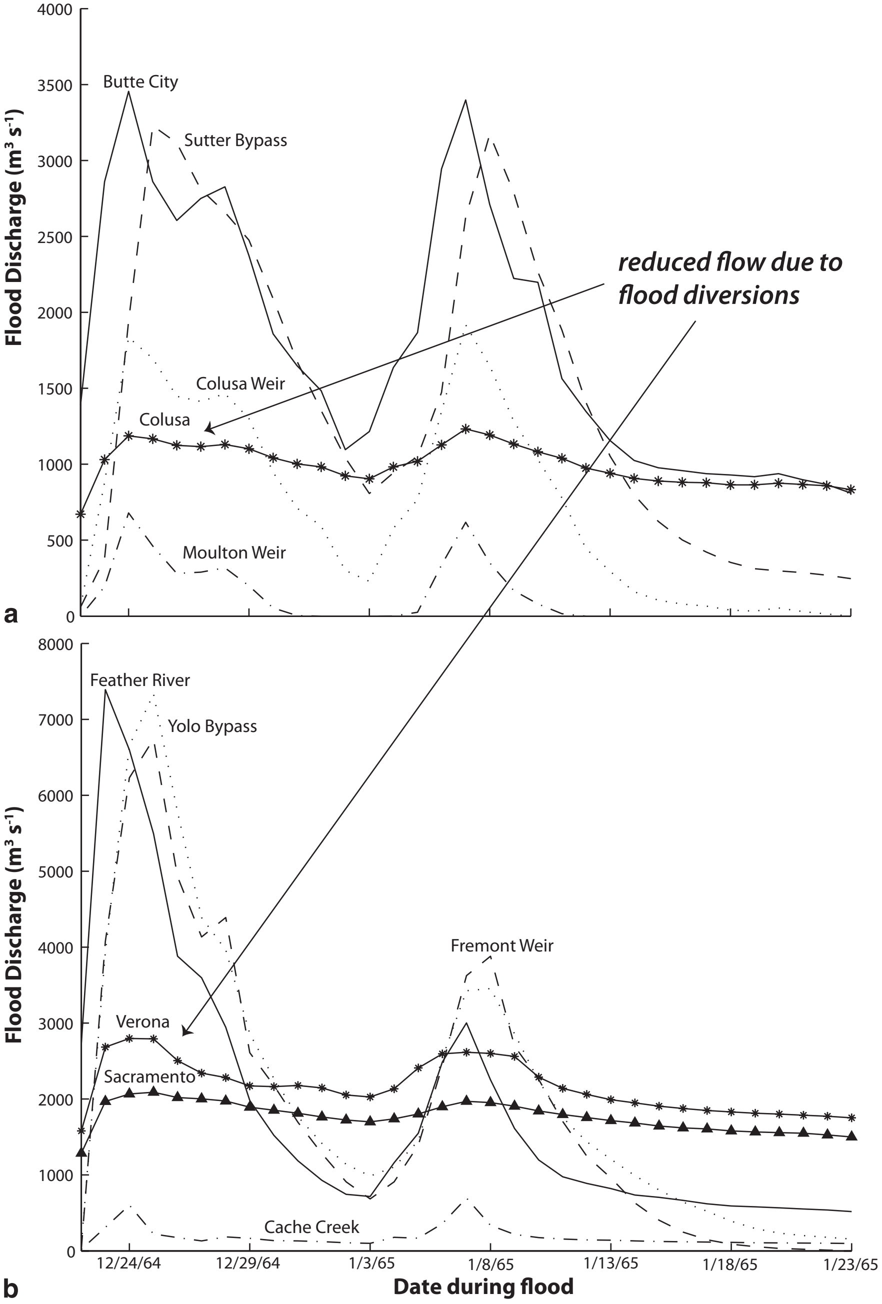

Fig. 10 In-flood hydrology for the 1964 flood event for: **a** the upper part of the flood control system, **b** the lower part. The plot indicates the impact of flood bypasses on mainstem flood flow. Adapted from Singer and Aalto (2009)

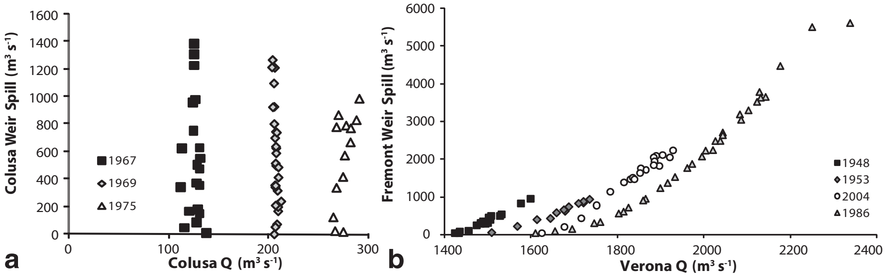

Fig. 11 The impact of bypass impairment by sediment deposition and/or channel erosion. Time series of flow partitioning at **a** Colusa Weir and **b** Fremont Weir. If there were no changes to the channel boundaries, we would expect a systematic relationship between flow in the mainstem Sacramento and spill over each passive weir. In contrast, the data in **a** and **b** show a progressive rightward shift of the x-intercept in these graphs, indicating that spill over the weir occurs under increasing values of mainstem discharge. This can be interpreted as erosion of the mainstem channel boundaries (thus increasing channel capacity) or as sediment accumulation upstream of the weir (thus limiting weir overtopping by flows entering the floodplain). Adapted from Singer et al. (2008)

the effects accumulate above the threshold for detection (e.g., sediment deposition that produces a hump in the longitudinal profile, Fig. 8a, 8b). In addition, transient behaviors in fluvial systems may be superimposed upon persistent ones, creating challenges for interpreting fluvial adjustment.

There are many anthropogenic impacts to river systems that develop as a consequence of a river management structures. Dams and flood control levees are two notable cases that have been described here using data from the Sacramento basin. Both of these produce alterations to hydrologic and sediment regimes with implications for morphological development. Dams (especially large ones) have local persistent impacts to streamflow that generally dissipate with distance downstream. This hydrologic alteration produces a concomitant sediment response directly downstream due to trapping of sediment, and it also generates an unexpected transient response of sediment redistribution with impacts to longitudinal grain size distributions, sediment mass balance, morphology, and the capacity for sediment flux. Flood control levees affect river hydraulics by increasing slope and depth and limiting dynamic adjustments of river width. Flood control systems that are furnished with passive weirs and bypasses have the additional complication of water partitioning during floods. Superimposition of the flood control system upon the natural geomorphic controls within the Sacramento Valley (e.g., neotectonics, volcanic extrusions, Pleistocene megafans, etc.) affects river alignment and leads to emergent behavior, for example, as sediment persistently accumulates in particular locations. Where such locations overlap with the entrances of lateral weirs, flood control impairment may result as the partitioning of water between the mainstem and the flood bypass changes. In other words, in contrast to the impact of dams on the fluvial system, the weir and bypass system produces persistence in sediment dynamics and transience in hydrologic partitioning. Persistent and transient fluvial adjustments coexist and interact in large, lowland river basins subject to anthropogenic perturbations in a manner than can produce unanticipated outcomes.

Given the impacts of river management to river behavior, river rehabilitation scenarios are designed to mitigate the negative effects (usually to habitat, etc.). The impact of three typical restoration scenarios was modeled for river gauging stations spanning ~ 400 river kilometers along the Sacramento River. Flow alteration, gravel augmentation, and levee setbacks were analyzed for their effects on flows and sediment transport based on a hypothesized stochastic flow distribution, representative of a range of potential flood scenarios (Singer and Dunne 2004a, b). It was found that each rehabilitation strategy would be expected to reduce sediment transport in its target reaches and modulate imbalances in total annual bed-material sediment budgets at the reach scale, although additional risk analysis is necessary to identify extreme conditions associated with variable hydrology that could affect rehabilitation over decades (Singer and Dunne 2006). In other words, emergent landforms that developed via sediment flux imbalances (perhaps in response to management structures such as dams and flood control levees), diminished in modeling output of rehabilitation scenarios designed for other purposes. These results suggest that there may be pathways available to river managers in achieving the benefits of river management, while minimizing the negative consequences of these management implementations.

This discussion is incomplete without at least brief mention of the fluvial responses to climate, which have been identified in various studies (e.g., Rumsby and Macklin 1994). Throughout the entire preceding discussion, the imprint of climate and climatic changes controls stream hydrology and to a lesser extent, sediment supply from drainage basins. Storms do not precipitate evenly across river basin and floods are thus generated in particular parts of drainage basins such that unique combinations of floods in the mainstem of a large river are possible. Such randomness in-flood generation and associated geomorphic responses (Kochel 1988; Slater and Singer 2013) is probably most reasonably represented within a stochastic framework (e.g., Benda and Dunne 1997a, b; Singer and Dunne 2004a) that takes into consideration the probabilities of various system responses to this climatic forcing. These climatic responses may also occur in persistent or transient ways. In the Sacramento River basin, the largest floods are generated by large frontal rainstorms that originate in the warm Pacific and are enabled by a collapse of the Pacific high. Such ‘atmospheric rivers’ (Dettinger 2011) persistently generate the major floods in most Sacramento tributary basins (Singer and Dunne 2004a). These floods, which occur on a nearly decadal timescale, are responsible for most of the geomorphic change in the Sacramento basin (Singer et al. 2008; Singer et al. 2013a). However, since the Sacramento and its tributaries are generally sediment supply-limited, the landform changes associated with individual events are hard to predict. Sediment may be episodically entrained from riverbanks and terraces on a localized basis, but the spatial distribution and probability of such failure is stochastic. Thus, sediment flux and landform response to such persistent large floods is more likely to be transient.

The examples discussed in this paper are relevant to aquatic and riparian ecosystems, but more germane to this volume, to flood control management, the stability of river infrastructure, and to human communities living in lowland floodplains.

As river managers grapple with the impacts of past management strategies and the design of future ones, it is critical to study the impact scales of such anthropogenic activities. How long will a particular impact manifest at a particular location and how will it persist or dissipate with distance? The answer to such questions requires detailed investigation through historical datasets and modeling to address the details of the fluvial response to particular management implementations, including the interactions between various adjustments. Unfortunately, there is no general, prescribed way of doing this. Ultimately, modern river management should involve a well-informed synoptic view of the river/floodplain that emphasizes spatial links through the fluvial system, while maintaining a decadal perspective that permits the construction of probability distributions of relevant fluvial variables.

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Flooding, Structural Flood Control Measures, and Recent Geomorphic Research along the Red River, Manitoba, Canada

Gregory R. Brooks and Scott St. George

Abstract The Red River, Manitoba, Canada, is a low-gradient, meandering river that traverses the broad, flat Red River Valley on the northeastern portion of the Great Plains of North America. The shallow stream-cut valley occupied by the river has insufficient capacity to contain large discharges, which allows higher magnitude flows to overtop the valley sides and spread up to 40 km across the adjacent clay plain. Major flooding impacts communities and rural areas, including the City of Winnipeg, and has caused significant flood disasters in the nineteenth and twentieth centuries. Since 1950, an array of structural flood control measures has been constructed (and some later upgraded) to mitigate flooding, including two diversion canals, a flood control dam, dyking (linear and ring dyking), and elevated earthen pads under structures. Multidisciplinary research initiated following the 1997 Red River flood provided a geomorphic context to the flood problem in support of decision making towards enhancing the flood-protection infrastructure. Based on flood signatures in the growth rings of bur oak trees (*Quercus macrocarpa* Michx.), the historic flood-of-record in 1826 is interpreted to be the largest Red River flood since at least 1648. An assessment of the decrease in river gradient arising from regional differential uplift revealed that the broad, shallow flood character is intrinsic to the landscape of the Red River Valley and that the contemporary rate of uplift is causing an insignificant change to the extent of flooding. An investigation of the evolution of the genetic floodplain indicates that fluvial geomorphic processes are not significantly enlarging or infilling the shallow stream-cut valley at rates relevant to altering the modern flood problem. Although flood management along the Red River is heavily dependent on structural measures, the design discharge of the integrated flood control works protecting Winnipeg has recently been enhanced to a 700-year return period, which reduces the flood hazard substantially.

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1 Introduction

Up to the middle of the twentieth century, flood management in Canada was primarily the responsibility of individuals or local government (Shrubsole et al. 2003). Major flood disasters in 1948 along the lower Fraser River, southwestern British Columbia, and in 1950 along the Red River, southern Manitoba, however, contributed to provisions within the Canada Water Conservation (CWC) Act (1953) that defined federal disaster assistance and established federal cost-sharing (up to 37.5%) of provincially proposed water storage projects (Quinn 1985). Through 'special agreements' to this Act, several major structural flood control projects were initiated in the 1950s and 1960s in southwestern British Columbia, southern Manitoba, southern Ontario and southern Saskatchewan that were funded jointly by the federal and respective provincial governments (Booth and Quinn 1995).

By the early 1970s, such projects were seen as representing a narrow, reactionary strategy of structural flood control measures, where the federal government approved/rejected expensive provincial initiatives without making any direct contribution to the design (Bruce 1976; Booth and Quinn 1995; Watt 1995). Other concerns included: recognition that urban sprawl would likely occur onto vacant flood-prone lands increasing both the exposure to flood damages and possible future requests for flood-protection projects; the rising cost of federal payouts to flood damages; and a growing perception that disaster payouts represented inequitable support to the occupants of flood-prone lands. These issues led to the establishment of the Flood Damage Reduction Program (FDRP) in 1975 as part of the Canada Water Act (1970) which had replaced the CWC Act (1953). Implemented through individual federal-provincial/territorial cost-sharing agreements, the main objective of the FDRP was to promote a nonstructural program of flood-risk mapping and the legal designation of flood zones to control and thus minimize development on flood-prone lands (Bruce 1976; Watt 1995; Booth and Quinn 1995). Other nonstructural measures in the FDRP included prohibiting federal and provincial government involvement in development on designated flood zones, providing disaster assistance only to structures predating the designation, and support for flood forecasting. Structural measures, however, continued to receive support under the FDRP in southwestern British Columbia, southern Manitoba, southern Quebec, New Brunswick and southern Ontario, including some projects initiated under special agreements to the CWC Act (1953) (Watt 1995).

By the mid-1990s, the floodplain mapping programs were mostly completed, and the FDRP was recognized as effective in redirecting vulnerable development away from flood-prone lands (Watt 1995). Nevertheless, the federal government decided not to renew the FDRP agreements due to budgetary reasons. The floodplain mapping program was thus terminated, although the floodplain designation and restrictions on federal damage compensation provisions remained in effect. Federal cost-sharing of structural flood control measures still continued into the late 1990s and 2000s, most prominently in response to requests from the Manitoba provincial government following a major flood disaster in southern Manitoba in 1997.

As a legacy of flood management decision making since 1950, the Red River Valley, Manitoba, received Canada's greatest investment of structural flood-control measures. These include major, integrated flood-control works (two diversion canals and a flood control dam), linear or ring dyking that protects major urban areas, towns and villages, and elevated earthen pads or small ring dykes that protect isolated rural structures. All have been constructed in response to broad, slow-moving floods that are unique within Canada to the Red River. This chapter reviews the geomorphic controls of Red River flooding and its flood history to provide a perspective for a summary of the evolution of the structural flood-control measures. It also reviews the contributions of recent geomorphic research undertaken following the 1997 Red River flood to provide a longer-term context to the flood problem. Finally, the chapter contrasts the structural approach utilized to manage floods in southern Manitoba with other flood management considerations. Although a significant portion of the Red River watershed is located in the USA, the chapter focuses on the Canadian portion of the watershed, reflecting the experience of the authors; however, much of the geomorphic context is relevant to the United States portion of the watershed.

2 Geomorphology of the Flood Problem

The Red River (known as the Red River of the North in the USA) is a north-flowing river located on the north-eastern portion of the Great Plains of North America. The river is about 880 km long by channel length (about 496 km long by valley length), extending from the confluence of the Bois de Sioux and Otter Tail rivers at Wahpeton, North Dakota, to Lake Winnipeg, Manitoba (Fig. 1). The watershed encompasses 290,000 km^2, including the Assiniboine River basin (163,000 km^2), which joins the Red River in Winnipeg. Other major tributaries include the Red Lake, Sheyenne and Pembina rivers (Fig. 1). Only about 16 % of the Red River basin, above the confluence with the Assiniboine basin, is located in Canada (Fig. 1). Winnipeg, Manitoba, and Grand Fork-East Grand Forks and Fargo-Moorhead, USA, are major population centres located along the river.

The river traverses the flat and gently northward sloping plain of the Red River Valley, where natural topographic variations, aside from incised stream courses and gullies, are subtle (Figs. 2 and 3a). The plain is about 554 km long and 24–160 km wide, stretching from Lake Traverse to Lake Winnipeg (Fig. 1; RRBI 1953a). Clay-rich glaciolacustrine sediments deposited within glacial Lake Agassiz (see Teller and Bluemle 1983; Teller and Clayton 1983) form the surface of the Red River Valley that hereafter is referred to as the 'clay plain'. The course of the Red River was established on the clay plain after glacial Lake Agassiz permanently abandoned its southern outlet into the Mississippi River watershed beginning at about 9200 ka BP (Teller et al. 1996). The net recession of the lake resulted in a north-flowing

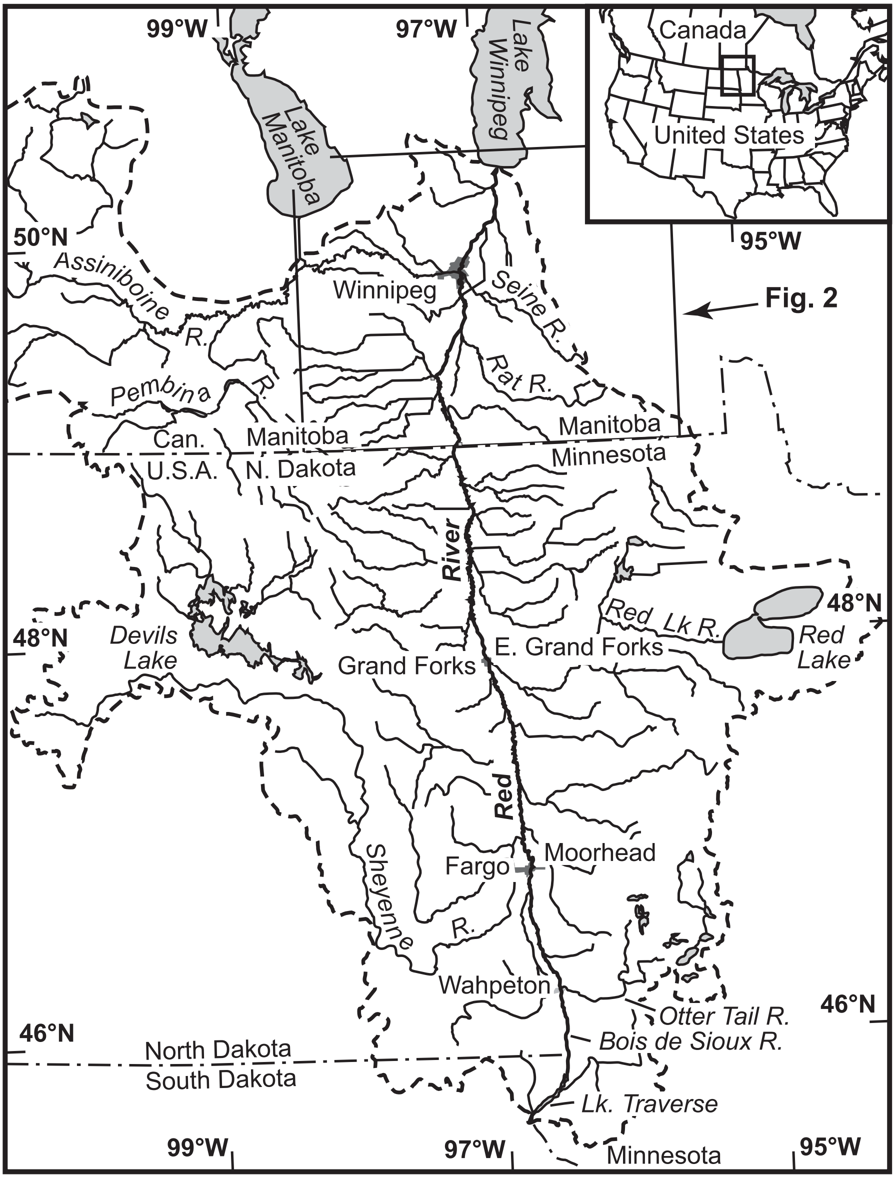

Fig. 1 Map of the Red River drainage basin showing major cities located along the north-flowing river

river, which became the Red River, developing upon and progressively extending its course onto the emerging lake bed. The river was established in southern Manitoba by between 8200 and 7800 year BP (Brooks 2003a).

Along the majority of its course, the Red River flows within a shallow stream-cut valley eroded into the clay plain (Fig. 3a). Between Winnipeg and Emerson (Fig. 2),

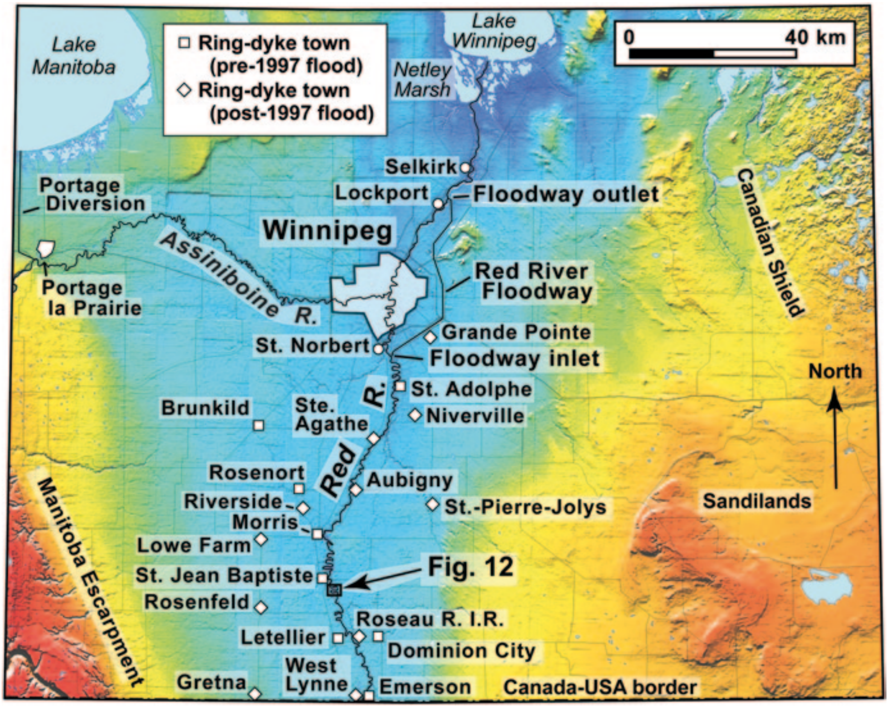

Fig. 2 Shaded relief map of the Manitoba portion of the Red River Valley showing the Red River Floodway, Portage Diversion, and towns and villages protected by ring dykes. (Map courtesy of Manitoba Geological Survey)

Fig. 3 Oblique aerial photographs of the Red River. **a** Meanders just upstream of St. Jean Baptiste, Manitoba, looking downstream (*north*) during a summer flow (photograph taken August 1999). The genetic floodplain of the river corresponds approximately to the width of the meander belt and is imperceptibly (in this photograph) lower than the surrounding Lake Agassiz clay plain, which forms the hydrologic floodplain. **b** The town of Morris, Manitoba, surrounded by water during the 1997 Red River flood, but protected by a ring dyke (photograph taken 9 May 1997). The Red River channel is delineated by riparian trees in the foreground

the stream-cut valley is up to 15 m deep and 2.5 km wide, based on the width of the meander belt (Brooks and Nielsen 2000; Brooks 2003a). The shallowness of the stream-cut valley reflects the flat topography and the gentle gradient of the clay plain; the difference in elevation between Wahpeton and Lake Winnipeg (located about 496 km apart) is approximately 70 m, yielding an average valley gradient of 0.00014. This shallow morphology contrasts markedly with other major rivers on or immediately marginal to the glaciated areas of the Great Plains that are underfit steams occupying a spillway eroded by melt water under a glacially influenced or glacial-lake-influenced hydrological regime (see Kehew and Lord 1986; Kehew and Teller 1994).

The river is a low-energy, suspended-sediment, mud-dominated, meandering stream, a morphology that contrasts markedly with the ubiquitous sand, sand-gravel or gravel beds streams on the Great Plains of North America. Important processes along the silty convex banks are overbank deposition, oblique accretion and large-scale (up to 200 m wide), very slow (up to ~1 m/year displacement), deep-seated rotational failures (Brooks 2003b). Along the outer banks, 'concave overbank deposits' aggrade annually on the surface of low-angled zones of landsliding, (up to 2.5 km long and extending 100 m back from the edge of the channel) that are common along the river where the meanders impinge against the glaciolacustrine sediments of glacial Lake Agassiz (Brooks 2005). These deposits form a continuous accretion of silt, up to 4 m thick at the river edge, that extends along a given landslide zone, merging onto the floodplain surface of the successive upstream and downstream meanders.

Major Red River floods historically occurred during the spring freshet and principally are the product of snowmelt runoff. Such floods characteristically form a broad, elongated flood zone (Fig. 4) that rises and falls slowly, as exemplified by flows in 1997 and 2009 that exceeded bankfull discharge at Emerson, Manitoba (Fig. 2), for periods of 47 and 67 days, respectively (Fig. 5). Correspondingly, the flood crest migrates slowly and can take several weeks or more to descend the river course. For example, the 1997 flood crested on 6th April at Wahpeton, North Dakota, and peaked at Winnipeg, 430 km downstream, on 3rd May (27 days later). Major Red River flows thus are slow-onset floods compared to rivers draining similar-sized basins elsewhere in North America. Ice jamming commonly occurs during spring break-up and can cause localized flooding, but it is not a factor forming the broad flood zone that is characteristic of major Red River floods south of Winnipeg (see Beltaos et al. 2000). Although Red River floods are a product of hydrology, their wide extent and slow-moving progression is fundamentally a function of the geomorphology of the river and the Red River Valley.

The combination of shallow stream-cut valley and low valley gradient results in the river valley having an insufficient capacity to contain higher magnitude flows. This results in flow overtopping the valley margins and inundating the flat clay plain (Fig. 3b). The clay plain thus functions as the hydraulic floodplain of the Red River, while the genetic floodplain of the river is contained entirely within the stream-cut valley (see Brooks 2003a). Because of the flat topography of the clay plain, extreme flows can spread for many kilometres on either side of the river valley. During the 1997 flood (Fig. 5), the flood zone in southern Manitoba was up to 40 km wide (Fig. 4).

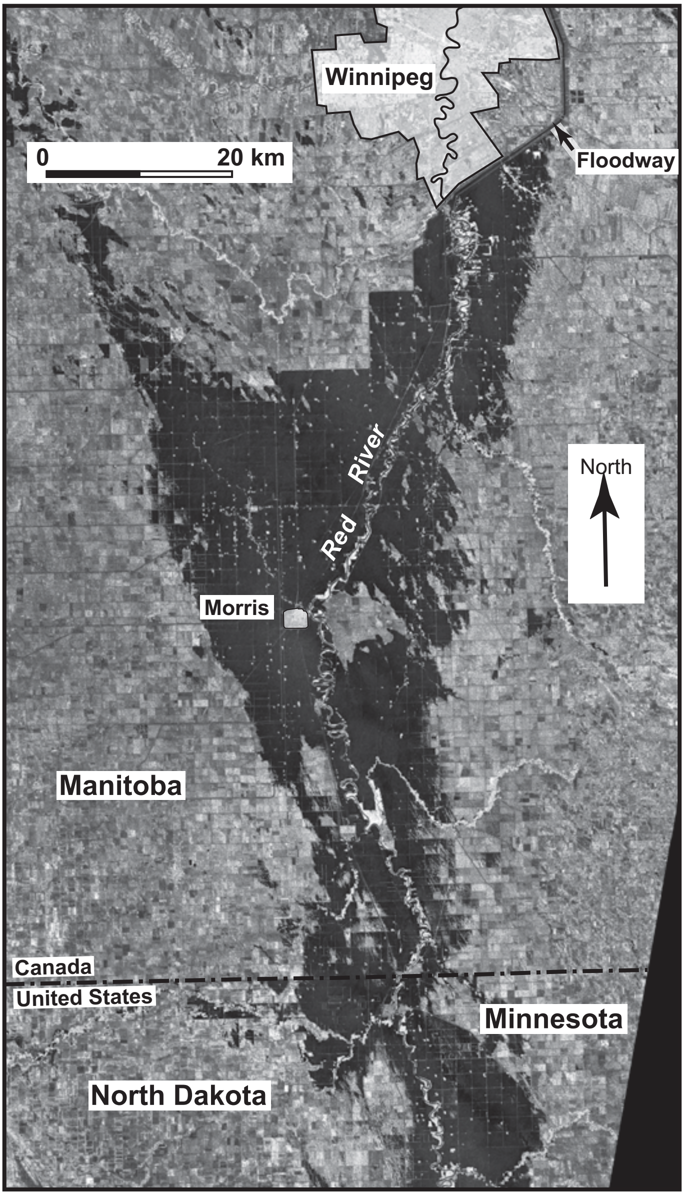

Fig. 4 Radarsat image of the 1997 Red River flood in Manitoba showing the near-maximum extent of inundation (*dark area*) in the northern portion of the flood zone (Radarsat-1 data acquired 4 May 1997, courtesy of Manitoba Remote Sensing Centre; ©Canadian Space Agency 1997)

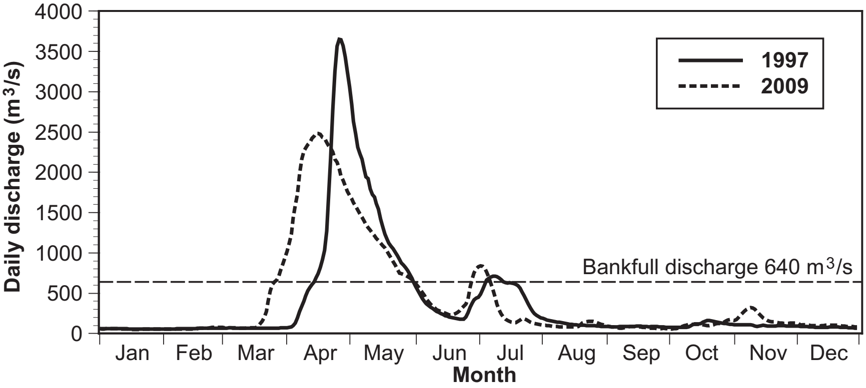

Fig. 5 Hydrographs of average daily flows of the Red River at Emerson for the major flood years of 1997 and 2009, which have estimated return periods of ~133 and ~28 year, respectively (data from Manitoba Water Stewardship). Reflecting the slow passage of the flood wave along the gentle gradient of the Red River Valley, the freshet flows in both years exceeded bankfull discharge for 47 and 67 days, respectively (bankfull discharge defined as flow with a 2-year return period)

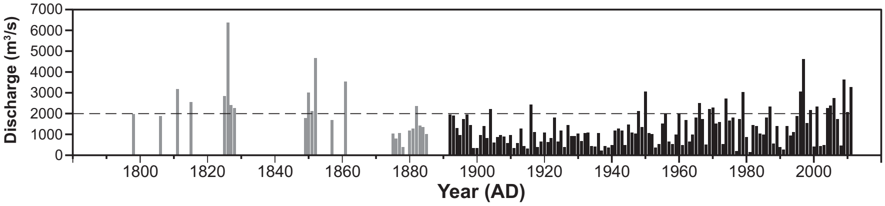

Fig. 6 The 1790–2011 record of Red River peak flows at Redwood bridge, Winnipeg, including floods inferred from historical accounts (*grey bars*) and those determined from measurements of stage (*black bars*; all data from Manitoba Water Stewardship). The pre-1870 portion of the record is based on written first-person accounts of flooding compiled by Rannie (1998a) who made inferences of flood magnitude based on the descriptions. The magnitudes of the 1826, 1852 and 1861 floods are estimates from RRBI (1953c). The post-1870 record is based on measured levels of peak stage. The post-1968 record consists of estimates of 'natural' peak flow at Redwood bridge without the regulating effects of the flood control works along the Red and Assiniboine rivers in Manitoba. The lack of peak flow estimates for some years during the eighteenth and nineteenth centuries reflects the occurrence of a 'nonflood' event (pre-1870) or a lack of data on peak flow stage (post-1870)

3 Historical Floods

The historical record of Red River flooding begins in the mid to late eighteenth century and is one of the longest in Canada (Fig. 6). The earliest reference to flooding is a brief second-hand account of a severe flood during 1776 in Ross (1856). First-person accounts of flooding begin in 1798 when fur traders located near the present Canada–USA border recorded that the river had risen 'to a prodigious height' by the middle of April, while the fur trader and explorer Alexander Henry described a flood during the summer of 1806 (see Rannie 1998a). More detailed observations on the stage, timing and extent of flooding began in 1812 with the establishment of the Selkirk Settlement (near present-day Winnipeg). These accounts indicate that significant floods (exceeding 2000 m^3/s) occurred in 1811, 1815 and 1825 (Rannie 1998a; Fig. 6).

The first flood to severely impact the Selkirk Settlement occurred in 1826. The magnitude of the 1826 flood was not directly measured, but peak discharge is estimated to be ~6400 m^3/s (RRBI 1953c). This estimate, as well as those for severe floods in 1852 and 1861, was made using high water marks obtained in 1876 or 1877 by Canadian Pacific Railway surveyors from interviews with older local residents (Fleming 1879; St. George and Rannie 2003). Nearly two centuries later, the 1826 flood remains the flood-of-record for the Red River at Winnipeg (Fig. 6).

No major floods occurred in the 1830s or 1840s, but the early 1850s brought a succession of three significant floods, culminating with the 1852 flood (~4700 m^3/s; RRBI 1953c), which was second only to the 1826 flood (Fig. 6). Following another major flood in 1861 (~3500 m^3/s; RRBI 1953c), the river entered a long period of relative quiescence. Between 1862 and 1949, peak flow exceeded 2000 m^3/s only four times, compared with ten times between 1798 and 1862. The largest of the post-1861 floods (which occurred in 1916) produced a maximum flow of ~2430 m^3/s, which was significantly smaller than the major floods in 1826, 1852 and 1861.

This nearly nine-decade interval of modest peak flows ended abruptly with the 1950 flood (3050 m^3/s; Fig. 6). As the first major flood in three generations, the 1950 flood caught the residents of Winnipeg and the Red River Valley unprepared, resulting in a major Canadian flood disaster. The flooding forced the evacuation of ~100,000 people from Winnipeg (one-third of the city) and caused an estimated $ 1.3 billion (CAD 2005 dollars; $ 1 CAD ≈ $ 0.84 US in 2005) in damage (Atlas of Canada 2012). During the latter half of the twentieth century, the river experienced 17 peak flows exceeding 2000 m^3/s, including the floods of 1979, 1996, 1997, 2009 and 2011, all of which approximated or exceeded the 1950 flood (Fig. 6). The largest of these events, the 1997 flood (4620 m^3/s), named 'The Flood of The Century' by local news media, was roughly equivalent in magnitude to the flood of 1852. The 1997 flood caused the evacuation of 25,450 people from the flood zone south of Winnipeg and over $ 944 million (2005 CAD dollars) in direct and indirect costs (Atlas of Canada 2012).

4 Mitigating Red River floods

The origin of permanent structural flood protection for the Red River Valley relates directly to the occurrence of the 1950 Red River flood disaster and the desire by the Canadian federal and Manitoba provincial governments to reduce flood hazards in the area. As summarized below, the flood-protection infrastructure has been augmented or upgraded periodically in the intervening years in response to larger more recent floods that caused significant flood disasters (1979 flood) or threatened to cause a catastrophic disaster (1997 flood).

4.1 Primary Dyking in Winnipeg

Permanent dykes were constructed within Winnipeg in the aftermath of the 1950 Red River flood disaster (see RRBI 1953d). About 110 km of 'primary dykes' were constructed between September 1950 and the end of 1951 at a cost of $ 4.6 million CAD (1951 dollars; ~$ 37 million CAD 2005 dollars). Most of the dykes run parallel to the Red River, but two pairs extend for several kilometers along the lower-most reaches of the Assiniboine and the Seine rivers (the latter is a smaller tributary of the Red River; Fig. 1). Dyke routing was complicated by pre-existing built-up areas within the city and hence are generally located upon or beside existing roadway beds. The widespread occurrence of highly plastic, glacial Lake Agassiz glaciolacustrine deposits, which are prone to deep-seated earth flows (see Baracos 1961; Baracos and Graham 1981), precluded routing dykes proximal to the river banks. Because of these routing constraints, approximately 1000 houses were situated (at that time) between the primary dykes and the river, necessitating the construction of 'secondary' dykes, many of which are temporary and need to be reconstructed for successive flood emergencies.

The primary dyking was built to a height of 8.1 m (RRBI 1953d; all stage figures refer to metres above local datum at the James Avenue Pumping Station (JAPS)), which provides a design discharge of ~2300 m^3/s with 0.6 m freeboard (Mudry et al. 1981). It was not deemed practical to build permanent dykes to the level of the 1950 flood, but the primary dykes can be raised temporally by up to 1.2 m to the level of this flood in an emergency (RRBI 1953c).

Following the 1997 flood, permanent secondary dyking within Winnipeg was expanded and some existing dyking strengthened (Caligiuri and Topping 1999). The need for emergency temporary dyke construction, however, is still required to protect 300–400 houses during flood emergencies, depending on the forecast level of stage within the city (City of Winnipeg, written communication, 18 January 2012). In 2012, approximately 800 houses are situated between the primary dykes and the river (City of Winnipeg, written communication, 18 January 2012).

4.2 Major Flood Control Works

Despite the construction of the primary dykes, the level of flood protection at Winnipeg in the early 1950s was still considered to be inadequate and a broad range of structural flood control options were considered (see RRBI 1953a). The economic benefits of these options were assessed in the late 1950s by the Royal Commission on Flood Cost-Benefit, who recommended construction of three major flood-control works that would provide integrated flood protection by reducing river stage within

Winnipeg during periods of flooding (Mudry et al. 1981). These became the Portage Diversion, the Shellmouth Dam and, most importantly, the Red River Floodway.

4.2.1 Red River Floodway (Original Design)

The Red River Floodway is a diversion canal, about 48-km long, that begins just upstream (south) of St. Norbert, extends northeasterly and then approximately northerly to bypass Winnipeg, before rejoining the river just downstream of Lockport (Fig. 2), where the river valley is deeper than south of Winnipeg and can accommodate a flood flow (see Weber 1967; Mudry et al. 1981). The trapezoidal-shaped channel was built between 1962 and 1968 at a cost of $ 63 million CAD (1962 dollars ~$ 427 million CAD 2005 dollars; see Table 1 for general attributes). Design capacity was 1700 m^3/s, which was intended to mitigate a 'natural' flow of 4790 m^3/s with a return period of 160 years (estimated in 1962), in combination with the discharge-reducing contributions from the Portage Diversion and Shellmouth Dam (Fig. 7 and below).

The Floodway is utilized when discharge exceeds 900–1000 m^3/s to limit flood stage through Winnipeg to about 7.5 m (JAPS datum) and protect freeboard along the primary dykes (RRFORC 1999). Flow into Winnipeg is regulated using the Inlet Control Structure by raising a pair of submersible gates, each 34.3 m wide, to control the proportion of flow entering the Floodway channel located immediately upstream (Table 1; Fig. 8a). Gates operations are governed by 'operating rules' that define when stage above the Inlet Structure is maintained at 'natural' levels, exceeds 'natural' levels, and the emergency conditions under which flow through Winnipeg is allowed to increase, even if the integrity of the primary dykes becomes threatened (see RRFORC 1999; FCGI & HNWA 2010). The latter situation could arise in order to avoid a catastrophic dyke breech of the Floodway infrastructure, when the Floodway reaches its maximum capacity during a severe flood that exceeds the design flow.

The energy gradient through the channel is controlled by the Floodway Outlet Structure, a 49.4 m wide, concrete ogee overflow spillway located about 250 m upstream of the confluence with the Red River (Fig. 8b; Gendzelevich et al. 2009). The outlet structure also allows water energy to dissipate rapidly as flow descends about 4 m through a rollway to the level of the water surface in the Red River channel (KGS Group 2001; Gendzelevich et al. 2009).

The Floodway infrastructure also includes linear dykes that extend east and west of the Inlet Control Structure to arrest the northern extent of overland flooding to the south of Winnipeg and direct flow through the Inlet Control Structure or Floodway channel (Fig. 8b). The East Dyke extends east of the Red River parallel to the Floodway (on the Winnipeg side) for about 10 km (KGS Group 2001). The West Dyke extends to the west of the Red River in a zig-zagging course for about 45 km.

The Floodway is the most important element of the Red River flood-protection infrastructure in Manitoba. Its contribution to flow reduction at Winnipeg (as designed) exceeds that of the Portage Diversion and Shellmouth Dam by 2.4 and

Table 1 Attributes of the original and expanded Red River Floodway

	Original	Expanded
Period of construction	1962–1968[a]	2005–2014[b]
Cost	$ 63 million CAD (1962 dollars)[a] (~$ 427 million CAD (2005 dollars))	$ 665 Million CAD (2005 dollars)[b]
Channel shape	Trapezoidal, slopes ranging from 3H:1V to 9H:1V[a]	Trapezoidal, slopes ranging from 3H:1V to 10H:1V[b]
Length	~48 km[a]	Unchanged
Width	98–165 m base[a,b] 160–305 m top[a,b]	98–286 m base[b] 160–370 m top[b]
Depth	up to 20 m (average 9.1 m)[a]	Unchanged
Fall in water surface along channel (design flow conditions)	~5.5 m[a]	~5.8 m[b]
Width of gates (two) at floodway inlet structure	34.3 m[d]	Unchanged
Threshold discharge when flow enters the floodway channel	900–1000 m^3/s[b,e]	Unchanged
Width of overflow spillway in floodway outlet structure	49.4 m[a]	90 m[c]
Volume of excavated materials	76 Mm^3[a]	21 Mm^3[f]
Design capacity of floodway channel	1700 m^3/s[a]	3960 m^3/s[b]
Upstream storage effects	Na	650 m^3/s[b]
Design flow (natural)	4790 m^3/s[a,g]	Up to 7700 m^3/s[b,g,h]
Design flow return period	160-year (1962 estimate)[d] 90- to 100-year (late 1990s estimate)[d]	Up to 700-year[b,h]

[a] Mudry et al. 1981
[b] Manitoba Floodway Authority, http://www.floodwayauthority.mb.ca/home.html and written communications, January-March 2012
[c] Gendzelevich et al. 2009
[d] KGS Group 2001
[e] Threshold discharge is variable and dependent on magnitude of flow from Assiniboine River
[f] Manitoba Floodway Authority, http://www.floodwayauthority.mb.ca/ floodway_expansion.html
[g] Flow within Winnipeg without the reducing effects of the Portage Division and Shellmouth Dam
[h] Depending on character of the flood peak

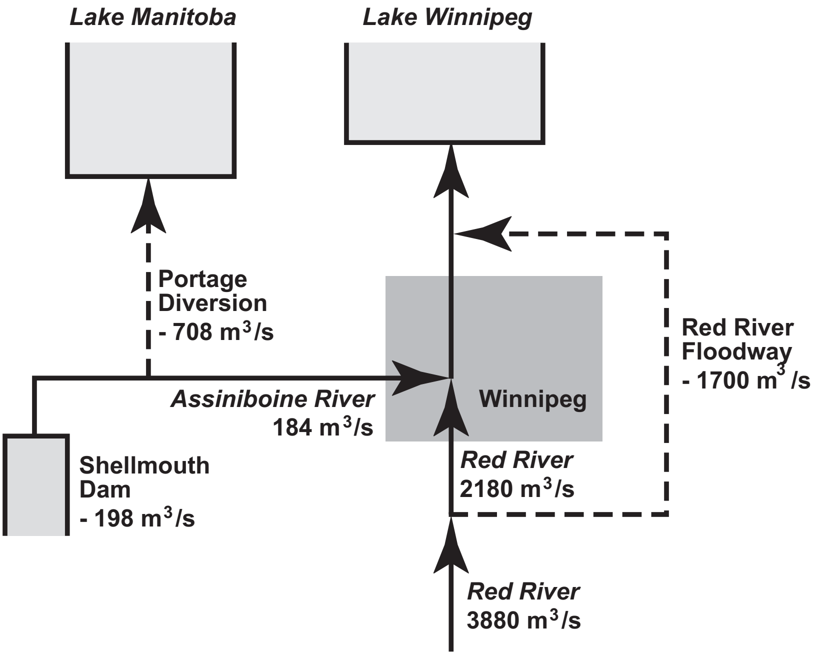

Fig. 7 Schematic diagram showing the integrated flow-reducing effects for the Red River at Winnipeg from the Floodway (original design), Portage Division, and Shellmouth Dam relative to the designed 'natural' flow of 4790 m^3/s at Winnipeg (modified from Mudry et al. 1981). The largest proportion of reduction is from the Floodway, but other two contributions are important, especially in years of major flooding when the Red and Assiniboine freshet flows arrive coincidentally. The capacity of the Floodway was increased from 1700 to 3960 m^3/s between 2005 and 2011, substantially increasing the level of flood protection at Winnipeg (see Table 1)

8.5 times, respectively (Fig. 7). This contribution has been increased substantially by the recent Floodway Expansion Project, which increased the design capacity of the Floodway from 1700 to 3960 m^3/s, as summarized below (see Table 1). Since becoming operational in 1969 and up to 2011, the Floodway has been used 28 times, preventing an estimated $ 30 billion CAD in flood damages in Winnipeg (Manitoba Water Stewardship data). Its unquestioned highlight occurred during the 1997 Red River flood when 1900 m^3/s were successfully diverted, exceeding the design capacity of 1700 m^3/s (IRRBTF 2000), and averting a multibillion dollar (CAD) disaster and the evacuation of a substantial proportion of Winnipeg (Rannie 1998b). In contrast, the 1997 flood caused $ 3.6 billion US (1997 dollars; ~$ 4.4 billion US 2005 dollars or ~$ 5.2 billion CAD 2005 dollars) in flood damages by overtopping dykes at Grand Forks, North Dakota, and East Grand Forks, Minnesota, in the USA portion of the Red River Valley (IRRBTF 2000),). Other years of significant flood mitigation occurred in 1974, 1979, 1996, 2006, 2009 and 2011, when 'natural' discharges at Winnipeg approached or exceeded that of the 1950 flood (Fig. 6). During all of these floods, including the 1997 flood, no flooding occurred in the areas of Winnipeg that the Floodway and primary dykes were designed to protect.

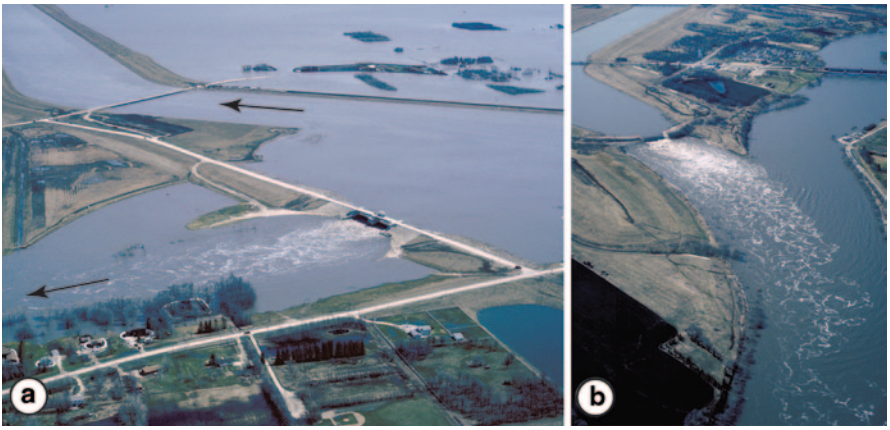

Fig. 8 Photographs during the 1997 Red River flood showing **a** the split of the flow between the Floodway (*flowing toward upper left*) and the Red River (*flowing towards the lower left*), as well as the Floodway Inlet Control Structure (*centre right*) and the flood zone (*top, beyond dyke*), and **b** the Floodway Outlet Structure and confluence of the Floodway (*entering from left*) and Red River (see Fig. 2 for locations). Note, in **b** the entire flow of the river is confined within the river channel in contrast to the situation upstream of the Floodway inlet. Photographs taken 9 May 1997

4.2.2 Portage Diversion

The Portage Diversion is a diversion canal extending from the Assiniboine River at Portage la Prairie to the southern end of Lake Manitoba (Fig. 2). Constructed between 1965 and 1970 for $ 20.5 million CAD (1965 dollars; ~$ 131 million CAD 2005 dollars), it is comprised of a 29 km long canal, a River Control Structure within the Assiniboine River, two gradient control structures located along the canal, and an outlet structure at the edge of Lake Manitoba (Mudry et al. 1981; KGS Group 2001). The canal is used during periods of Red River flooding to divert up to 708 m^3/s of Assiniboine River flow (design discharge) northwards into Lake Manitoba to reduce flow downstream, thus augmenting the flow reduction effects of the Red River Floodway and Shellmouth Dam (Fig. 7). The Portage Division can also reduce the effects of flooding along the Assiniboine River between Portage la Prairie and Winnipeg, as was the case during severe flooding in 1976, 2011 and 2014.

4.2.3 Shellmouth Dam

The Shellmouth Dam is a flood control dam, 21 m high, 1280 m long with a 55 km long reservoir, located along the Assiniboine River, about 470 km upstream of the Red-Assiniboine confluence, near the Manitoba-Saskatchewan border (the location is west of the area depicted in Fig. 1; Mudry et al. 1981; KGS-ACRES-UMA 2004). Built between 1964 and 1972 for $ 10.8 million CAD (1964 dollars; ~$ 70 million CAD 2005 dollars), the dam can reduce freshet flow downstream along Assiniboine River by up to 200 m^3/s, thus limiting discharge into Winnipeg in conjunction with the Portage Diversion and Red River Floodway (Fig. 7).

4.3 Ring-Dyked Communities and Isolated Rural Properties

The 1958 Royal Commission on Flood Cost-Benefit also advocated the construction of ring dykes around flood-vulnerable, rural towns and communities south of Winnipeg. Prompted by damage from the 1966 flood, ring dykes were established at eight communities (Fig. 2), and cost-sharing was available for the construction of ring dykes or elevated earthen pads to protect buildings on isolated rural properties (Mudry et al. 1981; Canada-Manitoba 1991). The construction program spanned 1967 to 1972 and cost $ 2.7 million CAD (1967 dollars; ~$ 16 million CAD 2005 dollars); the design flow was the level of the 1950 flood plus 0.6 m freeboard.

Following the 1979 flood, a federal-provincial program led to implementation of flood-protection measures for many individual rural farmsteads in the early 1980s. Benefit-cost studies under the FDRP led to the upgrading of the flood-protection level for the eight ring-dyked Red River Valley communities (Fig. 2) to the (then) 100-year flood plus 0.6 m freeboard and, in some cases, expanding the dyking to enclose a larger area (Canada-Manitoba1991). This work was undertaken from 1983 to 1991 at a cost of nearly $ 4 million CAD 1991 Dollars (~$ 5 million CAD 2005 dollars). Also under the FDRP, the flood-prone areas of the Red River Valley were formally defined under the Red River Designated Flood Area, requiring the main floor of new construction to be 1 m above the level of the 1979 flood (IRRBTF 1997), although this requirement does not apply to construction behind the primary dykes in Winnipeg or within the ring-dyked communities south of Winnipeg. Roughly a third of new construction within the designated area up to 1997, however, did not comply with the regulation due to a lack of enforcement (IRRBTF 1997).

During the 1997 flood, none of communities protected by permanent ring dykes were flooded, despite the level of flooding exceeding the design flow. All of these dykes were temporarily raised and/or reinforced, and the enclosed communities evacuated because of the emergency conditions and the threat of overtopping. Over 2500 homes were flooded outside of the protected communities (Shrubsole 2001), including in the northern portion of the flood zone, where water levels were accentuated by a backwater effect from Floodway operations (Manitoba Water Commission 1998; Rannie 1998b). Following the flood, a $ 130 million CAD (1999 dollars; ~$ 150 million CAD 2005 dollars) program to enhance flood protection in the Red River Valley included funding for the construction of permanent ring dykes at 10 additional rural communities (Fig. 2), all of which were subject to or threatened with flooding in 1997, as well as raising the dykes at the existing eight ring-dyked communities (Caligiuri and Topping 1999). The design flow was increased to the level of the 1997 flood plus 0.6 m. This program also supported new or enhanced ring dyke or elevated pad flood protection at isolated properties in the Red River Valley. Overall, enhanced structural flood protection is now provided for 95 % of the homes, businesses and farms in the rural Red River Valley (Manitoba government data). This enhanced level of flood protection was utilized during major floods in 2009 and 2011 (Fig. 6), although these floods did not exceed the design flow.

4.4 Expanded Floodway

Although the structural flood protection at Winnipeg successfully mitigated the 1997 flood, it was recognized that the flood defenses may be inadequate to mitigate a future flood of similar or higher magnitude (IJC 2000). In particular, a catastrophic dyke breach could have happened had significant precipitation fell over the flood zone just before the arrival of the flood peak. Re-calculation of the return period of the design flow of the flood protection indicated that the level of flood protection had decreased from the 160-year flow to between the 90- and 100-year flows, because of the post-1962 occurrence of elevated peak flows experienced by the Red River (KGS Group 2001). These considerations lead to a review of the capacities and vulnerabilities of the flood-protection system, including the preliminary engineering feasibility studies to substantially increase flood protection. Expanding the Floodway was the chosen option and construction began in 2006 and is [at the time of writing] expected to be fully completed by 2014. Concern about alteration of the flow regime arising from future climate change is not identified as an underlying reason for expanding the Floodway flood in the preliminary engineering study or the environmental assessment documentation (see KGS Group 2001; TetrES InterGroup Inc. 2004).

The expanded Floodway increases the design capacity of the channel to 3960 m^3/s and the design flow of the integrated Red River flood-protection infrastructure to up to 7700 m^3/s (depending on the character of the flood peak), representing an up to 700-year return period. This level of flood protection met the IJC (2000) recommendation that Winnipeg should be protected against a flood at least as large as the 1826 flood of record. Basic morphological attributes of the expanded Floodway are listed in Table 1 and can be compared with the original morphology.

5 A Geomorphic Context to the Flood Problem

The post-1950 emphasis on structural flood mitigation in Manitoba represents a predominantly engineering response to the flood problem. Specifically lacking, however, was an understanding of the modern flood problem from the perspective of hydrologic and geomorphic processes over a ‘geomorphic’ time-scale of centuries to millennia. Following the 1997 flood, a multidisciplinary research project was initiated by the Geological Survey of Canada and Manitoba Geological Survey to develop a paleoflood record to improve the understanding of the frequency and magnitude of extreme Red River floods (see Brooks et al. 2003). The project also examined two factors that may be altering the long-term flood hazard; regional differential uplift, which has caused the river to lose the gradient over time, and geomorphic change within the shallow, stream-cut valley occupied by the river. This

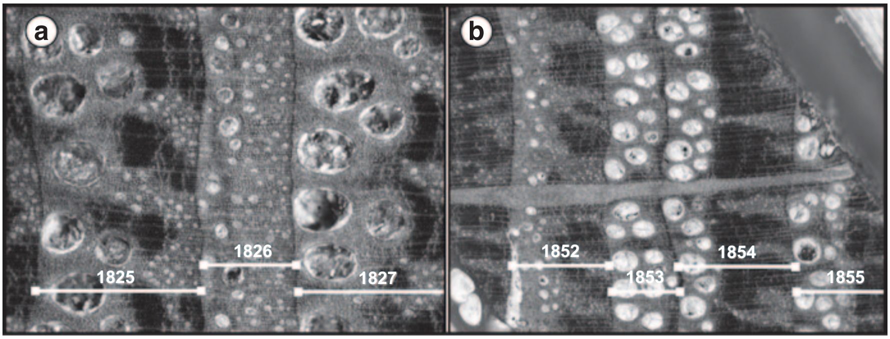

Fig. 9 Photographs of flood rings within oak trees that formed during **a** 1826 and **b** 1852. Both flood rings display unusually small conductive vessels within their earlywood caused by prolonged inundation during major floods. The 1826 'flood ring' has a lighter colour because its latewood is made up mainly of parenchyma and has very little fibre

review summarizes these studies as well as several others conducted outside of the project that are relevant to the geomorphic context theme.

5.1 Paleoflood Studies

Investigations were initiated to reconstruct a paleoflood record from stratigraphic records by examining alluvial deposits in the river banks (see Brooks, 2002) and lacustrine deposits in the south basin of Lake Winnipeg off the mouth of the Red River (see Simpson et al. 2003), in Netley Marsh, a back-barrier lagoon complex at the river mouth (see Nielson et al. 2003), and in three small lakes along the river within the flood zone (see Medioli 2003; Medioli et al. 2005; Medioli and Brooks 2003). None were successful because of difficulties in recognizing the deposits of the major nineteenth-century floods. Major challenges included a lack of significant textural variation between major to minor flood deposits (small lakes, river banks, Lake Winnipeg), a uniform black colour imparted by anoxic conditions (small lakes), bioturbation (small lakes and Netley Marsh), complex and incompletely understood depositional environments (Netley Marsh and Lake Winnipeg), and variability between preserved depositional records in recovered core (Lake Winnipeg).

Instead, the successful approach relied on recognizing flood signatures preserved within the annual rings of long-lived trees located within the Red River flood zone on or near the level of the clay plain (St. George 2010). St. George and Nielsen (2000) reported that tree-ring specimens obtained from bur oak (*Quercus macrocarpa* Michx.) growing along the river contained unusual anatomical features in the annual rings that coincided with the 1826 and 1852 floods (Fig. 9). These features, dubbed 'flood rings', were characterized by anomalously small conductive vessels within the earlywood and, in well-developed cases, featured amorphous latewood with disrupted flame parenchyma and little fibre in the latewood (St. George and

Nielsen 2000; 2003). Factors controlling flood-ring formation include the threshold stage of flooding inundating the base of a tree trunk (≈3000 m^3/s at Winnipeg, corresponding to the discharge of the 1950 or larger floods), an extended duration of inundation, and the timing of spring flooding relative to the growth of the earlywood portion of the annual ring (St. George and Nielsen 2002a).

The surrogate flood record developed from these signatures extends back to AD 1648 for the reach of river between Emerson and Winnipeg (referred to informally as the 'lower Red River basin'; St. George and Nielsen 2002a; 2003). St. George and Nielsen (2003) reported flood-ring evidence for the major historical flooding of 1997, 1979, 1950, 1852 and 1826, but also for previously unknown floods in 1747 and 1762 (Fig. 10). This record indicates that the Red River experienced several episodes of frequent major floods, including the mid-1700s, the early to mid-1800s and the latter half of the twentieth century. Conversely, there were long periods when the Red River was relatively quiescent, with almost a century passing without a major flood between 1648 and 1746. The relative frequency of flood rings was used to estimate the relative magnitude of past floods. The 1826 flood caused flood signatures to form in more oaks than any other event (Fig. 10), and its signatures also included disrupted parenchyma and little wood fibre, which were found rarely in other flood signatures. Based on this evidence, St. George and Nielsen (2003) inferred that the 1826 flood was the largest flood on the Red River since at least 1648.

The tree-ring record also helped clarify the earliest historical account of Red River flooding. In his description of the 1826 flood, Ross (1856) reports a statement made in 1826 by a Mr. Nolin, 'one of the first adventurers in these parts', claiming that an even larger Red River flood occurred in 1776. Based on this limited evidence, the 1776 flood was included in historical accounts of the Selkirk Settlement (Bumsted 1997, 2000) and early assessments of Red River flood hazard (Clark 1950; RRBI 1953b). Because of the lack of tree-ring evidence for flooding in 1776, this event is no longer used in Red River flood frequency analysis in Manitoba (Manitoba Water Stewardship data).

The tree-ring record of past floods in the upper Red River basin (upstream of the modern Canada-USA border) and the Assiniboine River, although based on a more limited set of trees, still provided useful insights into the behaviour of floods across the watershed. The upper Red River record contained anatomical signatures for several floods that did not occur in the lower reach, which suggested that the history of flooding has not been concordant throughout the basin (St. George and Nielsen 2002a). Trees from the Assiniboine River basin contained flood signatures for both 1826 and 1861, indicating that, although it is uncommon, it is possible for the Assiniboine River and Red River to produce a major flood in the same year (St. George and Nielsen 2002a).

A comparison of the tree-ring flood record for the lower Red River basin against surrogate climate records from tree rings and lake sediments by St. George and Nielsen 2002b showed that the relationship between large floods and long-term hydroclimatic change is not straightforward. A dendroclimatic reconstruction derived from the Red River tree-ring data set indicates that the interval between 1670 and 1775 was the most prolonged dry period of the last 600 years (St. George and

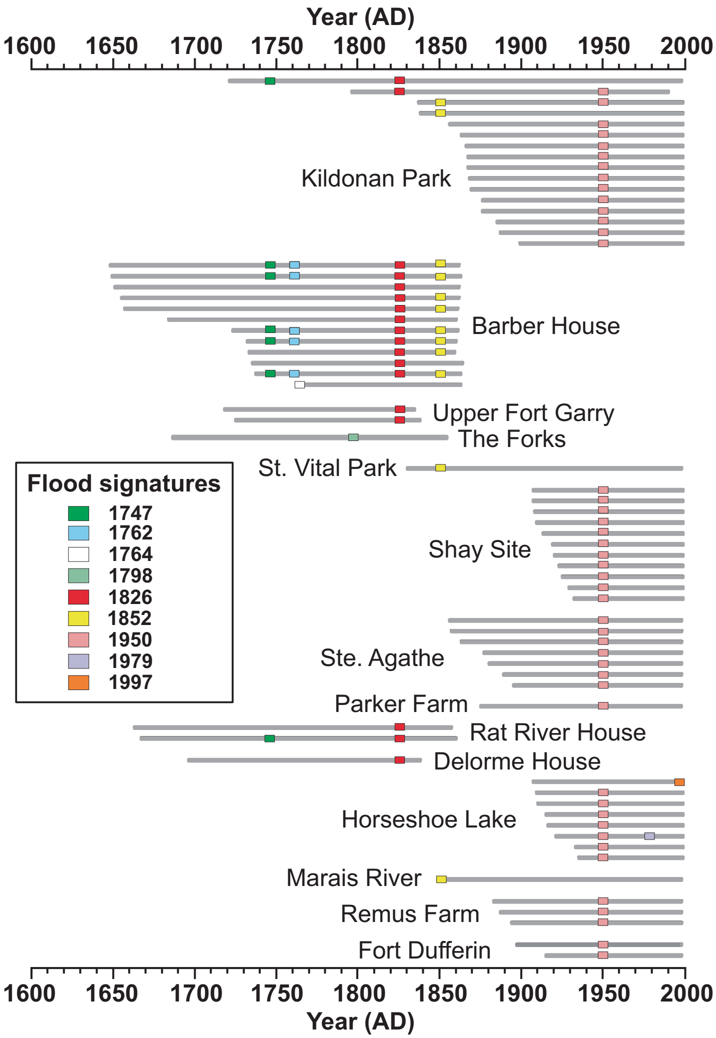

Fig. 10 Diagram showing the occurrence of flood signatures (*flood rings*) within the growth rings of oak trees growing along the Red River between Emerson and Winnipeg (after St. George and Nielsen 2003). *Grey bars* represent the span of record recovered from individual live trees or timbers from nineteenth-century buildings. Rings that contain anatomical signatures caused by flooding are marked by *small coloured rectangles* on the *grey bars*

Nielsen 2002b). Although major Red River floods in 1747 and 1762 also occurred during this interval, both years were situated within brief two-to-three year runs of above-normal precipitation. The 1826 and 1852 floods happened during the two most prolonged wet intervals of the last three centuries, but precipitation was close to the long-term average during the major flood-free intervals between 1763 and

1810 and from 1862 to 1949 (see St. George and Nielsen 2002b). The apparent lack of agreement between reconstructed precipitation and the history of Red River flooding suggests that other factors, which are not well captured by currently available paleoclimatic reconstructions, may exert a greater influence on the frequency of major floods.

5.2 Relevance of Differential Uplift

Regional differential isostatic uplift arising from the former presence and subsequent retreat of the Laurentide Ice Sheet in north-central North America during the late Quaternary has resulted in the north-flowing Red River in Manitoba losing ~60% of its valley gradient since ~8000 cal year BP (the gradient now averages 0.00007 in Manitoba; Brooks et al. 2005). Uplift is an active process in the contemporary southern Manitoba landscape, as revealed by regional water level gauge and geodetic data (e.g., Andrews 1989; Lambert et al. 1998; Tackman et al. 1999). Tackman et al. (1999) estimate that contemporary uplift in southern Manitoba is 10^{-9} rad/year, rising toward the northeast at a bearing of 43°C.

The relevance of the decrease in river gradient on the lateral extent and depth of flooding was assessed by Brooks et al. (2005), based on modelling of a 1997-magnitude flood in the contemporary landscape for scenarios of gradient at 8000, 6000, 4000 and 2000 years ago, and for 2000 years in the future. Notwithstanding the limitations of the modelling, the results revealed that a broad, shallow flood zone was present for all of the gradient scenarios (Fig. 11), but increased from 1186 to 1583 km^2 (~29%) with depth increasing along four east-west cross sections by 0.48–0.91 m (61–86%) between 8000 years ago and the modern scenario as gradient decreased. Proportionally, most of the change to the flood zone occurred between the 8000 and 2000 years ago scenarios, as expected because of the exponential decrease in uplift and tilt rates over time. The modelling also indicated that flood extent and depths would increase by 18 km^2 (~5%) and 0.04–0.06 m (2–5%), respectively, by 2000 years in the future.

The presence of a broad, shallow flood zone in all of the modelled scenarios implies that, for a 1997-magnitude flood, this style of flooding is intrinsic to the geomorphic setting of the river and is not strictly the result of the loss of river gradient from differential uplift. Thus, broad, shallow floods have always occurred in the Red River Valley and are not a ‘recent’ phenomenon of natural and/or human-induced environmental change. Relative to the freeboard height of modern dykes in the Red River Valley (0.6 m), Brooks et al. (2005) deemed that the projected minor rise in mean depth (0.04–0.06 m) between the present day and 2000 years in the future will not alter the flood hazard significantly, and therefore does not necessitate a reassessment of the design flow level in southern Manitoba in the foreseeable future.

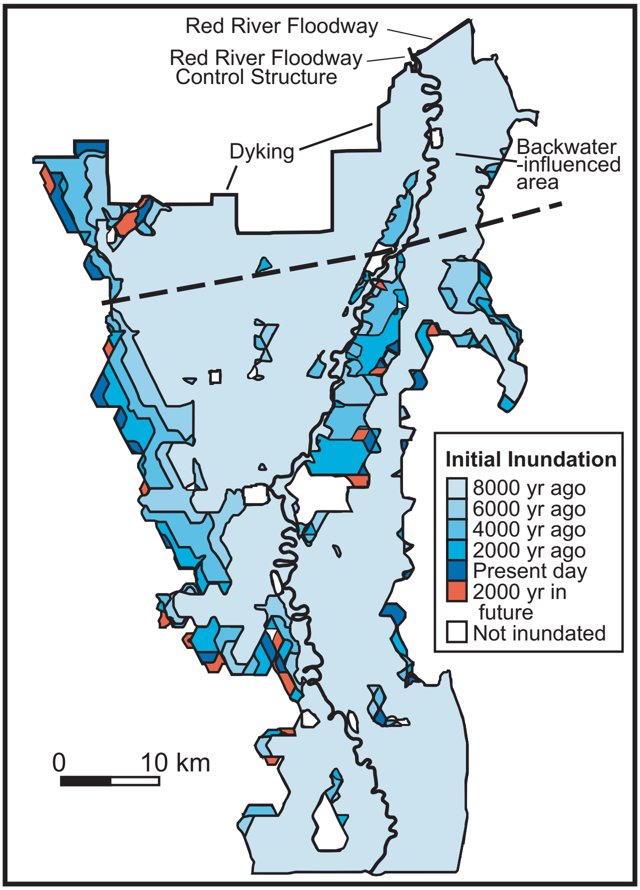

Fig. 11 Composite map showing the change in the extent of flooding in southern Manitoba for the modelled scenarios of gradient at 2000 yr intervals using a 1997-magnitude discharge (after Brooks et al. 2005). *The dashed line* towards the upper portion of the map delineates the approximate southern limit of the flood zone affected by backwater due to the presence of the East and West dykes adjacent to the Floodway control structure

5.3 Development of the Shallow Stream-Cut Valley

A fundamental factor contributing to the flood hazard is the shallow stream-cut valley occupied by the river that has an insufficient capacity to contain large flows. To assess the relevance of geomorphic change within this valley to the flood problem, floodplain deposits were cored and dated along two successive meanders near St. Jean Baptiste, as reported by Brooks et al. (2001) and Brooks (2003a; Fig. 2). The floodplain alluvium in ten cores (five from each meander) ranged from 15 to 22 m thick and was composed primarily of silt, as is consistent with the mud-dominated character of the river. The past positions of the inner banks were reconstructed us-

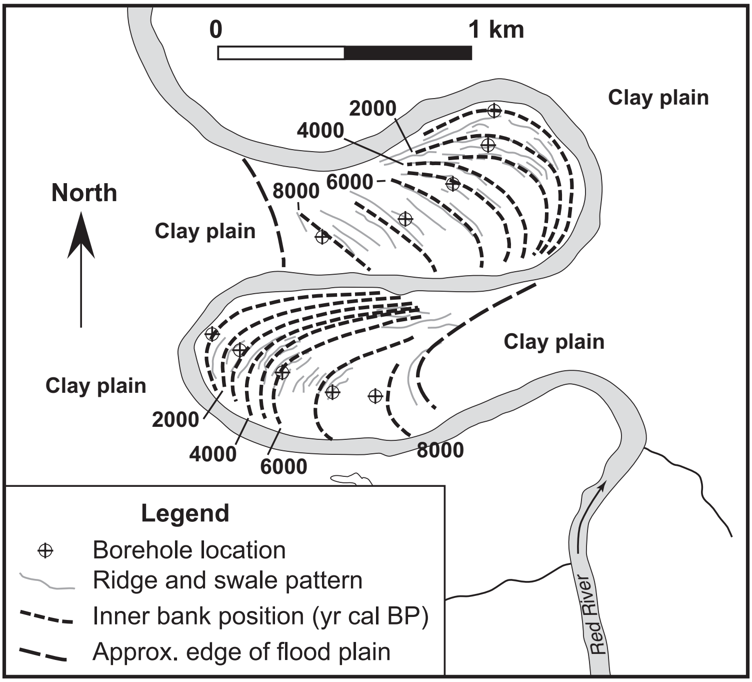

Fig. 12 Map showing lateral migration of the inner bank of two meanders over the past 8000 years located 3–4 km south of St. Jean Baptiste (see Fig. 2 for location; after Brooks 2003a). The positions of the 1000-year isochrones have been extrapolated from the calibrated radiocarbon age of lateral accretion deposits at ten borehole locations and positioned using a preserved pattern of ridge and swale topography on the floodplain as a guide

ing 1000-year isochrones (Fig. 12), revealing that the two meanders have extended outwards and rotated downvalley in a single sequence of lateral channel migration over the ~8000 years history of the river. Significantly, there has been appreciable lateral channel migration over the past 1000 years, when the rate of channel migration averaged ~0.04 m/year at both meanders. The average rates of channel incision at the two meanders between 8000 and 1000 years ago were estimated by Brooks (2003a) to be 0.4–0.8 mm/year. Overall, these results reveal that the channel has experienced low, long-term rates of lateral channel migration and incision. There is no evidence that the river is straightening its course, as suggested by Welsh (1973).

Other work along the Red River supports the conclusion of low rates of lateral migration and incision. Brooks and Nielsen (2000) observed that a single pattern of ridge and swale topography is present on the floodplain at most meanders along the river, implying that these meanders have undergone only a single (and continuing) sequence of lateral migration, as is consistent with a low rate of channel migration. It would thus be expected that 'old' alluvium is present in mid- and back areas of the floodplain, as Brooks (2002) confirmed based on radiocarbon ages of

3760–6710 cal BP that are related to the age of floodplain deposits exposed along the outer bank of seven meanders. Brooks and Medioli (2003) dated the formation of cut-off channels that created two ox-bow lakes at 1500 and 2000 years ago, respectively. These relatively recent ages (which reflect an extended period for the meanders to develop and then be cut off) as well as the overall low number (nine) of cut-off meander scars and ox-bow lakes along the Red River in Manitoba, also are consistent with a low rate of lateral channel migration along the river meanders. The low rate of channel migration is attributed by Brooks (2005) to be a product of low stream power, cohesive alluvial and glaciolacustrine deposits forming the eroding banks, and the buffering of bank erosion by the reworking of 'concave overbank deposits' on the lower slopes of low-angled, landslide zones that are pervasive along the concave side of the river meanders.

Brooks (2003a) reported that the valley cross section at the two St. Jean Baptiste meanders increased slightly by ~2 % (~52 m^2) and ~0.7 % (~9 m^2) over the past 1000 years at the upstream and downstream meanders, respectively. This change, in combination with the apparent low rates of migration elsewhere along the river, indicates that the shallow valley experienced only a slight increase in valley cross section and hence change in discharge capacity over the past 1000 years. When considered proportionally over timescales of a century, which is more relevant to modern flood planning, the amount of widening of the valley cross section is negligible and the resulting change in total valley conveyance would be within the error of discharge measurement. Geomorphic change to the shallow valley, therefore, was considered by Brooks (2003a) to be an insignificant factor affecting the modern flood hazard.

Some important aspects of the fluvial geomorphology are not known, however. Rannie (2010) presented historical accounts that indicated the Red River channel experienced a considerable widening following each of the nineteenth century major floods (1826, 1852, 1861), but this phenomenon has not been observed during the post-1950 period of flooding. If accurate, this widening has implications on magnitude estimates of these events that are based partly on the cross section of the modern channel, possibly resulting in over-estimated flows. The question of this widening remains unanswered, but accelerated bank failure along both concave and convex banks is a plausible process that could have produced this response (see Brooks 2003b, 2005).

5.4 Influence of Landscape Change on Flooding

Beginning in the nineteenth century, the establishment of European agricultural practices and development of communities and infrastructure modified the Red River Valley landscape, causing widespread replacement of native grassland and forest with cultivated fields, drainage and channel improvements, loss of wetlands (see Hanuta 2001), and the construction of raised road and railway beds. The occurrence of possible effects on flooding was recognized in the latter half of the twentieth century because of the general increase in peak flows after 1949 (Fig. 6). Miller and Frink (1984) conducted a review of the hydrological setting, previous floods, flood-control measures, and probable effects of land-use changes, but found little indication of change in flood response along the river. Modelling the specific influence of changes in wetland area using 1997 hydrological data from the Rat River watershed (a tributary of the Red River; Fig. 1), Simonovic and Juliano (2001) found that increasing the area of wetlands resulted in more surface water storage, which reduced the total volume of a 1997-magnitude flood flow, but did not change the level of peak flow. Their results suggest that a wetland restoration program within the watershed would have minor to negligible effect on the flood hazard and would remove productive agricultural land from cultivation. Regardless of the specific influence of landscape change to flood response, the 1826 flood of record occurred within a natural landscape, clearly demonstrating that extreme peak flows are not exclusive to the altered landscape of the twentieth and twenty-first centuries.

6 Discussion

Structural flood protection in southern Manitoba has been designed and funded to mitigate the flood problem in the Canadian portion of the Red River Valley and is not the product of an integrated basin-wide flood control strategy. An exception to this is the ring dyke at Emerson (Fig. 2), which was expanded (and raised) in the late 1980s to include the village of Noyes, Minnesota (Canada-Manitoba 1991). However, there is good cooperation and data sharing between Canadian and USA federal, provincial-state and other agencies on the flood problem that spans many decades, particularly concerning flood forecasting, emergency response and communications to the public during flood emergencies. Following the 1997 flood, a referral was made by the Canadian and USA governments to the International Joint Commission (IJC; which was established by treaty in 1909 to address water issues along shared watersheds and river courses) to examine and report on the cause of the flood and make recommendations for reducing damage from future major floods. The IJC and the International Red River Basin Task Force (IRRBTF; which was appointed by the IJC) subsequently released reports containing many basin-wide recommendations (see IRRBTF 1997, 2000; IJC 2000). The Red River Basin Commission (RRBC) is a binational organization that promotes and facilitates a comprehensive and cooperative approach to land and water management within the Red River watershed (see RRBC 2005). The RRBC recently released a comprehensive report examining and providing recommendations for flood mitigation for the USA portion of the watershed to the North Dakota and Minnesota state governments (who requested the study), but it also included some recommendations relevant to the Canadian portion of the basin and the Manitoba government (see RRBC 2011). Progress thus is being made towards a basin-wide approach to managing the flood problem, but the required involvement of two federal, two state, one provincial and numerous municipal governments will always complicate the interaction.

Decision making to mitigate Red River floods in southern Manitoba has yielded heavy investment in structural flood control measures. This is not to overlook nonstructural measures, as flood forecasting, in particular, is an important aspect of flood emergency preparedness. Despite the success of the structural controls at averting billions of dollars in flood losses, this flood management approach can be criticized as merely postponing losses from a catastrophic disaster that will occur when the inevitable rare, extreme flow overwhelms the flood protection. This is the disaster-by-design paradigm of Mileti (1999) that further suggests that the scale of the disaster will be compounded if postponement occurs over many years and development takes place on protected, flood-prone lands, causing potential losses to accrue. The latter circumstance may occur where the presence of the structural mitigation is erroneously considered to have eliminated the risk of flooding. Given the post-1950 history of Red River flooding, Winnipeg and the Manitoba provincial government do not have a lack of flood awareness, nevertheless, significant urban expansion has occurred in the south part of the city on flood-prone lands protected behind the primary dykes. The increase in flood protection from a design flow of 160-year (1962 estimate) to a (up to) 700-year return period under the Floodway Expansion Project, however, represents a substantial reduction in the probability of a catastrophic flood disaster and thus further postpones a 'catastrophic' disaster to an 'acceptable' level. No flood-risk management program, of course, can provide absolute protection from losses because occasionally and unavoidably disasters are caused by rare, extreme floods (Shrubsole et al. 2003). By way of comparison, the new design flow markedly exceeds the 100-year, 200-year or 500-year return periods (which vary by province) used for floodplain mapping in Canada under the FDRP (see Watt 1989).

Effective flood management is generally seen as being the 'correct' balance between structural and nonstructural measures, although there is no perfect mix for all scenarios (Shrubsole 2007). The dominance of structural measures in southern Manitoba reflects the broad, shallow character of Red River floods in combination with the need to mitigate floods for communities that were well-established before the interval of more frequent, higher magnitude flooding that began with the 1950 flood and which precipitated the modern impetus for structural mitigation. South of Winnipeg, a nonstructural approach of restrictive zoning would require impeding development over distances in excess of 10 km from some communities, thus severely (and politically unacceptable) restricting growth in some rural municipalities (Bowering 2002). At Winnipeg, initiating restrictive zoning on the protected, flood-prone areas would be not only difficult and controversial due to the impact on property values and the economic organization of the city, but also because it would contradict the recent decision to fund the Floodway Expansion Project. Interestingly, an opportunity to deflect settlement away from the flood-prone lands at Winnipeg occurred in early 1880s when Sir Sandford Fleming, Engineer-in-Chief, Canadian Pacific Railway, recommended that the routing of the first cross-Canada railway line, then being planned, should cross the Red River at Selkirk (Fig. 2), where the flood zone is contained entirely within the narrow stream-cut valley, rather than to the south at Winnipeg because of the known flood problems there during 1826, 1852 and 1861 (Fleming 1879). This advice was not followed, in part because of 'forceful' lobbying by Winnipeg business leaders, who recognized that future economic growth would become focused on the Selkirk area if the railway bypassed Winnipeg (Bumsted 1997).

The structural flood controls protecting the Red River, Manitoba, are similar in concept, but different in detail to many other rivers in North America. Reflecting the character of the broad, shallow flood zone and the predominantly rural setting, ring dykes protect numerous towns and villages, while isolated structures are situated behind ring dykes or on elevated earthen pads, as opposed to protecting the flood-prone zone by elongated linear dyking. Within Winnipeg, linear dykes along the Red, Assiniboine and Seine rivers are an important component of the flood protection, but the regulation of flow by the Portage Diversion, Shellmouth Dam, and especially the Red River Floodway is critical to maintaining linear dyke freeboard during major foods. The use of diversion canals (or bypasses) to protect urban areas is not unique to the Red River and occurs along rivers of widely varying scale, as the following examples from North America demonstrate. Several floodways (or spillways) are present along the Mississippi River, USA, to protect the levees (dykes) at urban centres during major flooding. The operation of the Bird Point-New Madrid Floodway, Missouri, is designed to lower flood stage at Cairo, Illinois, although it has been used only twice (in 1937 and 2011) since completed in 1932 (see USACE 2012a). Along the lower Mississippi River, stage at Baton Rouge and New Orleans, Louisiana, can be lowered by diverting flow through the Moranza Floodway (used twice in 1973 and 2011) into the lower Atchafalaya basin, and the Bonnet Carré Spillway (used ten times since 1931) into Lake Pontchartrain (see USACE 2012a; 2012b). In both cases, excess flow eventually enters the Gulf of Mexico. An integrated system of structural flood controls along the Sacramento River, Sacramento Valley, California, USA, including the Yolo and Sutter bypass floodways, protects Sacramento and other communities from flooding (see Russo 2010). Along smaller-scale watersheds, the Tampa Bypass Canal, ~22 km long, diverts floodwaters from the upper portion of the Hillsborough River basin into Tampa Bay to protect part of Tampa, Florida USA (Southwest Florida Water Management District, written communication, 19 November 2012). At Thunder Bay, Ontario, Canada, an urban area is protected from flooding by the Neebing-McIntyre Floodway. This is an excavated channel, ~1.5 km long, that carries 'excess' flow from the Neebing River to the expanded course of the lower 3.5 km of the McIntyre River, which then enters Lake Superior (Lakehead Region Conservation Authority, written communication, 19 November 2012). Influenced in part by the success of the Red River Floodway at Winnipeg, plans are proceeding [as of February 2015] for the construction of a diversion canal, ~35 km long, to mitigate flooding at the Fargo, North Dakota-Moorhead, Minnesota (Fig. 1), along the Red River in the USA (see http://www.fmdiversion.com).

7 Concluding Remarks

Following the 1997 flood, the decision to enhance flood protection at Winnipeg by expanding the Floodway was inevitable given the previous nearly half century of reliance on structural flood control measures. Unlike previous projects, the Floodway Expansion Project proceeded with a greatly improved understanding of longer-term hydrologic and geomorphic processes. In particular, dendrochronologic research utilizing flood signatures in tree rings indicates that the 1826 flood was likely the largest Red River flood in over three and a half centuries and that there is no evidence to support the occurrence of a severe flood in 1776. Regional differential uplift, although causing the continued gradual loss in river gradient, is deemed not to be significantly changing the flood hazard. Similarly, the flood hazard is not being changed significantly by erosion and sedimentation processes within the shallow stream-cut valley, which cannot contain the higher magnitude flows of the river. Overall, the geomorphic and hydrologic attributes of the Red River, which is distinctive geomorphically and subject to a unique flood character in Canada, are now better understood and have been applied to improve the management of flooding in southern Manitoba.

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Promoting Atmospheric-River and Snowmelt-Fueled Biogeomorphic Processes by Restoring River-Floodplain Connectivity in California's Central Valley

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Abstract Potential biogeomorphic benefits from intentional levee breaks and weir overflow on the managed floodplain-river system of California's Sacramento and San Joaquin River watershed (Central Valley) are discussed here. Prior to the nineteenth century, the system was characterized by natural levees alongside complex multichanneled rivers and tributaries, and geomorphic processes such as channel migration and avulsion, typical in lowland floodplain-river systems globally, dominated. Today, the floodplain-river system has been heavily modified with infrastructure such as levee embankments that disconnect floodplains from channels and diminish key processes of floodplain-river ecology. Unintentional levee breaks in river systems where floodplains have been developed for agriculture or urban uses still occur regularly (in a quarter of twentieth century years) and are sometimes catastrophic. Floodplain inundation, erosion, and sedimentation, the dominant geomorphic processes that occur during unintentional levee breaks, are flood risks in such embanked river systems. Climate and flood variability still dictate the frequency of unintentional levee breaks despite many decades of engineering. Of particular consequence are the so-called atmospheric-river (AR) storms. Since 1951, 81 % of breaks have occurred as a result of AR storms and flooding, while most of the rest occurred during snowmelt floods. Intentional levee breaks or planned weir overflows that are designed for floodplain restoration can facilitate a return towards more natural and dynamic biogeomorphic processes. In areas where room for flood-driven geomorphic processes is available on floodplains, local sediment scour and deposition near a levee break promote topographic diversity that enhances vegetation establishment and floodplain habitat. This chapter summarizes our current understanding of climate processes and flood variability that govern unintentional levee breaks or weir overflow. We also review examples of alternative flood management approaches in the Central Valley that promote processes necessary to restore or sustain lowland floodplain biogeomorphology. Future climate-driven

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changes in flood regime, such as enhanced flooding during winter months or more frequent atmospheric rivers, could be accommodated by additional intentional levee breaks or planned weir overflow for restoration. Implementation of these alternatives could be used to improve restoration policy and management of floods in embanked river floodplains.

Keywords Floodplain · Sediment · Hydrology · Atmospheric river · Levee break · Weir overflow · Geomorphology · Biogeomorphology

1 Introduction

The Sacramento and San Joaquin Rivers and their tributaries are managed lowland-floodplain rivers bounded in many places by levee embankments. The Sacramento River drains the northern part and the San Joaquin River drains the southern part of California's Central Valley watershed (Fig. 1). The Central Valley is the California's largest watershed (153,000 km^2) and is bounded by the Sierra Nevada on the east and the Coast Ranges on the west. The two rivers meet in an inland freshwater-tidal Delta before discharging into the San Francisco Bay Estuary from the east. This chapter synthesizes recent findings regarding intentional levee breaks, planned weir overflow, and their promotion of lowland floodplain biogeomorphic processes in this setting, with special attention to the particularly important roles of atmospheric-river storms (Ralph and Dettinger 2011) in flooding and floodplain processes.

The Sacramento-San Joaquin River system is of critical importance in California because the rivers convey over 50 % of California's total streamflow. Historically, they supported a dynamic ecosystem with vigorous floodplain riparian forests, and thriving salmon, bird, and other wildlife populations (Sands 1977). Conservation and restoration of these natural resources has emerged as a management goal that is "co-equal" with traditional resource management and extraction objectives (Isenberg et al. 2008). In this context, the present synthesis provides an example of looking backward at historical changes as a basis for looking forward toward restoration of geomorphic processes on floodplains as a first step in conservation and management of critical natural resources in this heavily modified landscape.

This chapter begins with a brief review of historical biogeomorphic processes on lowland Central Valley floodplains and of climate-forcing factors that both supported ecology and governed changes prior to anthropogenic alteration. We then review anthropogenic alterations and their current influences on floodplain hydrology and biogeomorphic processes. In particular, we illustrate the system-scale effects of levees on changes in floodplain processes and hydrology within the embanked system. Finally, we provide two examples as case studies illustrating flood hydrology related to (1) intentional levee breaks and (2) planned weir overflow into flood basins or low lying floodplain areas. Both of these alternatives to more traditional approaches to flood management can be used to facilitate restoration of flows and biogeomorphic processes on floodplains within this system.

Fig. 1 Map of the Central Valley, California, indicating the Sacramento and San Joaquin Rivers

2 Central Valley Floodplain Processes Prior to nineteenth Century Modification

2.1 Biogeomorphic Processes

Prior to Euro-American activities and disturbances in the region, a main river channel augmented by interconnected networks of multiple smaller channels drained lowland portions of the Central Valley, as was common in many lowland systems globally prior to widespread channelization (Ward and Stanford 1995; Brown 1998; Ward and Trockner 2001). The main channel conveyed flow and sediment during a wide range of small frequent to large infrequent floods, with the larger floods also filling the secondary channels in low lying areas, or flood basins, adjacent to the main channel, but separated from it by natural alluvial levees (Fig. 2; Gilbert 1917; Bryan 1923). Main and secondary channels were connected through crevasses, or natural levee breaks, that formed during floods and remained open (Kelley 1989). In multiple-channel lowland fluvial systems, sediment transport in the main channel sometimes raises main-channel bed elevation above that of the adjacent floodplain, promoting avulsion, through levee breaks and crevasse splay and channel complex development, in the adjacent floodplain (Smith et al. 1989). Prior to the 1850s, floodplains in lowland Central Valley rivers and tributaries contained multiple channel networks, over-bank deposits, crevasse splays, abandoned channels and oxbows, and seasonal and perennial lakes, marshes, and inter-channel wetlands (Gilbert 1917; Bryan 1923; Olmsted and Davis 1961; Atwater and Marchand 1980; Florsheim and Mount 2002, 2003; Florsheim et al. 2006). Generally, the channels and floodplains were hydrologically connected in lowland areas of the Sacramento-San Joaquin River systems on a regular basis, during frequent floods. This connec-

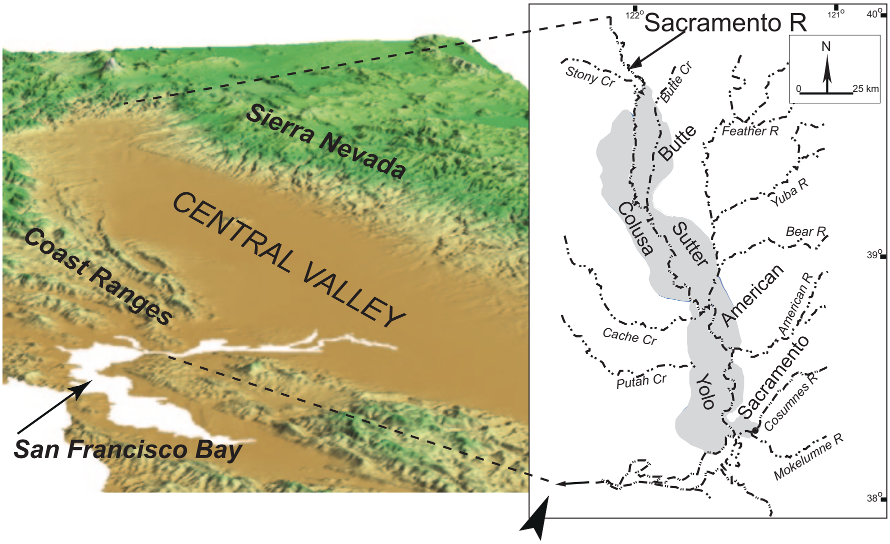

Fig. 2 **a** Oblique image of lowland Central Valley, **b** Flood basins (*gray areas*) along Sacramento River (Gilbert 1917; Bryan 1923), *arrowhead* indicates direction illustrated in oblique image

tivity facilitated transport of water, sediment, wood, and nutrients that supported heterogeneous habitats and riparian biodiversity.

Floods of a wide range of magnitudes created a dynamic system dominated by episodic avulsion, channel migration, erosion, and sedimentation. Biogeomorphic processes such as channel migration formed sediment deposits on the inside of river bends; new deposits supplied bare substrate that facilitated riparian establishment (such as currently occurs at along a meandering portion of the Sacramento River between Red Bluff and Colusa; Larsen et al. 2007; Michalkova et al. 2010; Micheli and Larsen 2011) and topographic diversity resulting in oxbow lakes (Costantine and Dunne 2008). Similarly, riparian establishment likely occurred in patches on new bare sandy crevasse splays similar to one formed following restoration on the Cosumnes River floodplain (Florsheim and Mount 2002, 2003). The resulting riparian settings and seasonal floodplain wetlands were important elements of the "Pacific Flyway" for migrating birds (Shuford et al 1998), and home to four salmon runs that once thrived in the complex multiple channel and floodplain system (Yoshiyama et al. 1998).

2.2 Climate and Floodplain Inundation

Prior to historical modifications, the dynamic fluvial system of the Central Valley was largely governed by floods associated with California's unusually variable climatic and hydrometeorological extremes (Dettinger et al 2011). In a review of paleoclimate evidence from the Central Valley, Malamud-Roam et al. (2006, 2007) indicated that large natural climate variations and changes capable of driving geomorphic change, such as erosion and sedimentation disturbances, were common during the past 5000 years, and indeed for most of that period the variations were large relative to the comparatively benign climate of the first part of the twentieth century.

Storms and floods differ from north to south and from west to east in the Central Valley. The Sierra Nevada mountains form the eastern ramparts and receive much of its precipitation as winter snows, rather than as rain. As a consequence, much of the precipitation from winter storms is stored in the mountains until springtime when snowfields melt. However, warm winter storms also arrive in California from time to time; so that large floods from the Sierra Nevada can be fed by immediate runoff from warm storms that rain heavily (even) in the Sierra. Even more regularly, moderate to high flood flows also arrive in springtime when abundant snowpacks melt rapidly. There are seasonal differences between north and south with the relatively high southern Sierra receiving more precipitation as snowfall than the lower elevation northern Sierra. Thus, the southern part of the valley experienced more spring snowmelt floods and associated geomorphic change than the northern portion of the valley (and, today, most levee breaks during spring floods occur in the southern portion of the Central Valley (Florsheim and Dettinger 2007)). The Coast Ranges form the western boundary of the Central Valley and are relatively low in elevation, receiving little precipitation as snowfall. Floods emanating from the Coast Ranges are primarily fed by rapid runoff from episodic winter rain storms. Floodplain inundation occurred in tributary channel-floodplain systems formed in the low gradient distal ends of alluvial fans emanating from the Sierra Nevada and Coast Ranges (Florsheim et al 2011) and within the flood basins, with inundation of flood basins lasting for months (Gilbert 1917; Bryan 1923).

In recent years, there has been a growing understanding that floods from both the Coast Ranges and Sierra Nevada arise mostly from a particular storm type called “atmospheric rivers” (Ralph and Dettinger 2011; Dettinger and Ingram 2013). Atmospheric rivers (ARs) are narrow, transient corridors of strong atmospheric water-vapor transport occurring upwind from mid-latitude winter cyclones. The corridors of intense winds and moist air are roughly 400–500 km across and thousands of km long. ARs routinely transport water vapor over the Pacific Ocean at rates equivalent to 7–15 times the average daily discharge of the Mississippi River, and when they reach the West Coast, they may deposit almost 20% of that moisture load in the mountain ranges that they encounter there. The half dozen or so ARs per year that make landfall in California contribute an average of one third to one half of all the State’s precipitation, thereby supplying much of the State’s water resources. Meanwhile, AR storms also have been the causes of many (and in many rivers, most) historical floods in the State. For example, in the Coast Ranges north of San Francisco, all seven major (declared) floods of the Russian River since 1997 have been associated with landfalling ARs (Ralph et al. 2006), and of the 39 floods this large since 1948, 87% have been directly tied to ARs. Further inland, streamflow increments on rivers entering the Central Valley from the Sierra Nevada are an order of magnitude larger when the storms are ARs than from other storm types (Dettinger 2004; Dettinger 2005; Dettinger et al. 2011). As far inland as the eastern slopes of the Sierra Nevada, eleven of the twelve largest peak flows on the East Fork Carson River since 1948 were caused by ARs.

The largest floods in the Central Valley, at least since the mid-1800s, have been winter floods—mostly associated with exceptionally intense AR storms. Because large amounts of winter and spring precipitation in the Sierra Nevada fall as snow and form deep snowpacks there, when in some years the snow melts and runs off quickly (Lundquist et al. 2004), springtime floods also are a part of Central Valley flow regimes. Because most springs have some snowmelt peak flows, high flows during the springtime snowmelt seasons are more reliably present, and probably a much more frequent driver of small to moderate flooding and biogeomorphic process in floodplains adjacent to the snowmelt-fed rivers.

3 Changes Leading to Modern Characteristics of the Central Valley River Systems

3.1 Levee and Dam Construction

During the past two centuries, major alterations to the rivers and floodplain systems in California's Central Valley have been made for flood management and to support agriculture, mining, logging, and urbanization, largely through the construction of levees and dams (Kelley 1989; Mount 1995). These changes altered sediment supplies to the downstream San Francisco Bay Delta (Wright and Schoelhammer 2004; McKee et al 2006), hydrologic and geomorphic responses to climate variability (Florsheim and Dettinger 2007; Florsheim et al. 2011), and the ecology (Sands 1977; Sommer et al. 2004) of floodplains and flood basins throughout the Central Valley.

Pervasive structural control of the rivers and floods was initiated as part of land reclamation efforts in the mid-nineteenth century when Euro-Americans began to exploit the region's many resources. Early efforts included attempts to keep even occasional small floods from inundating floodplains and flood basins. These attempts included filling crevasses in the natural alluvial levee system alongside main channels and tributaries, as well as progressive extensions of the length and height of these naturally formed low, alluvial levees (Kelley 1989). The land-reclamation efforts confined flood flows to the river channels to the extent possible, where previously they had spread over vast areas (Dettinger and Ingram 2013). As a result, and increasingly over time, flood basins and floodplains were separated from channels, impacting habitats that previously had sustained important floodplain-based ecosystems.

The attempt to concentrate flood flows into isolated main channels was made more difficult in the late 1800s by an overwhelming new sediment source, the addition of vast sediment loads to Sierra Nevada rivers by hydraulic mining for gold.

Hydraulic mining resulted in greatly increased sedimentation in the Sacramento River and tributaries draining the Sierra, raising the river-bed elevation at Sacramento by over 3 m between 1890 and 1900, reducing channel flood-conveyance capacities, and depositing sediment on farmed floodplain fields along tributaries such as the Yuba River (Gilbert 1917). The lowland floodplains also received large quantities of this sediment, e.g., as in the Sutter flood basin along the heavily mined Feather River (Jones 1967). An "anthropogenic" layer of sediment derived from the combination of hydraulic mining and coeval watershed scale agricultural disturbances averages 1.5 m thick on floodplains in the Sacramento flood basin near the confluence of the Mokelumne and Cosumnes Rivers (Atwater and Marchand 1980). This anthropogenic layer, consisting of a relatively coarse reddish-brown sandy clay layer, was rapidly deposited on the lowland Cosumnes River floodplain between 1849 and 1920 at a rate of about 25 mm/year, in contrast to the slower natural deposition rate of about 3 mm/year over the previous 1000 years (Florsheim and Mount 2003). Eventually the supplies of hydraulic-mining sediments were reduced so that after the initial significant rise, there has been a subsequent decline in sediment delivery rates over the past 150 years, leading to a change from excessive sedimentation to incision, a pattern documented on other heavily mined tributaries to the Sacramento River (James 1997).

Since in the mid 1850s, about 1600 km of levees along main channels and a series of overflow weirs leading to bypass channels have been completed in the Central Valley (DWR 2005; James and Singer 2008). For example, the Yolo flood basin was incorporated into the Sacramento River Flood Control Project as a bypass channel in the 1930s as an alternative to more widespread and damaging flooding by other adjacent and downstream parts of the Sacramento River (Sommer et al. 2001). Current river flows transport sediment downstream in leveed channels and inhibit sediment storage or erosion off-channel except in cases of occasional levee breaks, accidental or intentional (Florsheim and Mount 2002). Because of the efficient routing of sediment through the main river channels, the amount of sediment yield from the Sacramento and San Joaquin River systems has progressively declined since the cessation of hydraulic mining in the late 1800s and increased trapping of sediments upstream of dams built to store water in Central Valley tributaries since the mid-twentieth Century (Schoellhamer et al. 2007). Because these levee systems separate floodplains from channels, there have been significant losses of riparian wetlands that once functioned to delay and dissipate flood peaks.

Today, geomorphic processes in the Central Valley are driven by a population of floods reflecting this modified channel system, no longer reflecting the natural mix of floods and ecosystem processes. Nevertheless, some components of the hydrologic system are unchanged. For example, the largest ARs still cause large floods throughout the Central Valley, creating the highest magnitude and longest duration floods, albeit not always as large as they would have been in the natural system. Other more frequent and (generally) less intense floods have been largely restricted from reaching and modifying much of the landscape beyond the embanked river channels. Thus, the magnitude, frequency, durations, timing, and connectivity characteristics between channels and floodplains are now different from those characteristics prior to anthropogenic changes. For example, flood basins, such as the Yolo, that once were routinely hydrologically connected to the main Sacramento River now are primarily operated as flood bypass channels to shunt flood flows out of the main Sacramento River channel to reduce downstream flood stages and risks. Flood basins are regularly dredged to maintain flood conveyance (Singer and Aalto 2009). In Willow Slough, a creek draining eastward to the Yolo flood basin from the Coast Ranges, winter-spring floods once drove essentially all geomorphic changes, and low- to no flows and drought prevailed each warm season. Today, by contrast, irrigation flow diversions ensure that flow persists throughout the dry season. Along with channelization and levee construction, hydrologic alteration contributed to transformation of the transport-limited depositional system to an erosional and transport dominated system where small spring floods are contained in incised channels (Florsheim et al. 2011). Spring snowmelt floods from the Sierra, which once were a significant flood and geomorphic driver, now occur earlier (Stewart et al. 2005) and are most often contained within levees. Moreover, their influence on geomorphic processes is expected to diminish in the future as global warming further reduces the snowmelt and springtime flows further (Knowles and Cayan 2004).

3.2 Levee Breaks as the New Dominant Process of Geomorphic Change

Although snowmelt floods would often overtop or circumvent the low and discontinuous natural levees of the past, in the modern embanked system, levees are higher and more complete, and the mix of floods that impact both levees and floodplain geomorphic (and ecologic) processes has changed. One consequence of these changes is that, in the embanked Sacramento-San Joaquin River system, levee breaks and associated processes appear to have become the dominant process of geomorphic change.

Certainly, geomorphic processes in twenty-first century California operate on a landscape dominated by levees and dams, and while not all levee breaks have been catastrophic, they remain frequent in the Central Valley—occurring during a quarter of years in the twentieth century (Fig. 3; Florsheim and Dettinger 2007). Historical records indicate that climate and flood variability govern these unintentional levee breaks, even now. A review of the timing of 128 well-reported (unintended) levee breaks since 1951 (roughly when we can begin to differentiate between ARs and other flood mechanisms) indicates that, in today's embanked system, 81 % of levee breaks along Central Valley rivers occurred during floods generated by wintertime ARs, with only 15 % occurring during snowmelt floods (Fig. 4). In the pre-development era, the mix, seasonality, and especially frequency of biogeomorphically significant flood flows and levee breaks was presumably quite different. In the pre-development era, floodplains presumably were inundated during more years, because floodplain inundation would (without modern levee systems) have been caused by snowmelt during many, if not most, springs, resulting in a more regular

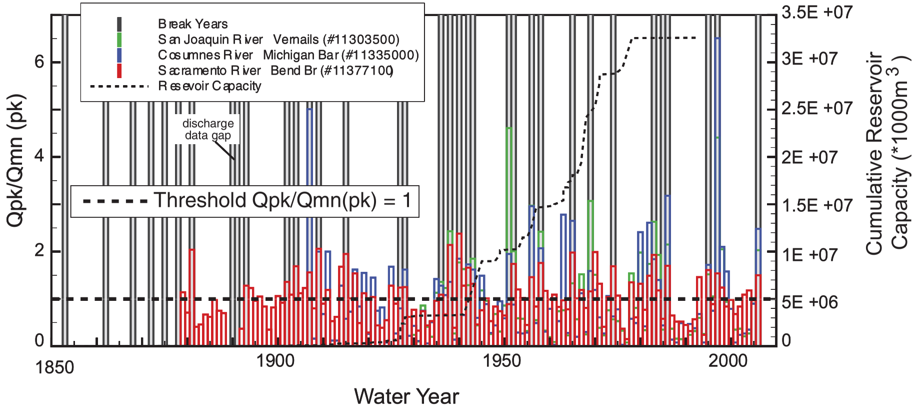

Fig. 3 Cumulative reservoir capacity and time series of $Q_{peak}/Q_{mean(pk)}$ showing variation at three gages within the Sacramento-San Joaquin River system. Gray bars indicate year when a levee break occurred within the system. Coincidence of break years and water years above the threshold $Q_{peak}/Q_{mean(pk)} = 1$ at at least one of the three gage locations suggest a strong system-scale relationship between levee break occurrence and climate variation. Adapted from Florsheim and Dettinger 2007

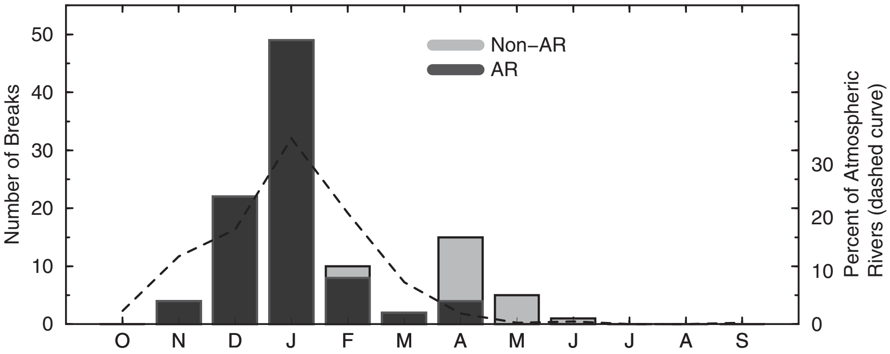

Fig. 4 Seasonality of 109 well-reported levee breaks on Central Valley rivers between 1951 and 2006, with indication of whether or not each levee break coincided with an atmospheric-river storm; *dashed curve* indicates average monthly frequencies (seasonality) of occurrence of all landfalling ARs in California (from Table 2, Dettinger et al. 2011)

"cycle" of inundations occasionally punctuated by very large wintertime floods, most often fed by ARs. Looking to the future, the mix of flood and geomorphic processes may change even more as global warming is currently projected to increase the frequency and magnitudes of ARs making landfall in central California (e.g., Dettinger 2011) while reducing the amount of snowmelt each spring (e.g., Knowles and Cayan 2004).

Unintended levee breaks are often damaging to economic assets, structures, and even human lives, and thus are generally viewed as extremely problematic. Furthermore, potential flood damage is not limited to humans. Loss of remaining vegetation and aquatic species during floods in constrained reaches where sediment deposits and large wood have already been removed can devastate struggling habitats. Thus alternative approaches to the use and design of levees, and to the management of storms and floods, may be in order. We provide two case studies as examples that illustrate the landscape-scale effects of intentional levee breaks and planned weir overflow on floodplain processes.

4 Examples of Intentional Levee Modifications and Management

Intentional levee breaks and planned weir overflows offer alternatives for river-floodplain flood management that may increase the capacity of the Central Valley lowlands to accommodate California's climate variability while providing direct biogeomorphic benefits. There are several examples of levee modifications for floodplain restoration along channels of embanked channels in the lowland Central Valley currently slated for intentional breaks or removal, e.g., in the Sacramento River National Wildlife Refuge: the Flynn and La Barranca Units in Tehama

County, and the Rio Vista Unit in Butte County (Kelly Moroney, Fish and Wildlife Service, personal communication 2012). Similarly, along the San Joaquin River, levee setbacks are under consideration as part of a program to restore floodplain flows to benefit fish habitats. Intentional levee modifications that allow flood flows onto floodplains provide an alternative management approach to achieve multiple goals including habitat restoration. The following describes two landscape-scale restoration projects that provide such benefits through intentional levee breaks and through planned weir overflow.

4.1 Cosumnes River Floodplain-Intentional Levee Breaks

A historical example of intentional levee breaks for floodplain habitat restoration comes from the Cosumnes River, a tributary draining the Sierra Nevada and entering the Central Valley near where the Sacramento and San Joaquin River join. Several agencies and nongovernmental organizations partnered to create intentional levee breaks, by excavating gaps in the levees, along the Cosumnes almost 20 years ago. In its natural state, the lowland reaches of the Cosumnes River were a distal part of the Sacramento flood basin (see Fig. 2; Gilbert 1917; Bryan 1923) with multiple-channel anastomosing river processes (including avulsion and deposition of crevasse splays and seasonal overbank floods) being the dominant geomorphic processes of floodplain deposition (Florsheim and Mount 2003). Flow in the Cosumnes River occurs mostly between October and May with the majority of the precipitation falling as rain. The lowland part of the Cosumnes River was a good location for a levee break restoration project because no large upstream dams are present on the Cosumnes to modify its hydrograph from natural regimes, thus allowing floodplain inundation during floods. Levee breaks constructed in 1995 and 1997 reestablished hydrologic connectivity between the Cosumnes River and its floodplain, allowing for ready inundation of previously farmed floodplain fields.

Of biogeomorphic interest, the levee breaks allowed sediment and large woody material to be transported onto the floodplain during floods. Floodplain inundation enhanced dynamic geomorphic processes such as erosion of the floodplain (near the constructed levee break) and down-floodplain deposition of sand splay and channel complexes that enhanced floodplain topography. That topography, in turn, enhanced habitat diversity (Florsheim and Mount 2002). Subsequent overbank flows that inundated the floodplain yielded a dynamic prograding system where sand was eroded from upstream parts of the splay and deposited at the distal end. Over the past decade, vegetation that preferentially established on the slightly higher elevations of the sand splay has thrived, and splay complex channels have become more defined as subsequent floodplain flows eroded, transported, and deposited sand (Fig. 5). These are precisely the kinds of changes needed to reinvigorate and support diversity in the Cosumnes floodplain ecosystem. The greater connection of the river to floodplain is also likely to provide a natural form of flood-risk amelioration downstream river reaches.

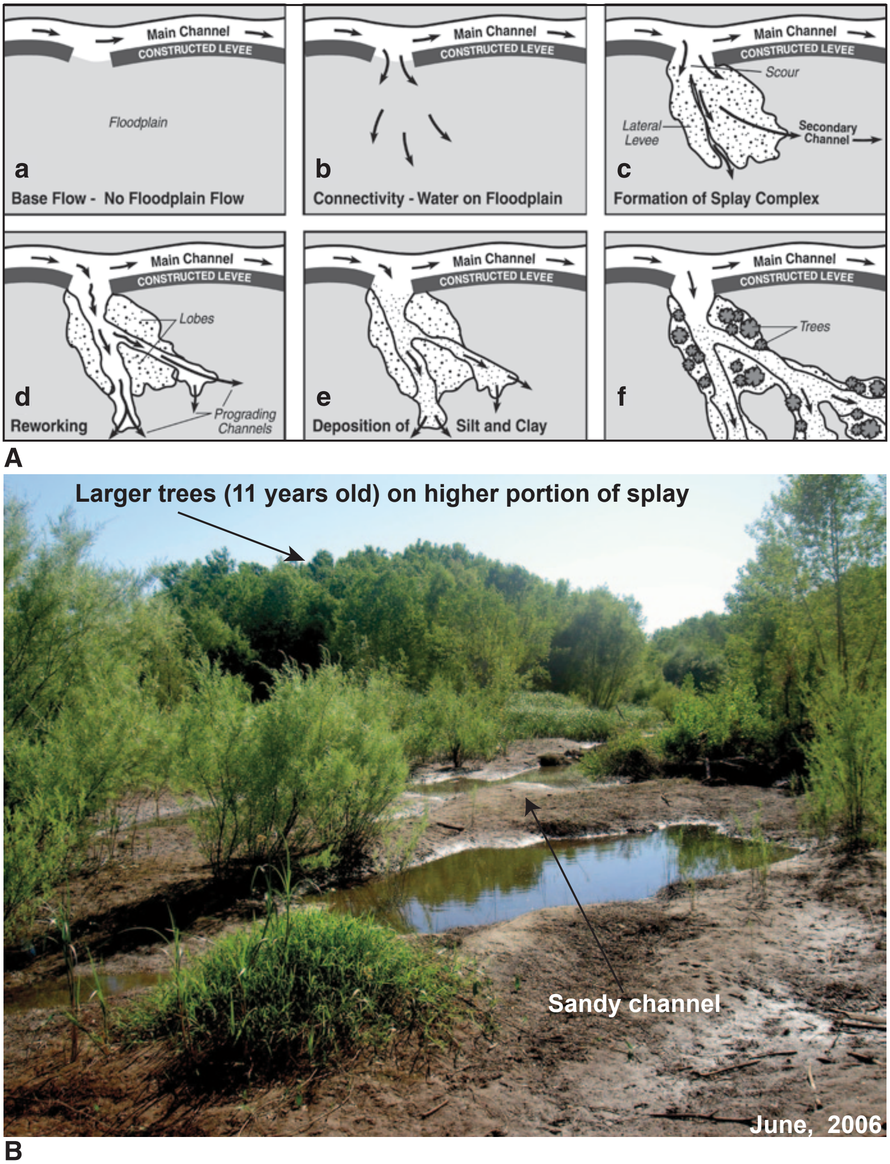

Fig. 5 A) Schematic of development of sand splay and channel complex on the Cosumnes River. **a** Low flow in main channel, **b** Connectivity of water from channel to floodplain, **c** Connectivity of bedload sediment from channel to floodplain and initial deposition of sand splay, **d** Continued or subsequent overbank flow that reworks sand splay and progrades channels, **e** Deposition of fine silt and clay as water recedes, **f** Establishment of riparian trees on higher portions of sand splay. Adapted from Florsheim and Mount 2002. B) 2006 Photograph looking down sandy splay channel at trees on splay

Analysis of the interaction between hydrology and geomorphic changes on the floodplain during the first eight years after the breaks were constructed (in 1995) suggested that the threshold for floodplain inundation (Q_c) was ~23–25.5 m^3/s (recurrence interval of ~1–3 years) and the threshold for bedload sediment transport from the main river through the break onto the floodplain was about 100 m^3/s (Fig. 6; Florsheim and Mount 2002; Florsheim et al. 2006). Finer silt and clay suspended in flows entering the floodplain through the break were deposited on the splay as flows receded. The number of days when flow (Q) exceeded the thresholds for hydrologic connectivity and for bedload sediment connectivity between 1995 and 2003 are illustrated in Fig. 7. During the first 6 years after the levee break, from 1995 to 2000, both flow and sediment connectivity occurred, whereas 2001 was a drought year, with limited connectivity. Conditions from 2002 to 2003 were also relatively dry—flows exceeded the threshold for flow connectivity, but were below the threshold for connectivity of sediment that moved on the floodplain as bedload. These observations show a high degree of climate-caused geomorphic variability, with water year 1997 being one of the wettest years and 2001 being one of the driest years of the century. However, the variability illustrated by this short-term record is representative of California's climate that Central Valley floodplain ecosystems had once been adapted to. This short-term variability did not hinder restoration of geomorphic processes needed to re-establish floodplain topography or provide substrate requisite for establishment of riparian vegetation. More work is warranted to answer questions about the likely trajectory that today's floodplain restoration projects will take over the long-term under current inundation duration and frequencies, or to answer questions about what inundation magnitude and frequency will be optimal for ecosystem sustainability.

To place the effects of the intentional levee break on the Cosumnes into a longer term perspective and to assess the role of atmospheric rivers there, we evaluated daily flow records from the Cosumnes River at Michigan Bar since 1930 (USGS gage #11335000) in terms of the historical occurrences of flows sufficient, given the recently intentional levees breaks, to result in river-floodplain flow connectivity (requiring flows $Q > Q_c$ or 25 m^3/s) and sediment connectivity (requiring flow $Q > 4Q_c$ or 100 m^3/s). Figure 8a shows historical seasonality of flows above these thresholds. Flow connectivity would have occurred—and will now occur—often in winter and spring, on average 16% of days during the year, whereas bedload sediment connectivity would have occurred more intermittently and mostly in winter, during 2% of days. A survey of meteorology (not shown in Fig. 8a) on days with flows surpassing the sediment-connectivity threshold, since water year 1950, indicates that AR storms initiated the historical floods greater than the sediment-connectivity threshold on 61% of the 88 historical occasions when connectivity lasting more than 2 days would have been established, and on 69% of the 56 occasions when connectivity would have lasted more than 3 days. Thus, sediment connectivity would have been (and will presumably continue to be) dominated by floods initiated by the arrivals of landfalling AR storms. Smaller floods, below the threshold of bedload sediment connectivity, are much more diverse in their meteorological origins.

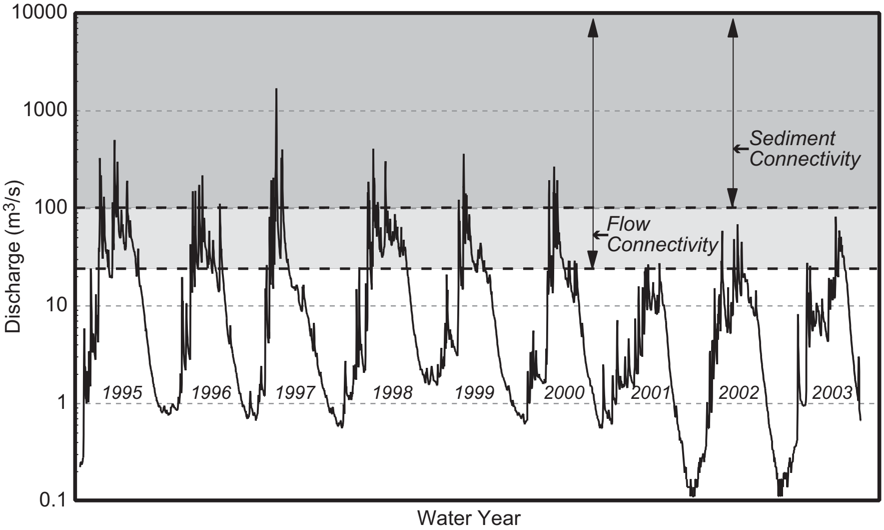

Fig. 6 Hydrograph from 1995 through 2003 showing thresholds for flow and sediment connectivity. Channel-floodplain flow connectivity occurred in all years, but sediment connectivity only occurred during 1995–2000. Adapted from Florsheim et al. 2006

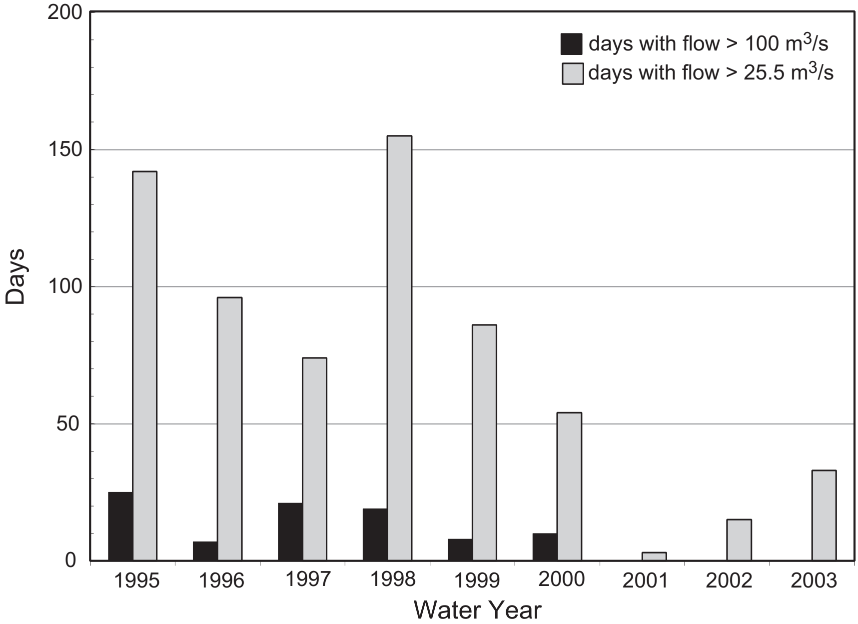

Fig. 7 The number of days when flow (Q) exceeded thresholds for hydrologic connectivity ($Q/Q_c > 1$ corresponding to 25.5 m³/s) and sediment connectivity ($Q/Q_c > 4$ corresponding to 100 m³/s) illustrated after intentional levee break for years between 1995 and 2003. Adapted from: Florsheim et al. 2006

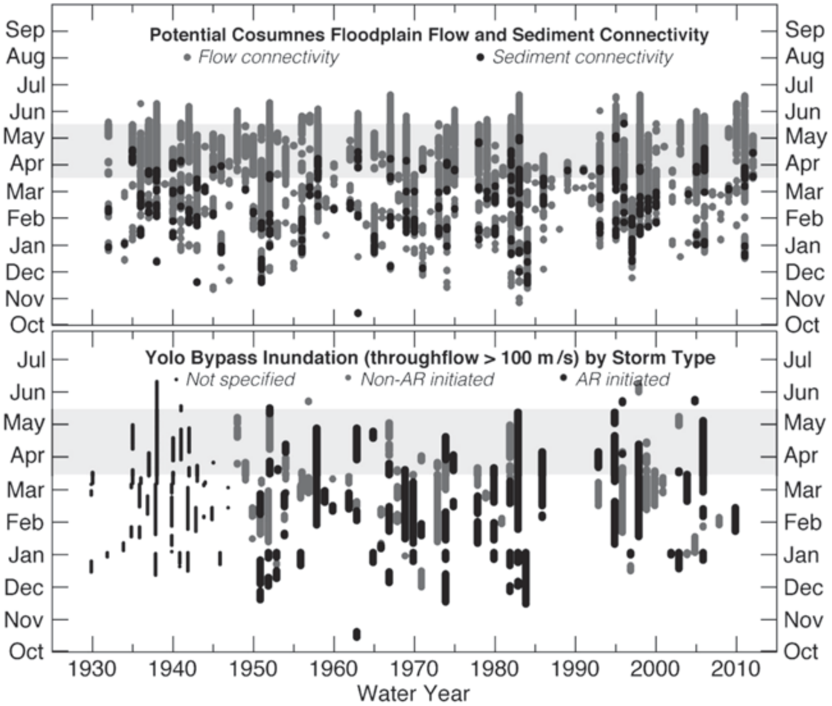

Fig. 8 **a** Timing and duration of Cosumnes River potential floodplain flow and sediment connectivity, under the scenario that existing levees that deter overbank flow had not been constructed, **b** Timing and duration of inundation of Yolo Bypass by day of year and water year, along with an indication of whether the inundation was initiated with an atmospheric-river storm (since 1948). *Pale gray band* indicates the March 15 and May 15 season of greatest floodplain-ecological benefit for fish (identified by Williams et al. 2009)

4.2 Yolo Bypass Floodplain-Weir Overflow

As a second example of intentional levee modifications, in the 1930s, the Yolo Bypass project was implemented on the western side of the Sacramento River, in a portion of the area formerly occupied by the Yolo flood basin on the opposite side of the Sacramento River from the Cosumnes system. Since 1997, about 25 % of the bypass has been converted to wildlife restoration areas compatible with flood control. The frequency and timing of Yolo Bypass inundations is critical to floodplain ecosystems there. Sommer et al. (2004) suggested that channel-floodplain connectivity supports rapid production in lower trophic levels in the restored Yolo system. Williams et al. (2009) suggest that a particular timing of spring floods, between March 15 and May 15, and inundation durations of at least seven days are required to activate and sustain key floodplain functions that support fish.

Sommer et al. (2001) summarize the complex hydrology of the system, noting that water inundating the low lying flood basin is derived from diverse sources, the most immediate being from the Sacramento River at the Freemont Weir, a passive weir that allows overflow from the Sacramento River over and onto the Yolo Bypass once the river exceeds a stage threshold, Qc (above 9.2 m NGVD). Water first enters the Yolo Bypass in the "toe drain," a small channel with capacity of ~ 100 m^3/s, and then, as stage rises, water spreads out to inundate the Yolo Bypass floodplain. Floodplain flows are augmented by water from local tributaries draining the Coast Ranges, including Cache Creek, Willow Slough, and Putah Creek. As an illustration to show how the Yolo Bypass functions as a flood-control mechanism, in 1999, flood flow in the main channel of the Sacramento River was kept below its 3100 m^3/s design flow by diversion of 1350 m^3/s onto the Yolo Bypass floodplain (Sommer et al. 2001). In addition to farmed areas within the bypass area, there are broad native habitats including wetlands, riparian, ponds, and uplands that are supported by flood flows greater than Qc.

A long-term perspective on the frequency, timing, and causes of these ecologically beneficial inundations of the Yolo Bypass can be obtained through analyses of histories of daily flows through the Bypass and of daily Central Valley outflows with and without management, based primarily on flow estimates from the California Department of Water Resources DAYFLOW Program (http://www.water.ca.gov/dayflow/; see Knowles 2002). The Program regularly estimates daily flow discharges in many parts of the Central Valley from observed flows and observed and modeled reservoir releases and water diversions. These estimates allow identification of occasions when the Yolo Bypass has been inundated since 1930. Combined with a 21-year set of records of upstream reservoir releases from the National Weather Service (NWS) California-Nevada River Forecast System, Knowles (2002) was able to further estimate the effects of modern water management on high flows that inundated the floodplain in the Yolo Bypass during the 1967–1987 sub-period.

Historically, the DAYFLOW estimates indicate partial inundations of the Yolo Bypass (> 100 m^3/s into the toe drain) on 2030 days from 1948–2010. During that period, a survey of various meteorological sources (e.g., as in Dettinger et al. 2011) shows that 66 % (1348 days) of those days occurred as part of floods that were initiated by AR storms. Figure 8b illustrates the timing and duration of such inundations since the early 1930s, along with indications of which inundations were initiated by ARs and which were not (since 1948). Of greater ecological concern, 68 % of all inundations (in the 1948–2010 period) lasting longer than 7 days, and 76 % of all inundations lasting longer than 28 days, were initiated by AR storms. Notice (in Fig. 4) that ARs most commonly arrive in California in winters, centered on Januaries, whereas Williams et al. (2009) argued that inundations between March 15 and May 15 were of greatest ecological benefit (pale gray band in Fig. 8). Nonetheless, because inundations associated with large ARs are so frequently long lasting, even in the March 15-May 15 season, 77 % of inundation days are parts of episodes initiated by ARs. Thus, even though AR storms are predominantly initiated during the winter months, in California the duration of inundation caused by ARs is sufficiently long lasting that they remain the dominant climatic factor governing Yolo Bypass floodplain-ecological benefits. In several ways, then, inundations, and especially ecologically important inundations of the

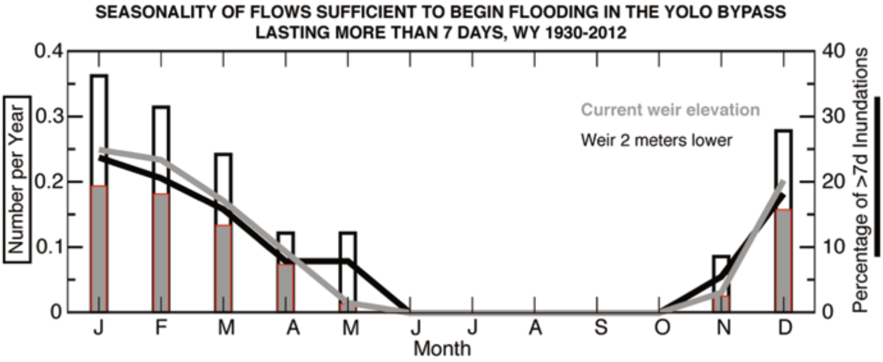

Fig. 9 Numbers (*bars*) and fractions (*curves*) of occasions when Sacramento River flows at Verona (USGS gage #11425500) were sufficient for overtopping the Fremont Weir that controls inundations of the Yolo Bypass floodplain, with the existing weir (*grays*) and for a hypothetical case of a weir height 2 m lower (*black*), from October 1929 through September 2012

Yolo Bypass floodplain, are overwhelmingly initiated, in the modern era, by AR storms and their attendant floods.

Human interventions and modifications of the rivers of the Central Valley have changed the role of these AR storms as initiators of sustained Yolo Bypass floodplain inundations from their likely role in the prehistoric past, in various ways. Locally, inundations of the Yolo Bypass are often determined by flows at Fremont Weir on the Sacramento River at the northern end of the Bypass. Flooding in the Yolo Bypass floodplain currently begins when the Sacramento River discharge at the Fremont Weir, which is upstream from the USGS Sacramento River at Verona streamflow-gaging station, exceeds 1585 m^3/s. Figure 9 compares the numbers and seasonalities of historical flows sufficient to initiate inundations (occurrences of flows greater than that threshold for overflow of the Fremont Weir) that lasted more than seven days, under current structural conditions at the Fremont Weir and under a hypothetical alternative configuration intended to (broadly) represent an intentional partial break or lowering of that weir. Gray bars and the gray curve in Fig. 9 correspond to the numbers and seasonalities, respectively, of occasions when that flow rate was exceeded for more than seven days in a row since October 1929. The black-edged bars and black curve in Fig. 9 correspond to numbers and seasonality of occasions when the flow rates exceeded ~1039 m^3/s for more than 7 days in a row; this lower flow rate corresponds to a river stage that would be needed to overtop the weir if it was 2 m lower. The bars indicate that, if the weir preventing the river from flowing into and through the Yolo Bypass historically had been 2 m lower, the Bypass would have received inflows twice as often (all other things being equal). Perhaps as importantly, the seasonalities of inundations indicated by the curves in Fig. 9 show that the weir reduces inundations disproportionately during springs, a time of year when Sommer et al. (2004) and Williams et al. (2009) have argued inundations are of particularly high ecological value. We have not specifically

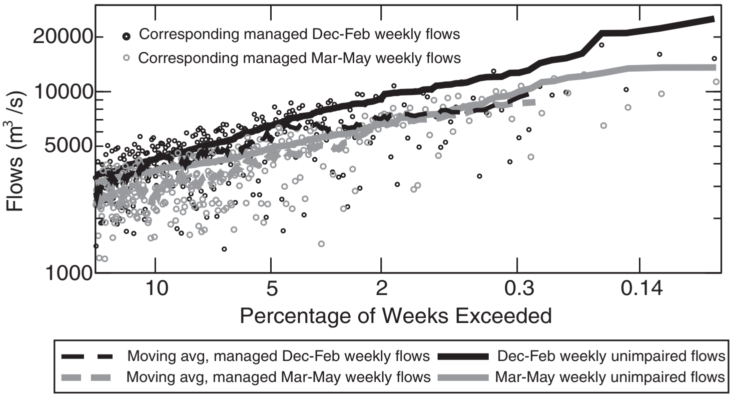

Fig. 10 Estimated exceedence probabilities (*solid curves*) of unmanaged 7-day average outflows from the Central Valley, above the Sacramento-San Joaquin Delta, in winters and springs, 1967–1987, with corresponding managed-flow estimates as *circles*, as based on time series from Knowles, 2002. *Dashed curves* are moving averages of circles, showing the 20-episode average managed flows around each level of unmanaged flow rate

separated snowmelt from atmospheric-river floodplain inundations in Fig. 9, but seasonality of effects of the weir (with largest reduction in the fraction of inundations happening in May when atmospheric-river storms are less common; dashed curve in Fig. 4) suggests that the local levee-weir structural control on Bypass inundations probably has preferentially reduced the opportunities for snowmelt-fed floodplain inundations compared to inundations caused by wintertime, often atmospheric-river storms.

On the larger scale of flow management in the Central Valley, river discharges and floods have been modified considerably with the introduction of hundreds of dams and diversions upstream from lowland floodplains like the Yolo Bypass. To understand some of the influences that these upstream controls have had on inundations at the Bypass, the daily estimates of Central Valley outflows, with and without reservoirs and diversions, at the high-flow end of a flow frequency diagram from Knowles (2002) are considered in Fig. 10. In Fig. 10, the solid curves are flow frequencies for the 7-day mean flows with upstream-reservoir effects removed (by Knowles 2002) during winter (black solid curve) and spring (gray solid curve). As discussed previously, the largest (natural) floods in the Central Valley are most often in winter with spring snowmelt peaks, on the whole, being smaller. For each 7-day flow comprising the solid curves in Fig. 10, there is a corresponding DAYFLOW estimate of the actual outflow from the Central Valley, inclusive of all the upstream-reservoir effects and diversions; these corresponding managed-flow values are plotted in Fig. 10 as the scatter of black and gray circles. Clearly, on many occasions historically, the managed outflows from the Central Valley have been larger than the unmanaged flows would have been, as water from various reservoirs and diversions has been added to the otherwise natural flow rates; on many occasions, water has been held back by reservoirs or diverted so that the managed outflows have been less than the unmanaged flows would have been. To determine the long-term net, the average effect of management on what would have been the highest outflows under natural conditions, a moving average was applied to the two (black and gray) clouds of dots. A comparison of the solid curves (unmanaged flood frequencies) with the resulting dashed curves (average of corresponding managed flood flows) shows that upstream management of 7-day flood flows during the 1967–1987 period reduced the largest winter flood flows just enough to make them just equal, on average, to the largest unmanaged springtime outflows. The management of springtime high flows, on average, did not reduce the outflows below the levels that would have been achieved under unmanaged conditions.

Although Fig. 9 showed that the local structural controls on inundation of the Yolo Bypass has disproportionately reduced the springtime snowmelt-fed inundations, at the larger scale of reservoir impacts on Central Valley flood flows more generally, reservoir impacts has left springtime flood flows more or less unchanged (on average) but has significantly reduced the largest wintertime flows. Thus at the whole-system scale of Central Valley outflows (of which the Sacramento River flows at Yolo Bypass are a large fraction), reservoir management has tended to de-emphasize wintertime floods, “starving” floodplains like the Yolo Bypass of those largest wintertime, and most often atmospheric-river derived, floods that the floodplains and floodplain ecosystems evolved under natural conditions to accommodate and indeed rely upon. A reduction of the Fremont Weir elevation, essentially an intentional partial levee break, would both increase the number of winter and springtime inundations towards somewhat more natural conditions, and could allow for more truly large inundations in winters (as in the natural state) along with an added emphasis on the ecologically crucial springtime floods.

5 Projected Geomorphic Response to Future Climate Variability and Change

As global warming progresses, winter floods increase, and spring snowmelt in Sierra Nevada progressively diminish, the historical tendency for winter inundations to be the most frequent and extreme inundations will likely be exacerbated (e.g., Knowles and Cayan 2004; Das et al. 2011). Under these circumstances, the nourishing floodplain inundations in the Central Valley may become more and more tightly interlinked with the most damaging floods. Alternative floodplain management strategies, including intentional levee breaks allowing easier and more frequent reintroduction of moderate flows onto the floodplains, especially from the remaining springtime snowmelt pulses, may be necessary to revitalize and even to sustain the Central Valley’s floodplain ecosystems and to better accommodate future flood-regime changes.

Recent climate-change projections for California suggest that the total volume of snowmelt runoff that might be shifted from spring and added to winter flows under some of the more modest projections of change is roughly 195 m^3/s, an amount similar to the total unfilled (free-board) volume currently held in abeyance in the major low-altitude Sierra Nevada reservoirs each winter for flood–capture and management. That is, the volume of additional winter flows projected under projections of modest warming (about + 2.5 °C warmer by midcentury; Knowles and Cayan 2004) is roughly equal to the amount of flood-control space currently maintained in Sierra reservoirs. Those additional winter flows will come at the expense of a reduction of springtime flows of nearly equal volume. Any modification of the timing of reservoir releases to accommodate these changes (e.g., any attempt to directly capture the "extra" winter flows, by reducing the free-board flood-control space) would likely add to either the magnitude or duration of winter flood peaks downstream from the major reservoirs, each causing different geomorphic responses. These additions would lead to increased overbank flow and flood extent and floodplain sedimentation and erosion in unconfined reaches.

These same increases in wintertime flows would increase flood flow depths and erodibility of the downstream flows, which could increase the risk of unintentional levee failures. Runoff released from reservoirs as a relatively constant addition to winter baseflow would increase the duration of bankfull or possibly "levee-full" flows. This scenario could lead to bank and levee failures through increased saturation and seepage erosion. Thus, geomorphic responses to future climate variation and change on floodplains will be closely tied to infrastructure and reservoir management policies established in recent decades and in the future to accommodate increased winter flows (and reduced spring and summer flows), with the survivability of infrastructure. Decisions about the future timing, magnitude, and duration of flow releases from upstream reservoirs under climate change are likely to determine the form of those geomorphic responses.

6 Conclusions

Major changes in the biogeomorphology of California's Central Valley river-floodplain system have resulted from human activities. Prior to the nineteenth century, the lowland system was characterized by natural levees alongside complex multichanneled rivers and tributaries. Flood basins, a characteristic landform of the Central Valley, were connected to the main river through multiple openings in the natural alluvial levees. Since then, more than 1000 km of engineered levees have been constructed and embanked the system, limiting connectivity between channels and floodplains and greatly reducing ecological attributes of the Central Valley. Despite construction of levees and other flood-control structures, climate and floods continue to cause unintentional levee breaks. Of concern, structural and management actions in the Central Valley have apparently, inadvertently given greater importance to the largest wintertime (dominantly AR) storms and floods, while reducing the roles of the usually less extreme but (prehistorically) more regular springtime snowmelt floods, in terms both of unintentional levee breaks and beneficial floodplain inundations.

We reviewed two examples from California's lowland Central Valley illustrating that intentional levee breaks and planned weir overflow designed for floodplain restoration along embanked lowland rivers can promote dynamic biogeomorphic processes. These alternative flood management approaches facilitate lowland river-floodplain flow and sediment connectivity that allows morpho-dynamic processes needed for ecological functions to be restored and sustained. Setting aside space on lowland floodplains and intentionally engineering levee breaks or lowering weirs promotes floodplain biodiversity by accommodating both the smallest over bank floods that would occur frequently as a result of a range of climate conditions such as rainfall and snowmelt, as well as the largest AR floods that exceed thresholds for sediment and water connectivity that would occur primarily in the fall and winter. Moreover, AR storms during fall and winter are responsible for a large proportion of the longest duration floodplain inundations and, because of their long durations, they are the initiators of most of the long springtime inundations that provide the most ecological benefits of floodplain inundation in the Yolo Bypass restoration. Therefore, flood management approaches that anticipate and accommodate the special role of AR floods may help to achieve more natural hydrologic and biogeomorphologic regimes.

Future climate-driven changes in flood regime, such as enhanced flooding during winter months or more frequent atmospheric rivers, need to be considered in planning for floodplain restorations and management, and might be accommodated by additional intentional levee breaks or planned weir overflow for restoration. Expansion of such approaches could improve restoration policy and management of floods in embanked river floodplains.

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Geomorphic Perspectives of Managing, Modifying, and Restoring a River with Prolonged Flooding: Kissimmee River, Florida, USA

Joann Mossa

Abstract The lower Kissimmee River in central peninsular Florida, southeastern USA, has been through multiple transformations. Historically, aquatic biota thrived in this lowland floodplain with multiple channels, sloughs, ponds, and inundated prairies that experienced prolonged flooding with overbank conditions for several months annually. The quest to drain land and reduce flooding inspired early modifications including some artificial cutoffs and dredging in the 1880s, and channelization of the lowermost 10.4 km of the river in the 1930s. More flooding resulted in a project, done largely in the 1960s, which altered the 1–4 m deep river into a straighter, 9 m deep canal known as C-38 with a much larger channel capacity and six dam-like control structures with locks that support navigation. While a success at reducing flooding, the project caused an immediate and drastic ecosystem response. Environmental and political efforts led to a restoration, which began in the late 1990s, has been progressing in phases and is due for completion by 2016 or thereabouts; it involves backfill of C-38 with dredge spoil from the original project, sending flow back through channels that had been stagnant for decades, creating new channels across backfilled C-38 known as connectors, recarving channels through spoil-filled portions of the floodplain, and removing two of the six control structures. The purpose of this chapter is to provide a geomorphic perspective of the management of this very distinctive river, manifest by the quest to modify through its different phases and transitions. Historic aerial photography, cross-sectional discharge measurements, and hydrologic data provide a basis for interpreting the flood regime and geomorphology of the system prior to drastic modification, and during channelization. The canal was much wider and deeper than the original main channel and low flows became much more prevalent. Some of the connectors had larger cross sections than the original channels, and field surveys showed that these had the most geomorphic adjustment. Sediment cores show thick accumulations of fines and organic sediments in the bottom of remnant channels that were inactive for decades and clean sand on the bottom of the channels where flow was restored. Geospatial data suggest that sand bars might be larger than historical predeces-

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sors. A comprehensive geomorphic overview of the system gives insights into how restored portions of the river are like and unlike the river prior to channelization and some challenges and unanswered questions regarding the hydrology, geomorphology, and sediments of a system in transition.

Keywords Fluvial geomorphology · Channelization · Restoration · Channel change · Flooding · Historical analysis

1 Introduction

Large numbers of the world's major rivers have been dammed or channelized (Dynesius and Nilsson 1994; Nilsson et al. 2005; Gregory 2006), disrupting longitudinal connectivity and changing the magnitude, duration, timing, and frequency of water flow (Nilsson et al. 2005; Poff et al. 2007). The rationale for these alterations is typically to obtain better control of flow for flood control, navigation, water supply, irrigation, recreation, and other purposes. However, fragmentation of the system, homogenization of flows (Poff et al. 2003), and alteration of channel planform, cross-section, and profile have caused changes in sedimentation and sediment supply, impacts to water quality and chemistry, decreased species diversity (Moyle and Mount 2007), increased biological invaders (Johnson et al. 2008), and brought other unintended consequences.

The effects of channelization and dams extend beyond rivers to adjoining floodplain by disrupting longitudinal and lateral connectivity (Kondolf et al. 2006). Floodplains are an important part of the river corridor, providing flood storage, adding roughness that results in velocity reductions, sequestering carbon, trapping sediment and nutrients, and performing other physical functions. Aquatic biota use floodplain habitats for nurseries. Due to the proximity and availability of water, floodplain habitats also have an abundance and diversity of flora and fauna.

In recent decades, especially in developed countries, due to increasing recognition of the value of these hydrologic and ecosystem functions and productivity, significant funding (billions of USD) is being dedicated to river restoration or rehabilitation (Bernhardt et al. 2005; Malakoff 2004; Moreno-Mateos et al. 2012). The degree to which such altered ecosystems will recover in its structure and functioning from such efforts remains uncertain, which makes monitoring an essential component of these projects. Another important aspect is understanding the historical character of these modified rivers, as it is difficult to set targets or goals without knowing specifics of what was there prior to modification. In many cases, modifications date back a century or more, and there are limited historical data.

The lower Kissimmee River, in central peninsular Florida in the southeastern USA (Fig. 1) has been through multiple transformations. Quite unique in its prolonged flooding, experiencing overbank conditions for several months annually, aquatic biota thrived in this unique water-rich setting containing multiple channels,

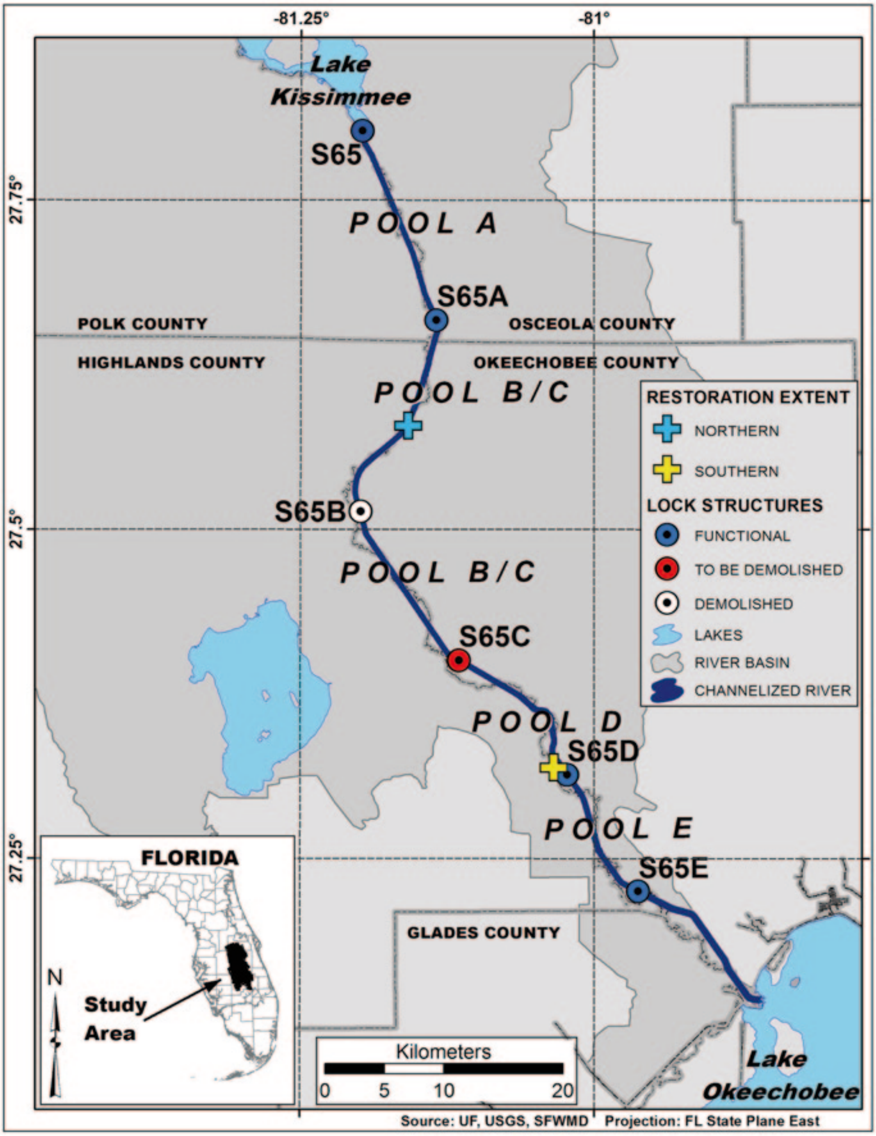


Fig. 1 Location of the Lower Kissimmee River, the historic main channel (*along county boundary*), the canal C-38 and associated water control structures and the zone of the river undergoing restoration

sloughs, ponds, and inundated prairies and lowlands. Following some lesser, but still noteworthy, modifications starting in the late 1800s, the U.S. Army Corps of Engineers channelized the 1–4 m deep river into a straighter, 9 m deep canal which was several times wider and emplaced six dam-like control structures and locks to control floods and support navigation in the 1960s. While a success at reducing flooding, the project caused an immediate and drastic ecosystem response. It then took several years to promulgate legally and financially, then plan and engineer a massive restoration effort.

The purpose of this chapter is to review some of the considerations and consequences in managing, modifying, and restoring this very distinctive river. First, the setting and early conditions of the Kissimmee River are reviewed, including its flood regime and geomorphology, and its relation to the historical development of Florida. Next, the impetus and rationale for channelizing the river are discussed, including the hydrologic and geomorphic changes, the ecosystem losses associated with the altered habitat, and the rally for restoration. Last, the restoration, which is nearing completion but still underway is examined, in particular the challenges and unanswered questions regarding the hydrology, geomorphology, and sediments of a system in transition.

2 The Historic Kissimmee and Changes Prior to Channelization

2.1 The Setting and Surroundings of the Historic Kissimmee

The Kissimmee River drains approximately 7804 km^2 of central Florida, and is part of the KOE (Kissimmee-Okeechobee-Everglades) system. The headwaters north of Lake Kissimmee near Orlando, Florida are at approximately 100 m elevation; the deranged, karst drainage of the upper Kissimmee is known as the Chain of Lakes and is comprised of sinkholes and lakes of various types (Kindinger et al. 1999). The lower Kissimmee River flows between two large lakes (Lakes Kissimmee and Okeechobee) in a low-gradient (0.07 m/km) trough formed in a late Tertiary setting modified by carbonate solution, subsidence (White 1970), and possibly isostatic uplift (Opdyke et al. 1984). Near Lake Kissimmee, historic lake levels typically varied between 14 and 17 m and at Lake Kissimmee and from 3 to 7 m at Lake Okeechobee (Anderson and Chamberlain 2005). Before channelization, the river was bordered by narrow levees of willows and wetland shrubs and a floodplain of broadleaf marsh, wet prairies, and live oak hummocks that flooded for weeks to months annually (Toth et al. 1995). Historically, the river supplied about one-third of the water entering Lake Okeechobee which in turn flowed into the Everglades when lake levels exceeded 5 m (Parker 1984).

The river and floodplain differ in many ways from rivers of comparable size (e.g., Koebel 1995; Warne et al. 2000) and some characteristics are listed in Table 1. Compared with other rivers, the historic Kissimmee had a much lower slope than rivers with similar bankfull discharges (Warne et al. 2000). It was compared to the straight, meandering, and braided streams in Leopold and Wolman (1957), and thus may differ from these because it is an anastomosing river (Figs. 2 and 3). In terms

Table 1 Some geomorphic characteristics of the historic and channelized Lower Kissimmee River, a sinuous river with anabranches and a drainage area of. (Koebel 1995; Warne et al. 2000; Horan 2012; U.S. Geological Survey, Google Earth and Mossa, unpublished data)

Characteristic	Historic values or range	Channelized values or range
Cross section		
Bankfull channel width	15–45 m	55–180 m
Bankfull channel depth at thalweg	1–5 m	7–10 m
Width-depth Ratio	6–10	8–20
Floodplain width	1.5–3 km	No change
Channel planform		
Sinousity (primary channel)	1.6–2.1	1.0–1.2
Meander wavelength (primary channel)	90–400 m	N/A
Radius of curvature/width ratio (primary channel)	0.7–7.5	N/A
Channel slope		
Average gradient, upstream	0.09 m/km	0.16 m/km
Average gradient, downstream	0.057 m/km	0.10 m/km
Discharge		
Bankfull discharge (primary channel)	40–57 m^3/s	>300 m^3/s
Q-95th percentile	169.1 m^3/s	158.9 m^3/s
Q-75th percentile	69.4 m^3/s	51 m^3/s
Q-median or 50th percentile	44.5 m^3/s	14.4 m^3/s
Q-25th percentile	28.6 m^3/s	2.4 m^3/s
Q-5th percentile	11.6 m^3/s	0 m^3/s

of its at-a-station hydraulic geometry relations, the main channel of the pre-canal Kissimmee was narrower, deeper, and slower than rivers with similar mean annual discharges (Warne et al. 2000), perhaps again due to the challenges of comparing multichannel or anastomosing rivers in a system designed more for single-thread channels. Also, the extreme or peak flood discharge was about two orders of magnitude less than rivers of comparable basin area (Warne et al. 2000); some of the reasons include the low slope, and the constraints of the flow between two lakes, one upstream with limited outflow capacity and one downstream with limited reservoir capacity, resulting in backwater and slow drainage.

Not noted prior is that the apex of some Kissimmee meander bends have nearly circular pools (Fig. 3) observed by others in seven states across the U.S. Gulf and Atlantic Coastal Plain (Alford et al. 1982), and in wetland streams in New York and Connecticut (Andrle 1994; Jurmu and Andrle 1997), British Columbia and Australia (Nanson 2010). The pools are wider than intervening segments, lack point bar development and have thalwegs closer to the convex bank (Jurmu and Andrle 1997). Of the ten rivers where these features were described by Alford et al. (1982), they were most abundant in the Houston River, Louisiana, which had the lowest gradient (0.03 m/km) of the rivers examined, lower than the Kissimmee, which

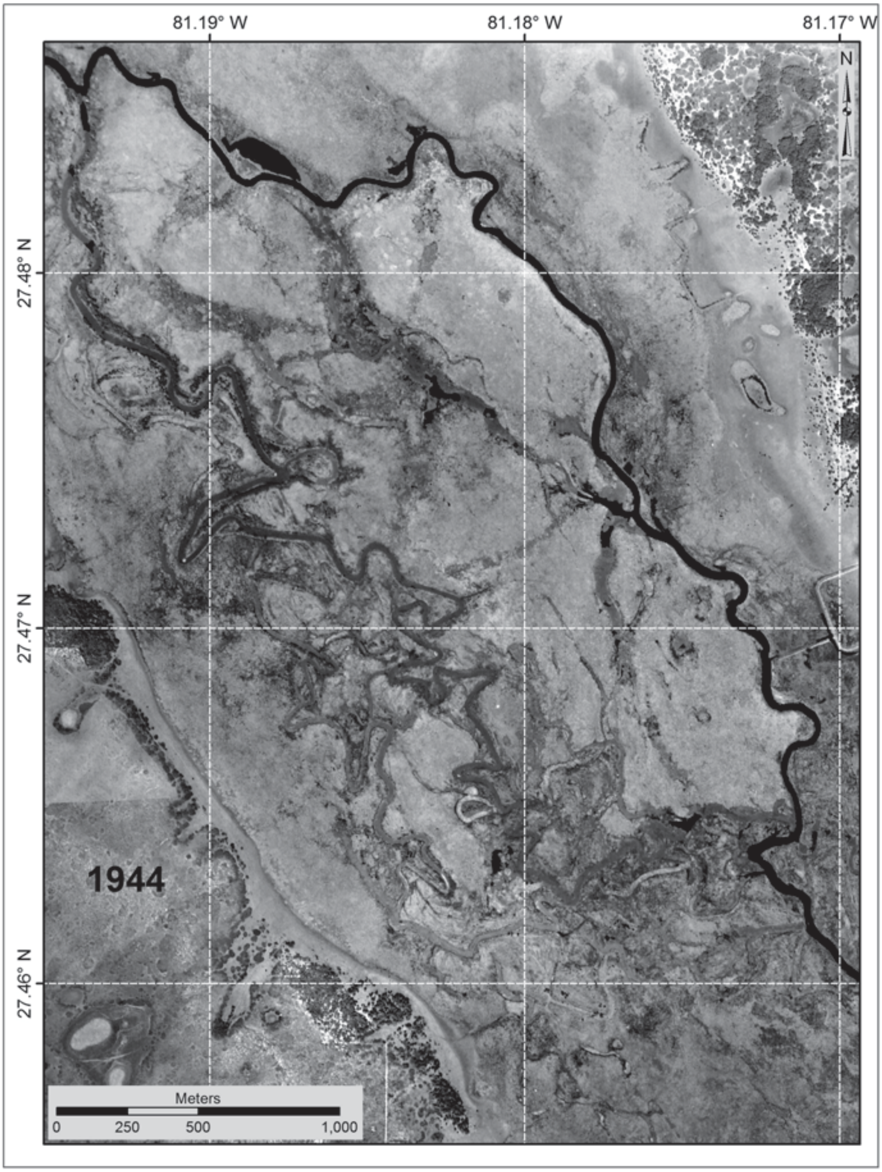


Fig. 2 Natural features of the Lower Kissimmee River and floodplain prior to channelization, including channel segments with anabranching and floodplain lakes, backwater features, and oxbow lakes. This section is located in Pool B/C and has been restored

in turn had a lower gradient than most other rivers with these pools. Benches on the concave banks might be associated with a countercurrent during floods (Alford et al. 1982) or during various flow levels (Andrle 1994). In a detailed study of one of these wetland streams in Connecticut, tight bends (low radius of curvature to

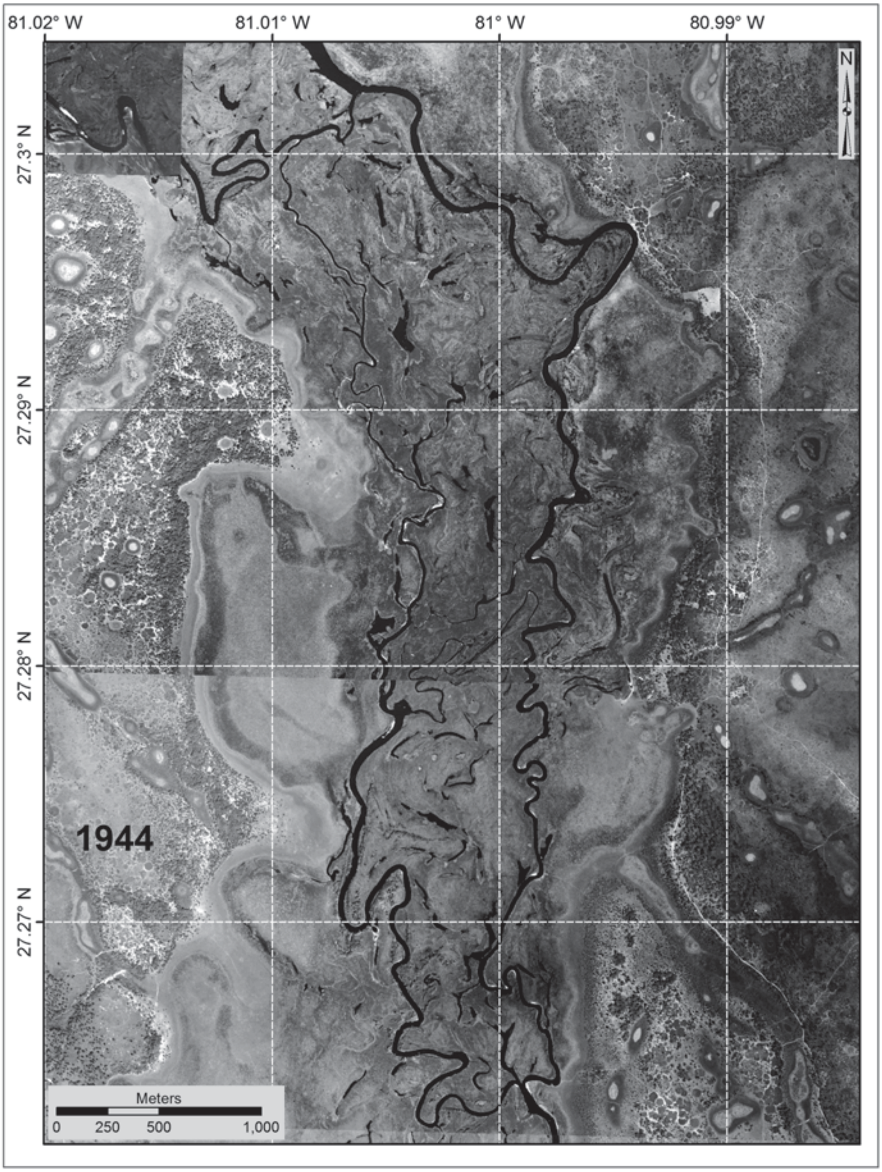


Fig. 3 Natural features of the Lower Kissimmee River and floodplain prior to channelization, including channel segments with anabranching and floodplain lakes, backwater features, clusters of oxbow lakes and circular meander pools in the central portion of the image. This section is located in Pool E and will not be restored

width ratio) and limited development of point bars on the convex banks of bends (Jurmu and Andrle 1997) also are typical of the Kissimmee.

2.2 Initial Transformations of the Historic Kissimmee

Compared to other eastern U.S. states, and the coastal areas of Florida, the inland portion of central Florida was slow to develop, in part due to the vast amounts of wetlands. Florida became a state in 1845, many decades later than the other eastern states, and was the 27th US state admitted to the union even though it was the first state explored by Europeans. Although it is currently recognized that wetlands, including riverine floodplains, are highly productive and economically valuable ecosystems (Costanza et al. 1997; Tockner and Stanford 2002), prevailing thought when Florida was first settled was that wetlands should be ditched and drained to become useful for agriculture and to minimize dangers from hurricane flooding (Meindl et al. 2002). Wetland drainage, combined with building railroads, roads, and population, resulted in a variety of hydrologic modifications which transformed the wet wilderness of central and southern Florida to a populous area with a diversity of land uses, including agriculture, urban, military, biodiversity, and water conservation (Gunderson and Light 2006).

One of the primary initial efforts to transform this area began in 1881, by Hamilton Disston, a Pennsylvania industrialist, who bargained with the state of Florida to receive half of the wetlands he drained in south and central Florida. By deepening and straightening the Kissimmee River, and by constructing canals connecting the various lakes that formed the headwaters of the river, Disston then sold the lands to ranchers in the 1880s (Godfrey and Catton 2011). Dredging, clearing, and snag removal were performed to maintain navigation, and cutoffs were made at an unknown number of sinuous meander bends, described in 1899 by Henry Jervey, Captain of the Corps of Engineers (Mueller 1966; Bousquin et al. 2005; Warner 2005). By 1883, Disston's engineers reported that lake levels in the upper Kissimmee River dropped by 0.8 m (2.5 ft), and Lake Okeechobee by 0.45 m (1.5 ft), but this coincided with a dry cycle. It was arduous work with multiple obstacles. When Disston died in 1896, his efforts fell short of his goal, but resulted in 40,000 ha (100,000 acres) drained and a marked imprint on both the Kissimmee and the Everglades.

Early historical maps (Butler 1845) dating back to the establishment of statehood show the Kissimmee River was the dividing line between adjoining counties. The county boundary thus records where the river was at that time, thus it can be used to interpret how the river changed in subsequent decades. Historic aerial photographs, which show the river in the 1940s, show some areas where the county boundary and river do not coincide, possible areas where Disston made artificial cutoffs in the 1880s. The river was surveyed in some detail in 1901 (US Army Corps of Engineers 1902), and channel maintenance was authorized in 1902 specifying that the channel from Kissimmee to Fort Basinger, about 160 km (100 mi), be maintained a minimum of 10–20 m (30–60 ft) wide and 1 m (3 ft) deep at low water (Godfrey and Catton 2011). This probably only resulted in some areas being altered, as much of the river probably already met these specifications.

2.3 Historic Floods and the Quest for Flood Control

More drainage led to reclamation then agricultural expansion, especially near Lake Okeechobee. Low dikes around the lake were breached during the Miami Hurricane of 1926, and again during the Okeechobee hurricane of 1928 which resulted in the deaths of over 2000 people, mostly migrant black laborers (Eliot 1928; Blake 1980). After these disasters, engineering became more sophisticated and involved federal assistance. Completed in 1938, the Hoover dike surrounding Lake Okeechobee protected surrounding lands from waters less than 10 m (33.5 ft) in height and facilitated drainage. The $ 16 million flood control project included floodway channels, canals, control gates, and channelized 10.4 km (6.5 mi) of the lowermost Kissimmee River.

Between 1944 and 1950, 11 hurricanes hit Florida, causing tremendous losses (Pielke and Landsea 1998). The worst year was 1947, during which two cyclones flooded 1.2 million ha (3 million acres) in central and south Florida for many months (Godfrey and Catton 2011). Thousands of cows died on the Kissimmee's floodplain ranches (Godfrey and Catton 2011). These events led Congress to authorize and task the Corps to manage flood and droughts for varied stakeholders (Derr 1989), beginning the quest to channelize the river.

Despite these early alterations, the Kissimmee retained most aspects of its rather unique hydrology and geomorphology, due in part to its topography and location between two large lakes. Photography from the 1940s shows the natural features of the Lower Kissimmee River and floodplain prior to channelization, including a multichannel pattern with varied floodplain lakes (Figs. 2 and 3). The sinuous and anabranching low-gradient (0.07 m/km) river had long-lasting floods, with some events exceeding bankfull stage for several months continuously (Koebel 1995; Toth et al. 1998, 2002; Warne et al. 2000). Floods were an important driver in establishing and maintaining an ecosystem rich in wetland plants, water birds, and aquatic biota. The sediment regime was less well known, but the presence of narrow sand bars and low natural levees suggests that erosion, transport, and deposition of sand were occurring. Because of the presence of point bars and "abandoned channels," Warne et al. (2000) inferred that there were "high rates of channel migration, cutoff, and avulsion in the pre-canal system." An alternative viewpoint, suggested here is that the narrow size of the historic point bars, the lack of ridge and scroll topography, and the coincidence of modern river boundaries on aerial photography with county boundaries established in 1845 suggests that the river was not highly migratory. There were, however, occasional cutoffs and changes in channel dominance in the multichannel pattern. Many of the features that Warne et al. (2000) characterized as abandoned channels were also active secondary channels that transported much of the discharge during the large floods of the historical river, shown by data from 1949 to 1950 (Fig. 4).

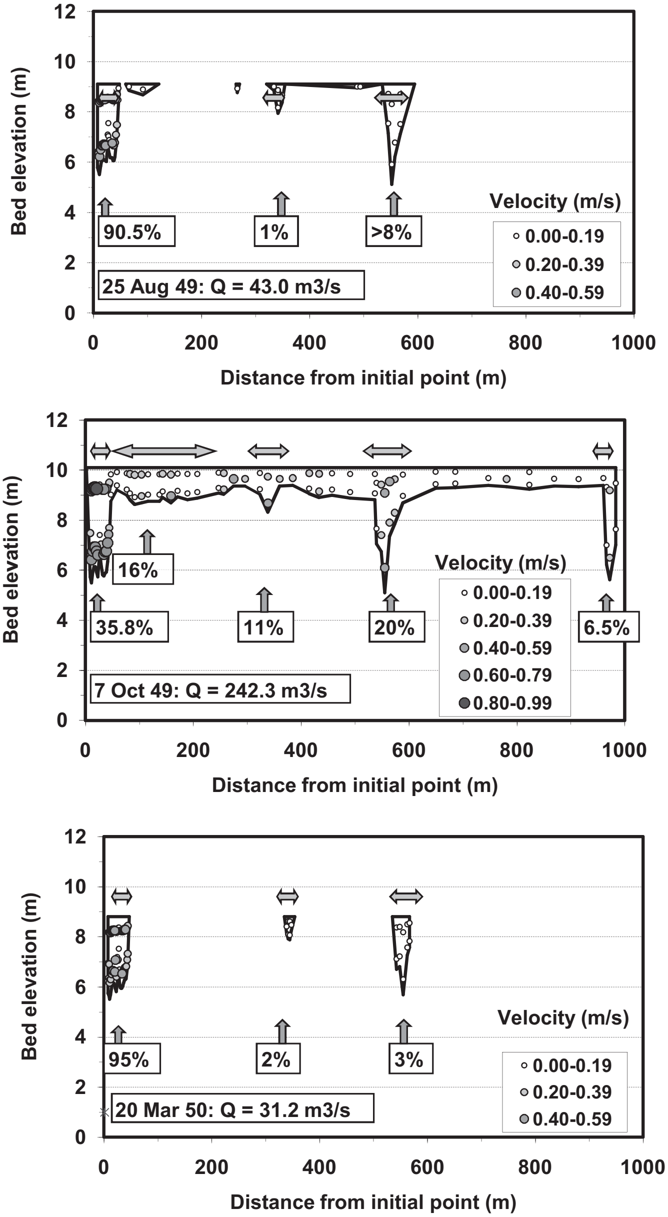


Fig. 4 Three discharge measurements during the 1949–1950 flood near Cornwell illustrate how the river was overbank for several months. In July 1949, the river was within its banks. August 1949 (*top*) shows overbank flows and flow in multiple channels at 43 m^3/s. In October 1949 (*middle*) near the flood peak, with at discharge of 242 m^3/s, about 36% of the flow is in the main channel. Several months later in March 1950 (*bottom*), the river is still flowing in multiple channels

3 Channelization

Despite much interest in flood control following the hurricanes in the 1920s and 1940s, no action was taken in the Kissimmee due to the lack of funds and more severe problem in South Florida. Three options suggested for controlling floods included levees, increasing channel capacity through channelization, and impounding reservoirs. Artificial levees would have to be spaced far apart to incorporate the anabranching channels, meaning that much of the channel complex would still flood and ranchers would have to deal with the potential consequences, and would also require a lot of clastic sediment of suitable quality. Because of the low gradient setting, impoundments would not be very effective at water storage and would inundate much of the floodplain, not providing the type of drainage desired. Thus, channelizing and creating a system with a much larger channel capacity best served the purpose. It took several years and political work to obtain funds, authorize the project, establish the local cost match, and engineering studies for the project to come to fruition.

Eventually, from 1962 to 1971, a canal named C-38 was built through the floodplain as part of a comprehensive project to control water and wetlands of central Florida, which left portions of the original channel intact and obliterated others (Figs. 1, 5 and 6). Six gated water and grade-control structures with locks were placed along the course, creating pools upstream of each structure. Dredging increased the width and depth of the river channel for navigation so that the channel was 9 m deep and 64–105 m wide (Toth et al. 1993), and the river was shortened from 167 to 90 km (Whalen et al. 2002) and its gradient was steepened in the process. The channelization modified natural water flow volume, hydroperiods, and hydropatterns as part of drainage and reclamation for agricultural use (Figs. 7 and 8), and in particular more frequent low flows (Table 1). Much of the river was not directly dredged but there were localized areas where the historic main channel was obliterated, covered or blocked with dredge spoil and the adjoining floodplain topography was changed. Yet, the project resulted in the loss of about several thousand hectares of wetlands; drastic declines in bird, fish, and other animal populations due to decreases in wetlands; and substantial reductions in water quality (Bousquin et al. 2005a; 2005b). Even before the channelization process was completed, various groups advocated for restoration of the river (Koebel 1995; Bousquin et al. 2005a).

Wetland habitat in the Kissimmee River Basin was degraded from the emplacement of water control structures and associated navigation locks, and more severely from channelization. Approximately 44 % of the riparian wet land was converted to pasture after channelization (Milleson et al. 1980). Estimates vary from 8000 to 14,000 ha of riparian wetlands were lost with the creation of the C-38 canal (Dahm et al. 1995; Koebel 1995; Toth et al. 1995, 1998; Bousquin et al. 2005a). In the river, the conversion of a shallow meandering river to deep stagnant pools resulted in minimal flow, dissolved oxygen, and impacted fish populations. Channelization led to major losses of small fish and game fish (Miller 1990) a 92 % decrease in wintering waterfowl on the wetland (Perrin et al. 1982). The project and the ac-

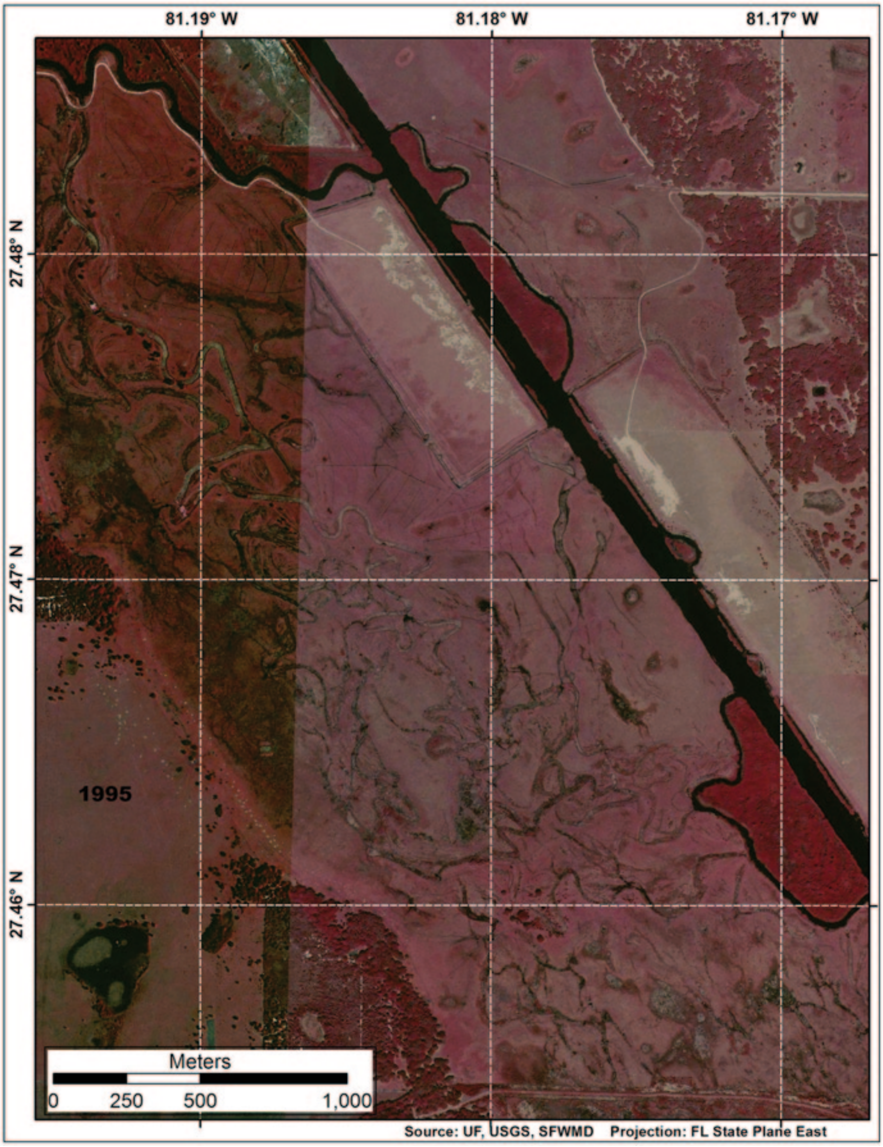


Fig. 5 Infrared photography from 1995 shows the canal C-38 and portions of the original channel. The canal is much wider than the historic channel when the river is within its banks. These figures also illustrate how different portions of the channel and floodplain were disturbed or obliterated by the channelization and dredge spoil, the light tan rectangular areas next to C-38. This section is the same as Fig. 2, which is located in Pool B/C

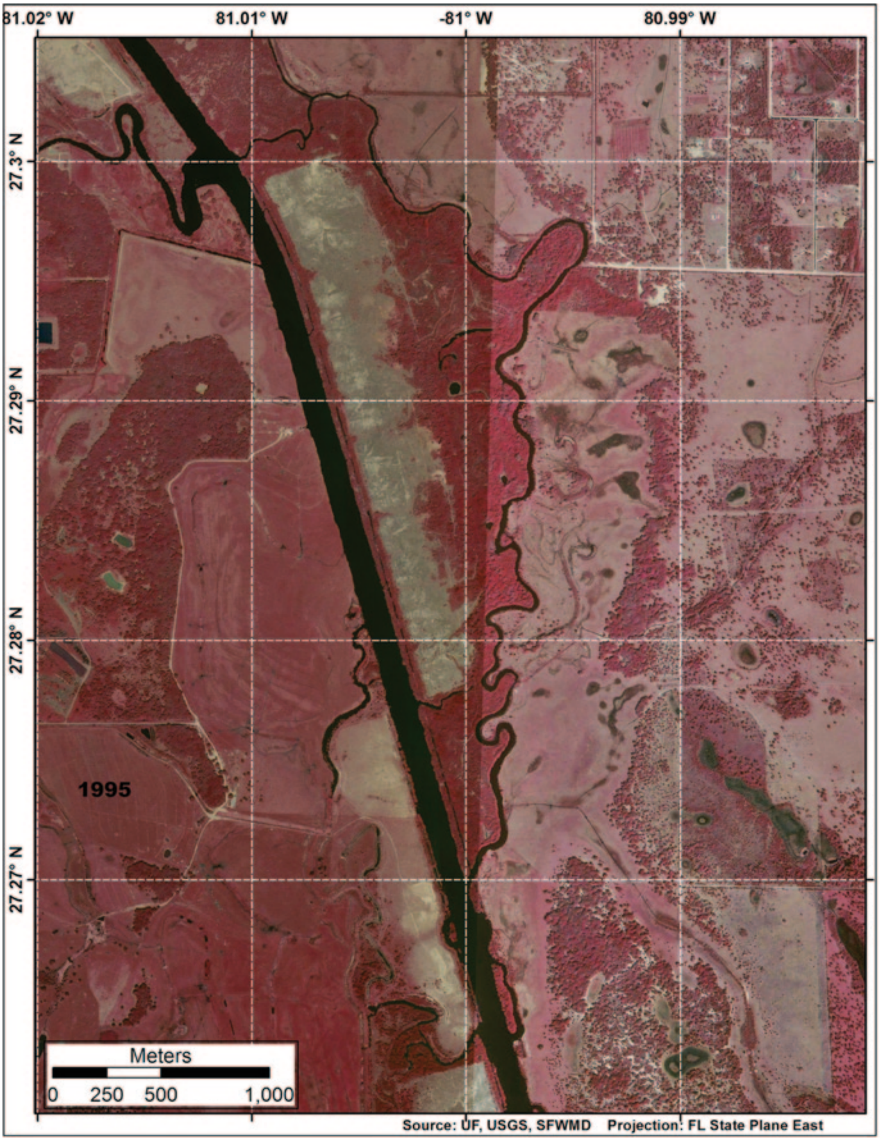


Fig. 6 Infrared photography from 1995 shows the canal C-38 and portions of the original channel. The canal is much wider than the historic channel when the river is within its banks. These figures also illustrate how different portions of the channel and floodplain were disturbed or obliterated by the channelization and dredge spoil, the light tan rectangular areas next to C-38. This section is the same as Fig. 3, which is located in Pool E

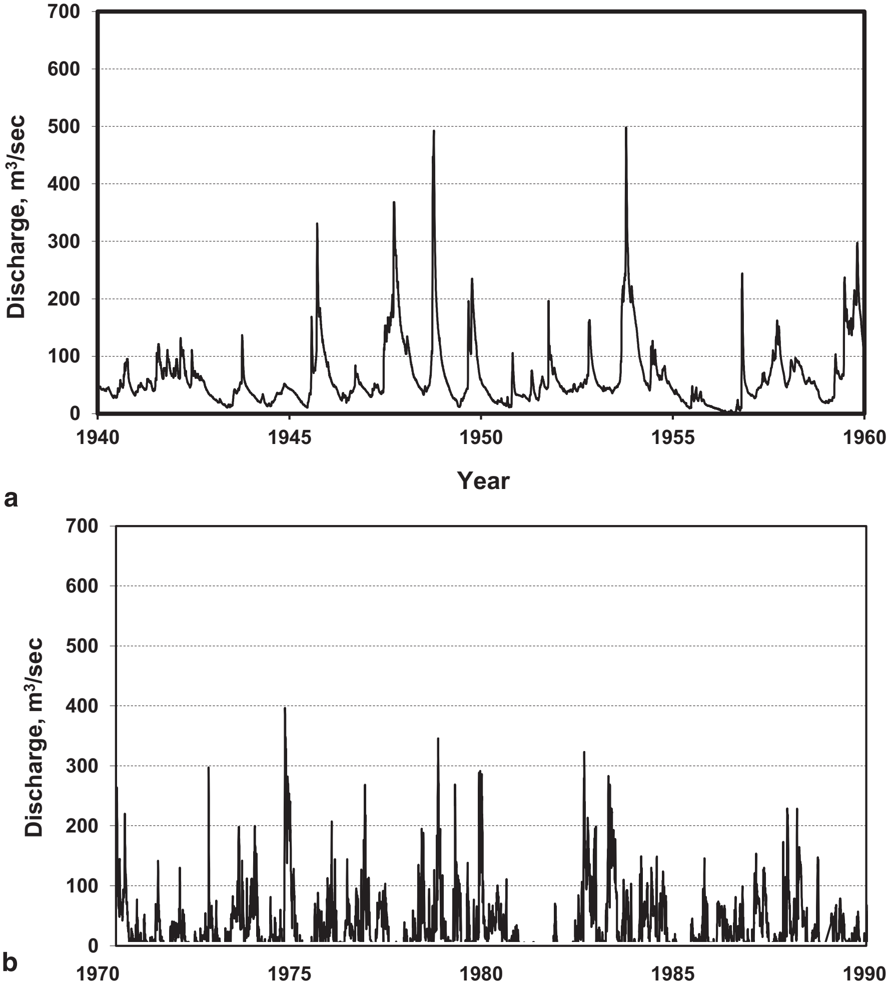


Fig. 7 Hydrographs showing 20 years of daily discharge measurements for the Kissimmee River near Okeechobee, pre-channelization (*top*) and post-channelization (*bottom*). The frequency and duration of events clearly changed following the completion of C-38

companying agricultural land use changes degraded water quality entering Lake Okeechobee and thus the Everglades (Toth 1995), expanding the extent of the area of impact beyond the lower basin.

From an engineering perspective, the channelization was quite successful. Flood waters were kept within C-38 and below the floodplain level as intended (Fig. 9). Stages and channel geometry variables (width, depth, and area) with water control show very little variation compared to the historic channel (Fig. 10); only velocities vary substantially. Prior studies characterize C-38 being wider than the historic channel, but this is only true for flows below bankfull and if only the main chan-

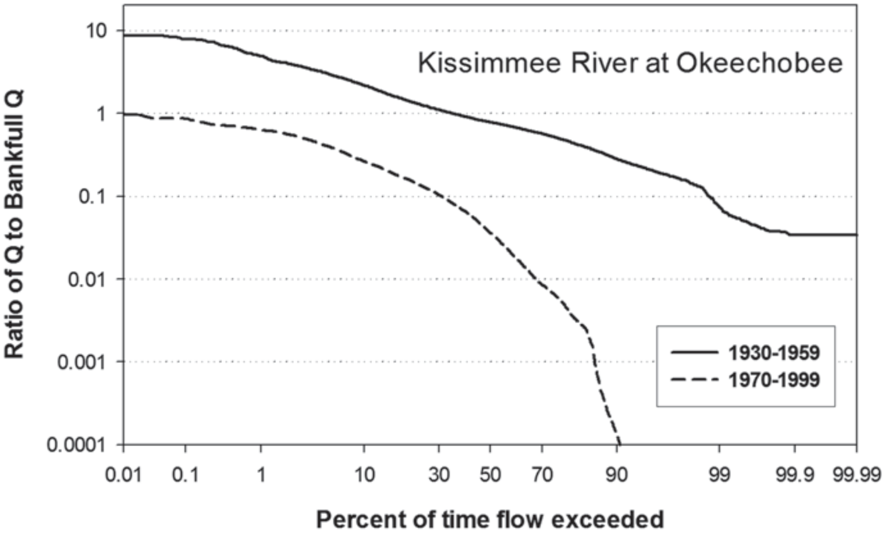


Fig. 8 Dimensionless flow duration curves for the Kissimmee River near Okeechobee, comparing a 30-year period prior to constructing the canal (1930–1959) to the 30-year period following channelization (1970–1999). The graphs used an estimated bankfull flow of 57 m^3/s for the historic channel (Toth 1993) and 760 m^3/s for C-38 based on a USGS discharge measurement just below that level with no floodplain flow. The intervening period between 1960 and 1969 is not shown because this was a period of canal construction and has data irregularities and does not represent a system condition. Current conditions since 2000 are not shown because the restoration is still in progress and the flows to the system are not what they will be following restoration

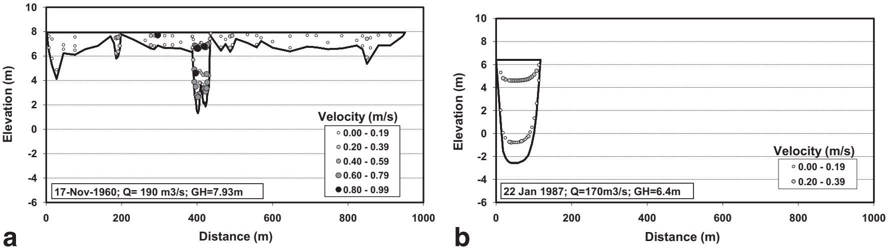


Fig. 9 Contrasting cross sections on the Kissimmee River near Okeechobee taken at similar discharge levels. The *left cross section* shows flooding in 1960 prior to construction of C-38. The *right cross section* shows a similar discharge in 1987. The stage and thalweg are lower, and the flow is confined to the channel

nel is compared (Figs. 5, 9 and 10). Pre-canal floods inundated multiple channels and portions or all of the intervening floodplain, thus the width was technically much larger historically during high flows. The wider channel in C-38 at most flows results in lower velocities and dissolved oxygen in the system, but it being regulated prevents lateral connectivity and exchanges between the river and floodplain and reduces the amount and quality of habitat for aquatic and wetland biota.

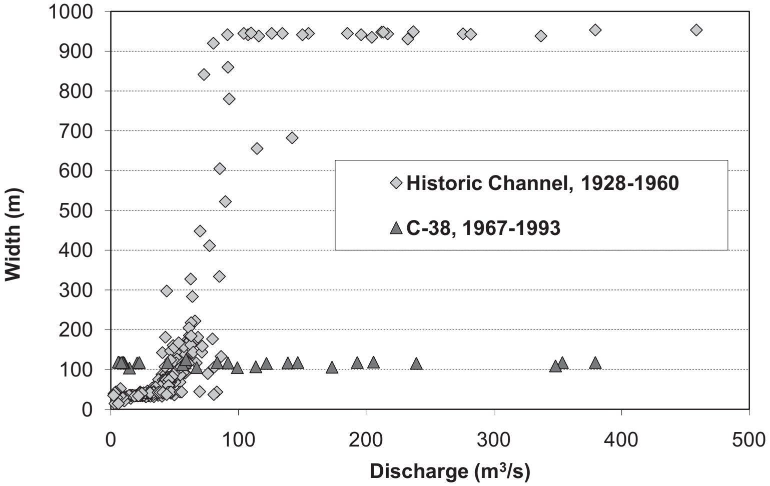


Fig. 10 In rivers with wide floodplains, marked increases in width as discharge increases is an indication that floodplain has been inundated. The historic channel experienced three conditions as follows: **a** at the lowest flows where the river is within its banks with widths generally less than about 50 m, **b** at higher flows where secondary channels and portions of the floodplain have flowing water and width ranges from 50 to 900 m, **c** at highest flows when the floodplain is completely inundated and width exceeds 900 m but is roughly constant. Not shown, depth and velocity also show nonlinear at-a-station hydraulic geometry changes. There are no marked increases on C-38, suggesting that the floodplain was not inundated during any of those discharge measurements

Channelization has long been a part of the Kissimmee and will still be used for water management near the lakes on both ends of the Lower Kissimmee. The lower most portion (approx. 12 km) below Pool E near Lake Okeechobee, was first channelized roughly 80 years since the 1930s as part of the Hoover Dike Project, then was enlarged with C-38 construction, and will remain that way. Structures will still control how much flow is allowed into Lake Okeechobee and other areas in south Florida connected to the Lake. Pools A and E, the uppermost portion of Pool B, and the lowermost portion of Pool D, having been channelized since the 1960s or for about 50 years at present will remain channelized. Only the central portion of the river, Pool C, the lowermost portion of Pool B, and the uppermost portion of Pool D which have been channelized for about 40–50 years are restored or undergoing restoration. The next section will give additional background on what the restoration entails, and how it is faring from a hydrologic and geomorphic perspective.

4 Restoration

As with the channelization, restoration had some opposition and required many steps; authorization took time, funding was not in place, and many at the Corps struggled with the concept of environmental restoration which was at odds to their typical work in water control (Godfrey and Catton 2011). Authorized by Congress with the Water Resources Development Act in 1992, the project is intended to restore a functioning ecosystem by re-establishing an environment conductive to the fauna and flora that existed there prior to channelization. Work began with land acquisition in the 1990s to allow prolonged floodplain overtopping and environmental studies by the South Florida Water Management District (SFWMD). Additionally, the Everglades is undergoing an even more ambitious restoration through the Comprehensive Everglades Restoration Program (CERP), with a cost estimate of US $ 13.5 billion at October 2009 price levels (Secretary of the Army and the Secretary of the Interior 2011).

Some label this the world's largest river restoration to date (e.g., Dahm et al. 1995), and certainly limited restoration had been done on this scale before, thus learning began within an adaptive management framework with demonstration projects to assess benefits and impacts. The U.S. Army Corps of Engineers is doing the construction, which consists of removing two of the six water-control structure s and accompanying locks (S65B and S65C, Fig. 1), backfilling approximately one third of the C-38 canal and restoring flow to approximately 70 km of sinuous channel (Dahm et al. 1995; Toth 2010a). Also, main channels that were obliterated by dredge spoil will be excavated or recarved. Once the canal is backfilled, flow re-enters former primary channels of the historic floodplain to re-establish wetland conditions. The current restoration cost estimate is approximately $ 620 million with a 50/50 cost share by the SFWMD and U.S. Army Corps of Engineers (Bousquin 2012). Besides the physical changes, it includes various types of monitoring, strategies, and targets to evaluate the success (Bousquin et al. 2005b). Because the Kissimmee River provides a major source of water for the Everglades, success here ties to the Everglades restoration where the goal is to bring the quantity, quality, spatial patterns, and timing of flow much closer to historical conditions.

Based on construction methods and location, terms have been developed to characterize different sections of channel. Restored sections were stagnant for decades, but represent the original channels isolated by C-38. Recarved channels were dug onto the floodplain, in a different position than formerly or in their former position where buried by spoil during canal construction. Photography and imagery shows that the restored channel from 2004 is not in the same position as it was in 1944 in a number of locations (Fig. 2). Connector channels were dug across the backfilled C-38; in some cases, the form of these resembles the original river, but in other cases the connectors appear anomalous (Fig. 11, near 27.473°N, 81.184°W and 27.476°N, 81.178°W). Such connectors are currently amongst the most unstable sections of the restoration, showing pronounced sedimentation between 2004 (Fig. 11) and 2010 (Fig. 12). Repeat cross-sectional surveys of these odd-shaped, wide connectors show the formation and marked adjustments of bars which cause these areas to narrow and become more like other portions of the channel, shown in contrast with a more typical restored cross section (Fig. 13). Besides the form of the channel, another anomaly is with the drainage network; in some locations there are channels that just end, sometimes without even tapering as they might do in nature.

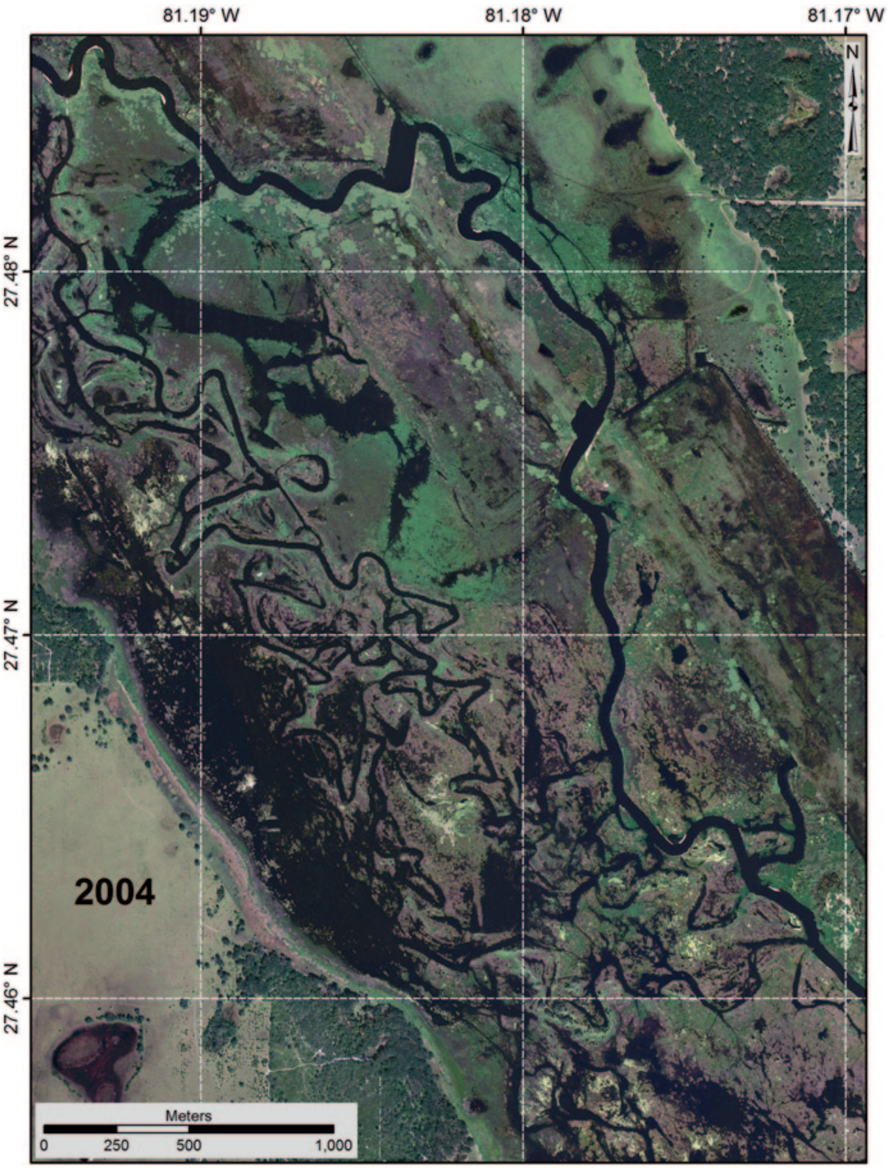


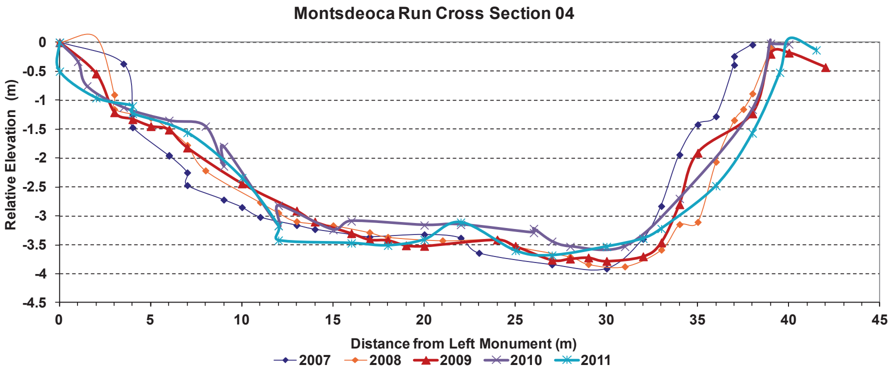
Fig. 11 Restored portions of the Kissimmee River in 2004 in which former C-38 is now backfilled with spoil, showing the same area as Figs. 2 and 5. Generally, most portions of the restored channel are former channels that were flowing. However, in some places recarved or new channels were created where a channel exists where none did formerly. Also, two anomalous connectors near 27.473°N, 81.184°W and 27.476°N, 81.178°W are shown

The intent of the river restoration is to return typical seasonal hydroperiods to the river and floodplain (Toth et al. 1995), an improvement over the initial pulse-like and out of phase flows with extended periods of low or no flow done during early demonstration work (Toth et al. 1993). By backfilling C-38 and removing

Source: Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, and the GIS User Community

Fig. 12 Restored portions of the Kissimmee River in 2010, showing the same area as Figs. 2, 5 and 11. The former location of C-38 is less obvious and the two anomalous connectors in the northern portion of the image and adjusting through sedimentation

the two central structures, the former pools (Pool B/C/D) will be combined. The upstream and downstream canal reaches (Pool A and E, respectively) will remain channelized and controlled by lock structures for flood abatement purposes. Once the restoration is completed, Lake Kissimmee's stage level will be managed by a regulation schedule. Flow release preferences will be full discharges from the lake



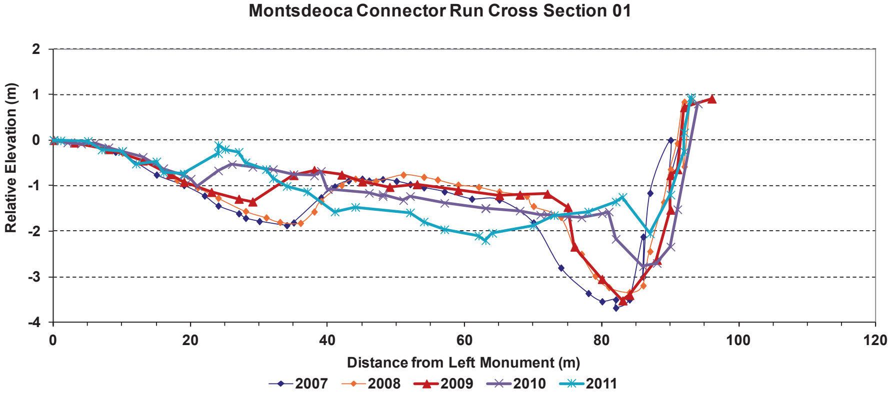


Fig. 13 A comparison of two transects in Montsdeoca Run in Pool B/C, one in the northernmost connector in Figs. 11 and 12 and the other in a restored reach just upstream. It shows that the connector is much wider and shallower than the other river transects, and is developing emergent bars

if flow is sufficient. Otherwise, releases will be controlled to fall within the range of historical discharges, aiming to maintain minimum discharges of 7.1 m^3/s (250 cfs). When lake levels drop below 14.8 m (48.5 ft), water will be held back in Lake Kissimmee (US Army Corps of Engineers 1993).

Much negotiation, design, and construction went towards the project, but this was necessary due to preexisting constraints, limited prior work on restoring systems of this nature and the learning through adaptive management. The baseline conditions were reconstructed by reviewing available data and prior studies in an effort to assess the restoration and guide future management (Bousquin et al. 2005b). A review of studies of hydrology, geomorphology, water quality and dissolved oxygen, littoral and floodplain vegetation, algae, invertebrates, fish, amphibians, reptiles, and birds give guidance to monitoring and some criteria for evaluating the success of the project (Bousquin et al. 2005b). Floodplain lands were purchased along the entire corridor to be restored, thus, for the most part there is no “new path” of the river determined by availability of land. Approximately 90 % of the restored main channel follows or will follow the original course, with local sections being recarved through spoil or built across backfilled C-38. The original remnants of the channel are for the most part the same ones in which flow will be restored. Updates on the restoration progress are given each year through environmental reports (Jones et al. 2011). Whatever plants and animals are introduced, are part of a deliberative, lengthy process of restoration expectations, based on preexisting data and knowing that restoring the system physically is only a beginning to restoring the biota that once thrived in it. Because the objective of the restoration is to return the river to a functioning ecosystem by re-establishing an environment conductive to the fauna and flora that existed there prior to channelization, then the work so far seems successful. Thus, there is truth that the health of the system does depend on the managers and scientists who are bringing varied skills, but also good intentions to restoring the system to the best extent practical.

Even though the restoration is not yet complete, there are both promising signs and uncertainties in terms of the hydrologic, geomorphic, and environmental function. Flooding occurs and wetland vegetative communities are increasing and there is less pasture, but some vegetative communities like the broadleaf marsh are not yet successful at reestablishing, in part because invasive plants are occupying these habitats (van der Valk et al. 2009; Toth 2010a, b). Earlier studies have noted a 10–30 cm thick layer of organic muck with fines that accumulated in the bottom of stagnant primary channels during the channelization (Toth 1993). In reaches not yet restored, sampling between 2006 and 2011 shows that the thickness of this material is variable, but locally thicker than previously reported, and accumulations from 50 cm to over 1 m of this organic muck are not uncommon. In restored reaches, this organic muck has been removed by flows and the river bed is now sand bottom. Sand bars, which had disappeared with channelization, are ubiquitous, and erosion and deposition are reoccurring due to the recent reintroduction of flow through the system.

Thus coupled with the successes are the unanswered questions. More work should go towards understanding the issues of managed water inputs, the role of secondary channels, the fate of organics and fine sediments, and the evolution of sand bars. Monitoring efforts continuing well past the restoration will give more insight to how the restored portions of the Kissimmee are faring compared to channelized sections and what is known of its historical predecessor.

5 Discussion

Looking historically at the Lower Kissimmee gives some understanding of the unique nature of the system. The setting of the river between two large lakes, the very long hydroperiods with stages being above bankfull for several months annually, and the complex floodplain with anabranches, lakes, and ponds make the Kissimmee different from many other alluvial rivers. Similarities with other low gradient wetland streams (Jurmu and Andrle 1997) include circular meander pools, tight bend ways with a low radius of curvature-to width ratio, and smaller point bars on the convex banks of bends than on other alluvial rivers of comparable size.

Channelization and the accompanying structures changed the hydrology, sedimentology, geomorphology, and biota of the system. As intended, hydrologic changes included eliminating overbank flows; stages varied little but the discharge range was similar to the past. Instead of the long hydroperiods, there were many short pulses. The remnant channels changed with channelization, accumulating fine and organic sediments and having vegetation colonize point bars and channel margins. There was no longer flow to sustain a dynamic river. The channel geometry was altered from multiple perspectives. The canal held the range of flows, was several times deeper, had a temporally consistent width which was wider than the low flow channel but narrower in flood, the planform was nearly straight and the slope overall increased by reducing the length but water surface slopes are also locally controlled by the presence of multiple structures. Biotic systems including riparian vegetation, fish, birds, reptiles and other species declined markedly as the physical system was altered, in particular when inundation diminished appreciably. Engineering successes were achieved with significant cost to the natural environment.

When rivers such as the Kissimmee have been altered to suit the needs of navigation and land development, rehabilitation or the partial restoration of riverine habitats and ecosystems is more feasible than restoration (Gore and Shields 1995), in part because it is impossible to reverse cumulative catchment-scale degradation (Bernhardt and Palmer 2011). This restoration or rehabilitation took decades to begin and has been underway for more than a decade. For the most part, this lengthy process is a favorable thing, allowing scientists to establish detailed restoration goals and expectations (Anderson et al. 2005), monitoring the structure and function as the restoration is in progress (e.g. Schenk et al. 2011), and learning through adaptive management. This is not the quick-fix, “natural channel design” or picture-book approach attempted in some areas where the system is viewed as static, an approach critiqued by many (e.g., Newson and Large 2006; Lave 2009; Lave et al. 2010; Wohl et al 2005; Gillilan et al. 2005). There is an understanding by restoration scientists that spatial and temporal variability are inherent, that floodplain lands are an essential part of river restoration and that hard structures are not necessary to create a desired form. Indeed, in a state like Florida that lacks mountains, with sand-dominated and spring fed streams, Rosgen’s (1994) few categories are not useful for characterizing the variety of streams even within the peninsula (Kiefer 2010).

The project is now at a stage where for much of Pool B/C most of the form and parts of the function are restored. Over time it is expected that the hydrologic function will improve, particularly after the regulation schedule is established, and hopefully other aspects of ecosystem function will recover. Despite some critics, for instance, one who condemns the idea that the restoration is an “artifact of human negotiation, design, and construction” (Goin 1997), the environmental benefits of the river rehabilitation are apparent. Given the multitude, variety, and complexity of factors that influence river ecosystems, defining an acceptable end point is difficult (Gore and Shields 1995), yet the goals are to direct hydrological process and geomorphic structure to improve biological functioning toward an end point closer to pre-disturbance conditions. Renewal of physical and biological interactions between the main channel, backwaters, and floodplains is central to the restoration.

River and floodplain management in central and southern Florida differs appreciably from the 1880s when the primary goal was land drainage for development. There are multiple stakeholders, within and adjoining the basin, those who want flood control at times but also those who water supply for communities, agricultural lands, and/or undeveloped areas like the Everglades. Not everyone will receive the optimum amount of water, at times too much and at times too little, thus difficult decisions need to be made about distributing water spatially and temporally and associated quantities. Multipurpose watershed management will be no easy task, particularly during droughts. Given competing constraints, an expectation that the restoration bring the ecosystem structure and functions to pre-impact levels is unrealistic, yet given the scale and the importance of this project in the overall US $ 70 billion spent in North America (including Canada, United States, and Mexico) in the last 20 years (Bernhardt and Palmer 2011), observable indicators of successes must outnumber failures. An additional challenge that this area faces due to its low elevation and connectivity with the Everglades is climate change, in particular sea level rise and associated impacts to water quality (Erwin, 2009).

Rehabilitation or restoration efforts, even if imperfect, matter. When left mostly intact, floodplains and riparian wetlands are highly productive ecosystems, performing functions such as carbon storage, biodiversity conservation, fish production, water purification, storm protection and trapping nutrients, sediments, and contaminants (Noe and Hupp 2009). Threats to floodplains include habitat alteration, flow and flood control, species invasion and pollution, ultimately causing loss of biodiversity and extinctions. One estimate is that up to 90 % of the floodplains in Europe and North America inadequately perform ecosystem functions of natural floodplains (Tockner and Stanford 2002), due to transformation of riparian areas, increased pollution, major and minor dam projects, water demands and more.

6 Conclusions

The Kissimmee River was transformed greatly from a complex lowland flood plain with multiple channels, sloughs, and ponds to a channelized river, and is currently undergoing another major transformation in which the main channel along the central portion of the river is being restored to a similar form as before the alteration. The canal or C-38 was much larger than the original main channel and low flows became much more prevalent. The restoration is taking many years, but fieldwork shows that selected connectors have undergone the most geomorphic adjustment. Thick accumulations of fines and organic sediments in the bottom of remnant channels that were inactive for decades have been replaced by clean sand beds where flow was restored. Restored portions of the river will have some constraints regarding water inputs compared to the river prior to channelization and this transition is still underway.

Geomorphology has more to contribute to understanding this unique river, floodplain and basin, including its processes, sediments and landforms, through historical geomorphology and Quaternary studies, collaborative work with ecologists and aquatic biologists on ecosystem integrity and recovery, experiments involving teams of researchers, and involvement in management and policy. The project is showing several promising signs, but the answer to whether or not the project reaches an end point that will satisfy those in the geomorphic and ecological communities, as well as the numerous stakeholders within the basin and elsewhere, is still several years down the road.

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Managing the Mississippi River Floodplain: Achieving Ecological Benefits Requires More Than Hydrological Connection to the River

Harold L. Schramm, William B. Richardson and Brent C. Knights

Abstract Floodplains are vital to the structure and function of river-floodplain ecosystems. Among the many ecological services provided by floodplains are nutrient cycling and seasonal habitats for fish, including spawning, nursery, foraging and wintering habitats. Connections between the river channel and floodplain habitats are essential to realize these ecological services, but spatial and temporal aspects of the connection and contemporary geomorphology must also be considered in restoration efforts. This chapter synthesizes available information to compare floodplain function and needed management strategies in two extensive reaches (upper impounded and lower free-flowing) of the Mississippi River, USA. The upper impounded reach is the 523-km reach from about Minneapolis, Minnesota to Clinton, Iowa. This reach has been impounded and channelized for navigation. Mean annual water-level fluctuation ranges from 1 to 2 m in the navigation pools in this reach. Floodplain environmental conditions that affect nitrogen cycling and fish production vary seasonally and longitudinally within and among navigation pools. Significant issues affecting ecological services include sedimentation, constrained water level fluctuations, island erosion and seasonal hypoxia. The lower free-flowing reach, the 1570-km reach from the confluence of the Ohio and Mississippi rivers to the Gulf of Mexico, has no dams and average annual fluctuations of 7 m throughout most of the reach. Despite the substantial flood pulse, floodplain inundation is often brief and may not occur annually. Significant issues affecting floodplain ecological function are the short duration and thermal asynchrony of the flood pulse, sedimentation and loss of connection between the river channel and permanent/semi-permanent floodplain water bodies due to channel incision. Needs and strategies for floodplain enhancement to increase ecological services, particularly nitrogen cycling and fish production, differ along the longitudinal gradient of the Mississippi River and provide informative contrasts to guide floodplain man-

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agement. Prediction of the effects of climate change on this system will be complicated by the magnitude of the watershed that encompasses 41 % of the continental USA and multiple climatic regions.

Keywords Floodplain · Mississippi River · Fish · Nutrients · Flood pulse · Management

1 The Mississippi River, Past and Present

The Mississippi River is a river-floodplain ecosystem. Alterations of the system to serve humans have affected the river and the floodplain in different ways throughout its 3700-km course. Floodplain systems are a heterogenous mix of channels, small lakes, forests and wetlands and, as such, provide habitat to a diversity of biota and ecological services that affect water quality and the hydrologic cycle (Ward 1998). Seasonally inundated floodplains contribute significantly to fisheries production in river-floodplain ecosystems, as described in the flood-pulse concept (Junk et al. 1989), and limited investigations indicate inundated floodplains benefit fisheries production in the Mississippi River (Gutreuter et al. 1999; Schramm and Eggleton 2006). Floodplains are wetlands, and wetlands affect nutrient cycling, particularly nitrogen. An issue of great economic concern is the large and growing areas of hypoxic water in the Gulf of Mexico. The hypoxic conditions result from algae blooms that are caused by high concentrations and the load of nitrate transported from agricultural fields to the Gulf of Mexico by the Mississippi River. Mitsch et al. (2001) suggested that restoration of 0.7–1.8 % of the Mississippi River basin wetlands and 2.7–6.6 % of riparian forests would reduce the amount of nitrogen reaching the Gulf of Mexico by 10–40 %. An ecologically functional Mississippi River floodplain could provide much of the wetlands area needed to reduce nitrogen input to the Gulf of Mexico. However, the benefits of the floodplain to fish production and nitrogen cycling, particularly denitrification, can only be realized if the floodplain is connected to the river (Galat et al. 1998; Weins 2002).

Under natural conditions, the Mississippi River meandered through its floodplain creating new channels and leaving in its wake a mosaic of natural levees, islands, abandoned channels and off-channel aquatic areas (i.e. backwaters). These geomorphic features were variously affected by a seasonally and inter-annually dynamic flow regime. The interactions between geomorphic features and the flow regime set the physicochemical template for a diverse and productive riverine biota. Native fish populations and flora likely evolved and thrived in the floodplain of the Mississippi River system under a natural hydrologic and geomorphic regime (Fremling 2005). In natural (unaltered) river-floodplain systems, annual floods inundate the floodplain and connect floodplain water bodies to the river channel, supplying nutrients and sediment that spur primary and secondary production (Junk et al. 1989; Lewis et al. 2000). The floodplain provides spawning, nursery and feeding areas for many species of fish. As floods recede, physicochemical conditions on the floodplain change, and fishes redistribute into the perennially inundated channel and off-channel habitats to meet other life-history requirements (Winemiller and Jepsen 1998). In the Mississippi River, the native flora and fauna provided sustenance to local humans in the form of food and building materials. Through time, humans intentionally and unintentionally altered this system to facilitate transportation, agriculture and human development (Anfinson 2003; Fremling 2005). Major modifications to the system included channelization and dams to facilitate commercial navigation and levees to reduce flooding of agricultural lands and human development. Fish and wildlife populations persisted, although relative abundances likely have changed, and the contemporary communities are now dependent on the altered environment (McGuiness 2000).

Collecting runoff from 41 % of continental United States, the Mississippi River historically transported large quantities of nitrogen (an estimated 0.3×10^6 mt year^{-1}, Mitsch et al. 2001) to the Gulf of Mexico; however, as inferred by Brauman et al. (2007), an expansive and functional floodplain may have greatly reduced nitrogen loading. Driven by changes in agricultural practices, present day loads of land-derived nitrogen have risen to 1.7×10^6 mt year^{-1}. Eutrophication of the Gulf of Mexico and development of areas of hypoxia are largely a result of Mississippi River-conveyed nitrogen inputs that are now overwhelming the assimilative capacity of the coastal marine ecosystem (Rabalais et al. 2002; Turner and Rabalais 2003). Understanding, managing and reducing loading of nutrients to Gulf of Mexico is one of the major environmental challenges facing the United States today (Mitsch et al. 2001) and requires new land and river management strategies. Possibly a restored and functional floodplain may help alleviate excessive nitrogen inputs to the Gulf of Mexico.

Modifications to the Mississippi River-floodplain ecosystem have changed not only the hydrology and geomorphology, but also the dynamic interaction between these two ecological drivers. Restoring seasonal inundation of the historical floodplain in the upper Mississippi River and reconnecting the lower Mississippi River to its historical floodplain are socially and economically untenable. Further, reconnection to the historical floodplain and the restoration of the hydrograph would probably be insufficient to restore the natural biotic production and nutrient cycling because the watershed, river and floodplain have changed. In the impounded upper Mississippi River, biotic communities composed of a mix of native and non-native species suited or able to adapt to these new and still-changing conditions have developed (McGuiness 2000; River Resources Forum 2004). In some reaches, these communities are still highly productive and provide valuable ecosystem services (Fremling et al. 1989). In all reaches, the communities have changed; and natural resource managers are trying to make the best of the altered system to support "desirable" (i.e. of greatest direct human interest) biotic communities.

The questions we explore here are not related to how society should manage the historical Mississippi River-floodplain ecosystem, but rather are related to the ecological functions and management of the remaining floodplain–the seasonally and permanently inundated lands lateral to the river and riverward of the man-made levees (Table 1) and new habitats under contemporary constraints. We address the

Table 1 A floodplain is the land adjacent to the river that is intermittently inundated as the river elevation fluctuates. Engineering activities have changed the Mississippi River floodplain over time, and these changes differ between reaches of the Mississippi River. We have adopted the terminology below for clarity in this chapter

	Upper impounded reach	Lower free-flowing reach
Historical floodplain	The floodplain occupied by the river before construction of locks and dams and levees	The floodplain occupied by the river before construction of continuous tall levees
Active floodplain	The portion of the floodplain that is seasonally inundated	The portion of the floodplain that is seasonally inundated
Impounded area	Permanently inundated open-water areas in the lower (downstream) portion of navigation pools	
Floodplain lakes	Lake-like habitats that are connected to the river channel at least seasonally during some years	Lake-like habitats that are connected to the river channel at least seasonally during some years
Backwaters	Floodplain lakes (see above) and permanently inundated historical floodplain in the mid and upper portions of navigation pools (also referred to as shallow aquatic areas)	

ecology and management of the Mississippi River ecosystem by examining two very different reaches of the River, the upper impounded reach and the lower free-flowing reach (Fig. 1). Our purpose in this chapter is to describe the varying geomorphology, hydrology and modifications to these reaches; summarize documented and inferred effects of these variations on fish production and nitrogen cycling; and give examples or suggest considerations for achieving more of the ecological services that the floodplain can provide. The information will be useful to the society as it decides how to manage reaches of the Mississippi River and other large river-floodplain ecosystems in the future.

2 The Mississippi River: A Heterogeneous System

The Mississippi River has been variously divided into reaches to satisfy different purposes. Schramm (2004) recognized three ecologically distinct reaches: the headwaters; the impounded upper Mississippi River that includes 29 navigation locks and dams; and the free-flowing (no dams), mostly leveed, lower Mississippi River. These ecological reaches have been uniquely modified in accordance with their climate, geomorphology, hydrology and natural resources to meet modern human needs. The impounded Mississippi River warrants further ecological division into upper and lower impounded reaches because mainstem levees that separate the main

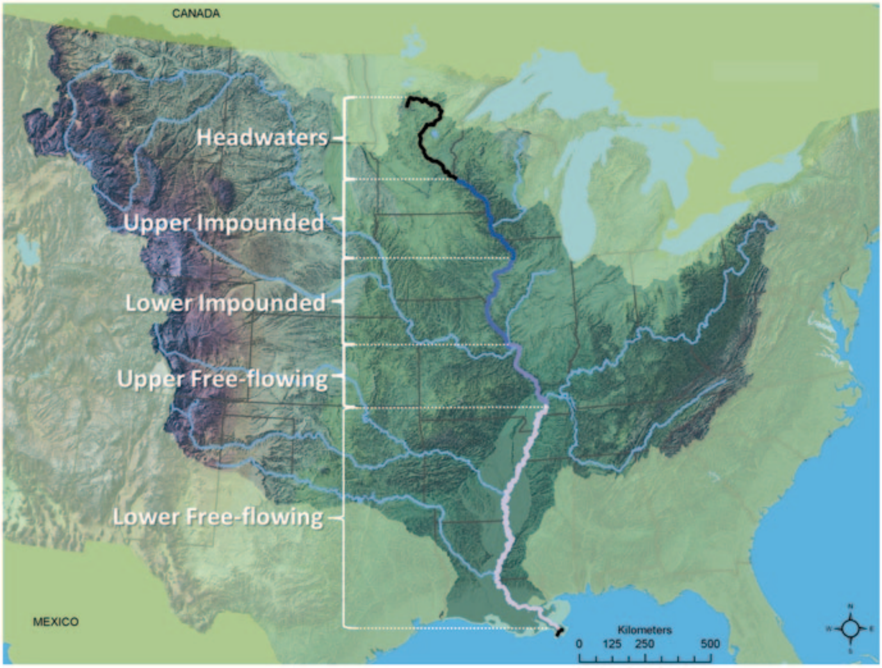

Fig. 1 Ecological reaches of the Mississippi River in the USA. *Grey tone* demarcates the Mississippi River basin

channel from the floodplain are rare in the upper reach but prevalent in the lower reach (Theiling and Nestler 2010). Further, the free-flowing Mississippi River can be divided into upper and lower reaches because the lower free-flowing reach occurs in a meander belt on a broad floodplain, whereas the upper free-flowing reach is an anastomosing channel on a relatively narrow floodplain. We have selected the upper impounded reach and the lower free-flowing reach to depict the scope of ecological issues and potential management strategies in the Mississippi River. The reaches differ in a variety of ways, as described below. From the perspective of ecological function of the floodplain and floodplain connectivity, the reaches also differ in a fundamental but less-than-apparent way. The upper impounded reach is extensively used for both commercial navigation and recreation (e.g. fishing, hunting, boating and swimming). The value as a recreational resource is partly a result of the impoundment in support of commercial and nationally strategic navigation. The recognized value has stimulated natural resource management and extensive scientific study of ecosystem structure and function of this reach. The lower, free-flowing reach has been managed for commercial navigation and flood control to facilitate human development and agricultural production in the vast, fertile historical floodplain. Although commercial fishing occurs, recreational use is minor. As neither of the primary management objectives (navigation and flood control) include ecological concerns, and essentially lacking other human-related benefits such as recreation or fishing, the lower reach has received little management as a natural resource or ecological study.

3 Contrasting the Upper Impounded and Lower Free-Flowing Reaches

3.1 Hydrology and Geomorphology

3.1.1 Upper Impounded Reach

The upper impounded reach of the Mississippi River is the 523-km segment that occupies a relatively narrow floodplain (1.6–4.8-km wide; Johnson and Hagerty 2008) from Lock and Dam 1 in Minneapolis, Minnesota to Lock and Dam 13 near Clinton, Iowa (Fig. 1). The original forest- and prairie-covered watershed of this reach has generally been replaced with row-crop agriculture and urban development, but some forest remains (Knox 2006). The major modifications to the river in this reach include channelization and installation of 14 low-head dams in the 1930s to create a 9-ft (2.7-m) minimum-depth channel for commercial navigation. Much of the historical floodplain in this reach (390 of 523 river km) became part of a national wildlife refuge (Upper Mississippi River National Wildlife & Fish Refuge) in 1924 (Anfinson 2003) and remains hydrologically connected to the river channel through either seasonal or permanent (i.e. impoundments) inundation.

The navigation dams form “pools”, defined as the section of river between two consecutive dams. The dams in the upper impounded reach serve only to elevate water levels a few meters (average hydraulic head at dams is 3.3 m) for commercial navigation rather than for water storage (Fig. 2). The average water retention time of each of the 14 pools is on the order of days to weeks rather than months or years. For example, Lake Pepin, a natural riverine lake that constitutes most of the largest navigation pool in this reach, has a retention time of 6–47 days (Maurer et al. 1995). The impounding effect of the dams increased connectivity between the main channel and floodplain lakes that, before impoundment, were seasonally isolated or dried out completely at low discharge. This increased connectivity with the main channel also increased sedimentation rates in these backwaters (Theis and Knox 2003; Knox 2006). Much of the historical floodplain that was subjected to an annual wet-dry cycle under unaltered flow regimes was lost to permanent inundation from dams (Fig. 3). For example, the area of the historical floodplain in what is now Pool 8 near La Crosse, Wisconsin was 8937 ha. After construction of Lock and Dam 8, 5543 ha of historical floodplain were permanently inundated and only 3394 ha of floodplain are now seasonally wetted by a typical flood (i.e. a discharge that occurs in 2 of 3 years on average) (James Rogala, U.S. Geological Survey, Upper Midwest Environmental Sciences Center, unpublished data).

Typical navigation pools in the upper impounded reach have three distinct areas: a riverine (upper pool); transitional (mid pool); and impoundment (lower pool)

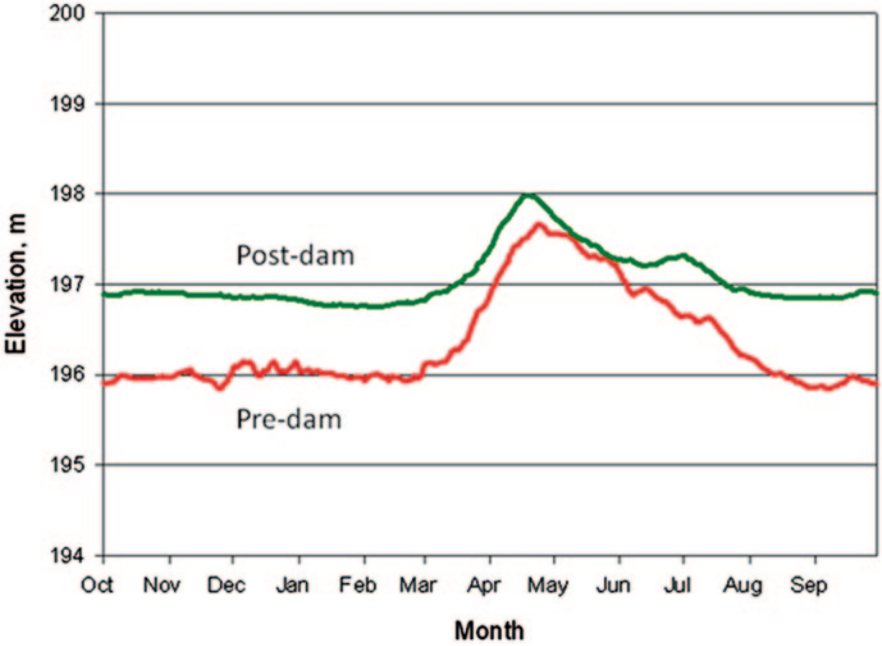

Fig. 2 Mean surface water elevation (mean sea level) at the control point in Navigation Pool 6 (Winona, Minnesota gage) in the upper impounded reach of the Mississippi River before (1888–1903 and 1928–1929; *red line*) and after (1940–2004; *green line*) dam construction. Adapted from Johnson and Hagerty (2008)

area (Fig. 3). The riverine area retains some pre-dam geomorphic and hydrologic characteristics including numerous channels, backwaters and an active floodplain (Theiling and Nestler 2010). In the transitional area, the moderate water level increase resulting from impoundment has resulted in abundant shallow aquatic areas (backwaters, Table 1) on much of the historical floodplain that are now connected to the main channel year round. The impounded area is a large, open-water area with depths in most of the area, except the former river channels and floodplain lakes, approximately equivalent to the hydraulic head at the downstream dam. Immediately post-dam, depth diversity was high and islands, previously natural channel levees, were abundant in this impounded area. These features provided a variety of habitat for aquatic vegetation, fishes and waterfowl (Theiling and Nestler 2010). As the system aged, the islands and depth diversity in the impounded area were mostly lost to erosion and sedimentation (U.S. Geological Survey 1999).

3.1.2 Lower Free-Flowing Reach

The lower free-flowing reach is the 1570-km segment from the confluence of the Ohio and Mississippi rivers to the Gulf of Mexico that historically meandered

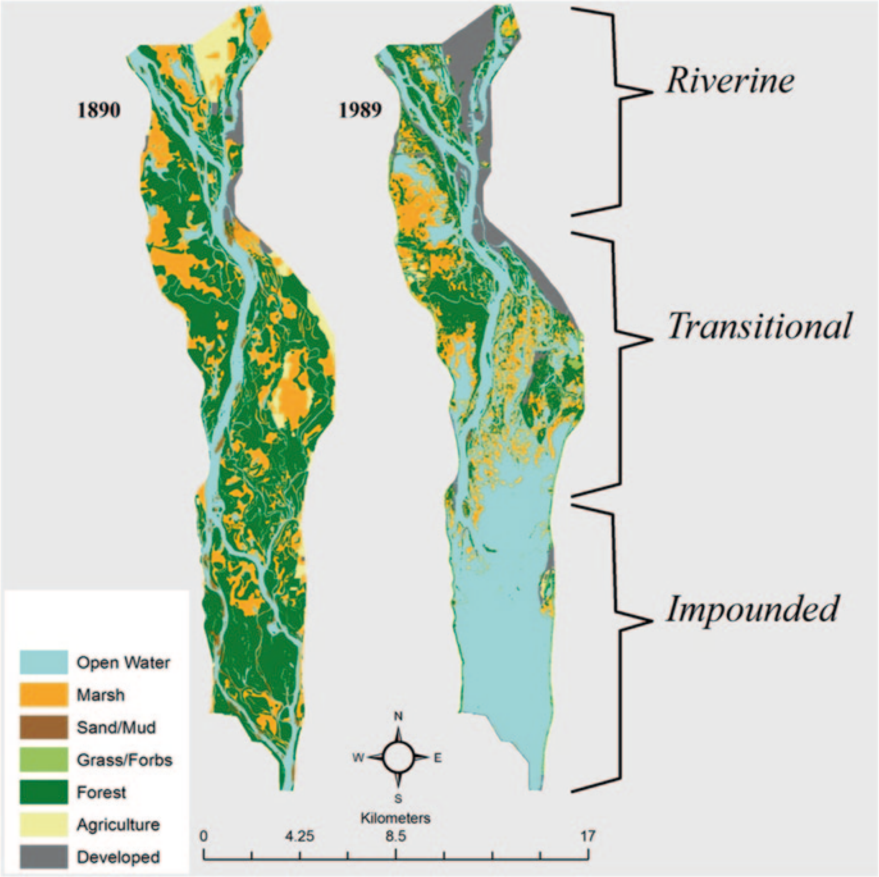

Fig. 3 Land and water cover in Navigation Pool 8 in the upper impounded reach of the Mississippi River before (1890) and after (1989) impoundment. Adapted from UMRR EMP (1989, 1999)

through a broad alluvial plain. The free-flowing river has been altered by rock wing dikes that direct flows to create a self-dredging navigation channel and by revetted banks to forestall bank erosion; together, these engineered features maintain the present channel configuration and prevent meandering. In its current state, this reach is entirely flanked by continuous tall levees, interrupted only by 19 tributaries, built to withstand floods in excess of the 100-year flood. The historical floodplain varies from 50- to 200-km wide. The levees have separated the river from about 90% of its historical floodplain (Weiner et al. 1998); however, 650,000 ha of active floodplain (the batture or the land between the natural river bank and the levees) remains (Schramm et al. 1999). The active floodplain is not uniformly distributed; rather, it consists of alternating wide and narrow areas, and there is no active floodplain remaining in the lower one fourth of the lower free-flowing reach (downstream of river km 400) where the levees have been constructed immediately

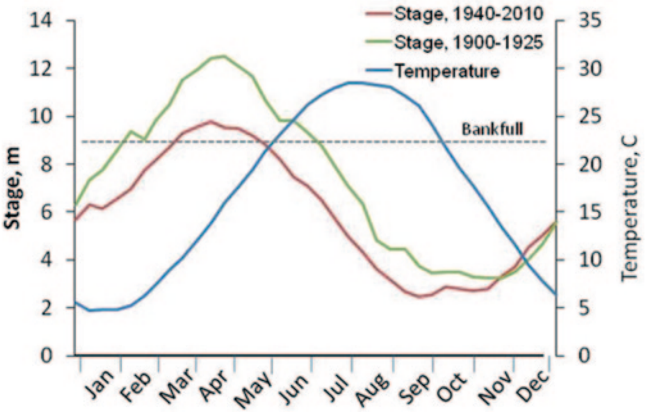

Fig. 4 Mean annual fluctuations in elevation (gauge reading) and temperature of the Mississippi River measured at Vicksburg, Mississippi before (1900–1925) and after (1940–2010) neck cutoffs that shortened the river and the installation of tall levees

adjacent to the river bank. The active floodplain is a mosaic of habitats but largely consists of floodplain forests. The historical floodplain obviously has been reduced by the tall levees, but the often-stated 90% loss of floodplain habitat needs to be viewed within the dynamic nature of a river that fluctuated more than 9 m, on average, annually (Fig. 4). Floods that inundated the entire 103,000 km^2 historical floodplain were rare, and far less floodplain was inundated in most years.

Loss of connection of the river to historical floodplain lakes and wetlands that are now landward of the levees has significant ecological and conservation consequences, but of greater biological significance to the present and future river-floodplain ecosystem is the change in the river hydrograph and channel incision. During 1929–1942, 16 meander loops (“oxbows”) were bypassed by constructed cut-off channels (Baker et al. 1991). These “neck cut-offs” shortened the river by 245 km and subsequently increased the slope. The hydrologic consequences of the cut-offs were lower, shorter-duration, and less frequent flood pulses (Fig. 4). Presently, the floodwaters inundate the active floodplain relatively briefly and subside earlier in the year; consequently, the water is colder during the flood pulse. The cut-offs were a double-edge sword. By changing the slope, the construction of the cutoffs also initiated headcutting and channel incision throughout the upper half of the lower free-flowing reach, while deposition is occurring in the lower half (the “hinge point” for headcutting is in the vicinity of Greenville, Mississippi near rkm 870). As a result, an even greater rise in river stage is needed in the upper half of this reach for the flood waters to spill onto the active floodplain, and some floodplain lakes connect to the river only at relatively high river stages.

3.2 Legislative Mandates for Environmental Management

Except for the federally binding U.S. Clean Water Act (33 U.S.C. 1251 et seq.) and Endangered Species Act (16 U.S.C. § 1531 et seq.), environmental management mandates vary across the ecological reaches of the Mississippi River and, in particular, between the upper impounded and lower free-flowing reach.

3.2.1 Upper Impounded Reach

The initial impetus for the establishment of the Upper Mississippi River National Fish and Wildlife Refuge in the upper impounded reach included the conservation of waterfowl and fish (Anfinson 2003; U.S. Fish and Wildlife Service 2006). However, refuge management by the U.S. Fish and Wildlife Service has typically focused on waterfowl and terrestrial biota rather than fish. Fishery management issues on the refuge generally came under the purview of state agencies working in cooperation with the federal refuge managers (U.S. Fish and Wildlife Service 2006). The upper Mississippi River is considered a wetland of international significance by the Ramsar Convention (http://www.ramsar.org/cda/en/ramsar-documents-list-anno-list-usa/main/ramsar/1-31-218%5E15774_4000_0__) and serves as the core of a migratory route (Mississippi Flyway) for 40 % of North American waterfowl.

The U.S. Army Corps of Engineers has a long history in the modification and management of the Upper Mississippi River System (UMRS; Anfinson 2003: Fremling 2005), which includes the upper and lower impounded reaches. Their early efforts focused on navigation-related issues (e.g. channel surveys, snag removal, channelization, dredging and dam construction and operation) rather than the environment. However in 1986, Congress designated the entire UMRS as a nationally significant navigation system and ecosystem and authorized the Environmental Management Program "to improve the environmental health of the UMRS and increase our understanding of its natural resources". The program, managed by the Corps of Engineers in partnership with state and other federal agencies, funded two major components: the Long Term Resource Monitoring Program (LTRMP) and Habitat Rehabilitation and Enhancement Projects (HREP).

From 1986 through 2010, the U.S. Congress had allocated about $ 126 million and $ 242 million for LTRMP and HREP, respectively (UMRR EMP 2010). The LTRMP monitors fish, aquatic vegetation and water quality using standardized methods in six areas including three navigation pools in the upper impounded reach (Johnson and Hagerty 2008). Most HREP projects in the upper impounded reach have focused on enhancing backwater areas because of their degrading condition after dam closure and importance as habitat for waterfowl and fishes desirable to the public (UMRR EMP 2010). Habitat projects in the main channel and large secondary channels of this reach have been less prevalent, presumably because habitat there is viewed as less degraded or navigation priorities take precedence. As the name implies, a project-centric (small-scale) approach to management, rather than a systems approach, has been taken by

HREPs. However, current natural resource management efforts and planning incorporate a broader systems view that considers ecological concerns over larger scales such as the cumulative effects of projects, longitudinal fish passage, hydrologic regimes, floodplain processes, nutrient cycling and species diversity (Galat et al. 2007).

3.2.2 Lower Free-Flowing Reach

The lower free-flowing reach has not been afforded similar environmental legislation as the upper impounded reach; rather, management priorities are limited to navigation and flood control as described in the Mississippi River and Tributaries Project as part of the Flood Control Act of 1928. Consequently, fish, wildlife and habitat of the lower free-flowing reach have received little study or management. However, in 1994 states along the lower Mississippi River (Arkansas, Kentucky, Louisiana, Mississippi, Missouri and Tennessee) formed a coalition of natural resource managers and interests as part of the Lower Mississippi River Conservation Committee. This committee has developed a Mississippi River Conservation Initiative to identify wildlife issues and habitat needs and to develop site-specific lists of potential habitat projects. Several recently completed projects have focused on maintaining or restoring flow in secondary channels by notching dikes to allow water to flow through secondary channels. The secondary channels benefit catfishes (Ictaluridae; Driscoll et al. 1999) and probably other rheophilic and euryceous fishes and maintain habitat diversity. Additional secondary channel restoration projects have been requested by state fisheries management agencies.

3.3 Fish and Fish Production

3.3.1 Upper Impounded Reach

The upper impounded reach of the Mississippi River is renowned for its scenery and abundant wildlife including its rich and productive fishery (Fremling et al. 1989; Steuck et al. 2010; Garvey et al. 2010). Recreational fishing accounted for about half of the total visitor days to this reach in the 1990s (~850,000 visitor days fishing; Carlson et al. 1995). Although more recent angler surveys have not been conducted, recreational fishing remains a significant use and sport-fishing tournaments have become common (U.S. Fish and Wildlife Service 2006). As well, the reach still supports a viable commercial fishery, although catch of most species is reduced from historical levels (Pitlo and Rasmussen 2004; Schramm 2004). The combined commercial fishery of the upper and lower impounded reaches averaged about US$ 4 million (adjusted for 2010 dollars) from 2001 to 2005 (U.S. Army Corps of Engineers 2012). Despite significant system modifications, most of the native fish species are still present in the upper impounded reach; missing species mostly are riverine and cyprinid species historically considered rare (Ickes et al. 2005; Steuck et al. 2010). The persistence of most and great abundance of some species in the upper impounded reach might be attributable to their generalist nature. For example, most of the recreationally and commercially important fish species are habitat generalists usually abundant in lakes, reservoirs and river floodplain systems (Becker 1983; Pflieger 1975).

The continued high fish diversity and productivity of the upper impounded reach is likely predicated on its unique hydrology, geomorphology and management history, a history that excluded mainstem levees but allowed for modifications, especially low-head navigation dams. The diversity of aquatic habitat types (i.e. geomorphology) is greater in the upper than in the lower impounded reach where levees separate much of the historical floodplain from the river (Koel 2004; De Jager and Rohweder 2012), and native fish species richness is strongly related to geomorphic diversity (Koel 2004). How the structure of the fish assemblage (i.e. species relative abundance) has changed in the upper impounded reach post-dam is mostly unknown because data from pre-dam times are limited (see Janvrin 2005). Permanent inundation of much of the historical floodplain, continuous connectivity of floodplain lakes, and the development of submersed aquatic vegetation in newly inundated shallow aquatic areas post-dam were thought to have benefited some lentic fishes, including recreationally important centrarchids (Fremling and Claflin 1984; U.S. Fish and Wildlife Service 2006). However, these conclusions were based on anecdotal information, and some lentic centrarchids (e.g. largemouth bass [*Micropterus salmoides*], bluegill [*Lepomis macrochirus*] and crappie [*Pomoxis* spp.]) might have been as prevalent in the system before dams as after (Janvrin 2005). Regardless, these centrarchids have become focal species for management efforts because of their post-dam abundance (i.e. adaptability) and appeal to anglers.

Factors important to fish production, in particular the recreationally valuable centrarchids, in the contemporary upper impounded reach likely includes the quantity and quality of the connected floodplain lakes, permanently inundated shallow aquatic areas, and the active floodplain. Shallow backwaters connected to the main channel (i.e. contiguous) during the warm-water season serve as important spawning, nursery and feeding areas for lentic species (Schramm and Eggleton 2006; Junk et al. 1989). In the upper impounded reach, these areas in the mid and upper portions of the pools are available year round due to permanent inundation of the historical floodplain by dams more so than annual floods. Gutreuter (2004) found that centrarchid abundance, particularly bluegill, largemouth bass and crappies, was greater in the upper than lower reaches of the Upper Mississippi River, and that this difference was related to the quantity of contiguous backwaters greater than 1-m deep. Others have shown that the quality of contiguous backwaters as habitat for lentic fishes in river floodplain ecosystems, including the upper impounded reach of the Mississippi River, is likely dependent on interrelated processes and features including the degree of connectivity to channels, sediment and nutrient inputs, dissolved oxygen and temperature regimes, current velocities, substrate composition, depth and abundance of aquatic and terrestrial vegetation (e.g. Knights et al. 1995;

Rodriguez and Lewis 1997; Miranda 2005). Taken together, these studies imply that fish production is about more than a connection between the river and its floodplain, and that spatial and temporal aspects of the connection determine seasonal habitat quality.

As in other systems and reaches (Junk et al. 1989; Barko et al. 2006; Schramm and Eggleton 2006), some portion of fish production in the upper impounded reach might still be dependent on the characteristics of the flood pulse and active floodplain. For example, Gutreuter et al. (1999) found that lentic species in the upper impounded reach, including bluegill and largemouth bass, grew more during a year with a large and extended warm-water (early summer) flood than during years with more typical floods that are briefer and occur during spring. However, the active floodplain in this reach has received little attention by fish managers compared to backwaters.

3.3.2 Lower Free-Flowing Reach

A comprehensive assessment of the lower Mississippi River has not been conducted in at least four decades. Recreational use and value of the lower river is minimal and has never been quantified. The Lower Mississippi River Conservation Committee has initiated efforts to increase awareness of and access to the recreational resources, but access remains limited (Schramm 2004). Limited commercial fisheries remain active; historical data are not available and current estimated annual landings, albeit based on incomplete reporting, are probably less than 500 t.

Although highly regulated, the lower free-flowing reach provides diverse fish habitats—such as sandbars, steep natural banks, secondary and abandoned channels and main channel—typical of an unaltered river plus additional unique habitats created by wing dikes and revetted banks. Perennial fish habitat on the active floodplain includes borrow pits (ponds resulting from excavating soil to construct the levees) and a variety of abandoned-channel lakes (Schramm 2004). Although recent comprehensive icthyofauna surveys have not been performed, the resident fish fauna of the lower free-flowing reach is presumed to include 109 species, and at least 46 of these species can be classified as dependent on lentic habitats (backwater dependent) during at least a portion of their life cycle (Schramm 2004). Permanent floodplain lakes and borrow pits provide deepwater lentic habitats; but the floodplain itself, when inundated, provides an expansive shallow, standing-water habitat required by many of these backwater-dependent fish. For backwater/floodplain spawners, minimum time for successful reproduction (spawning plus egg incubation) ranges from 1 to 3 weeks. A warm-season flood duration of 6 or more weeks has been suggested as necessary for warm-water fishes to successfully use the inundated floodplain for recruitment (Sparks et al. 1998; King et al. 2003; Janáč et al. 2010). Thus, protracted standing-water conditions provided by an inundated floodplain will benefit the growth and survival of the young of many species.

The inundated floodplain also provides food resources to fishes (Junk et al. 1989). Some fishes migrate onto the inundated floodplain to consume plants and animals. These fish include low trophic-level fishes that forage on the floodplain and then export the energy when they return to the river as the flood waters recede. The floodplain visitors also include higher trophic-level fish, such as blue catfish (*Ictalurus furcatus*) and channel catfish (*Ictalurus punctatus*), that migrate onto the floodplain to benefit directly from the abundant food (Eggleton and Schramm 2004). The floodplain further nourishes the river fish fauna when the progeny of floodplain spawners, containing the energy acquired feeding on the floodplain, return to the river with the receding floodwaters. Although the flood pulse concept (Junk et al. 1989), which is based largely on tropical rivers, predicts that fish growth should be related to the duration and area of floodplain inundation, the relationship is not necessarily simple in temperate rivers. Rutherford et al. (1995) found no relationships between growth and abundance of age-0 and age-1 Mississippi River fishes and measures of floodplain inundation and attributed the lack of the expected relationship to the separation of much the historical floodplain from the river by levees. Schramm and Eggleton (2006) failed to find a positive relationship between the annual growth increment and duration of active floodplain inundation for channel catfish and blue catfish in the lower Mississippi River; however, the annual growth increment was positively related to the days of inundation when water temperature (measured in the river) exceeded 15 °C. In other words, the flood-pulse concept applies to catfish growth in the lower Mississippi River but only when thermal conditions are considered. Several other studies have also demonstrated the importance of coupling temperature and hydrologic conditions to benefit from floodplain inundation (e.g. Ovens River, King et al. 2003; Missouri River, Gelwicks 1995; Mississippi River, Barko et al. 2006; Volga River, Górski et al. 2011). Bioenergetics modelling suggests that extending the current 15 March–15 May average flood pulse (Fig. 4) by 1 month (i.e. to 15 June) would approximately double the production of gizzard shad (*Dorosoma cepedianum*), smallmouth buffalo (*Ictiobus bubalus*), and blue catfish (Schramm et al. 2009); the increased production resulted from the greater duration of floodplain inundation and greater water temperatures during the additional month of inundation (see below).

The modified hydrograph of the lower Mississippi River has resulted in, on average, a briefer and lower flood pulse (Fig. 4). The lower Mississippi River fish assemblage is a warm-water fauna. All species except one resume active feeding and spawn at temperatures above 18 ºC (Schramm 2004). Assessing 70-year-average hydrographs and temperatures, the contemporary lower, free-flowing reach inundates the floodplain for only a few weeks when the water temperature exceeds 18 °C. This contrasts to a 2-month period of warm-water (> 18 °C) inundation before river modifications following the flood of 1927.

There is no “average year”, and river fish must survive diverse environmental conditions, not averages. Under pre-alteration conditions (1900–1925), floodplain inundation at water temperatures greater than 18 °C exceeded 42 days (the 6 weeks suggested as necessary for successful recruitment by Sparks et al. (1998), King et al. (2003) and Janac et al. (2010)) in at least half of the years (Fig. 5). Under post-alteration conditions (1940–2010), floodplain inundation at water temperatures greater than 18 °C exceeded 42 days in only 30 % of the years. Although further

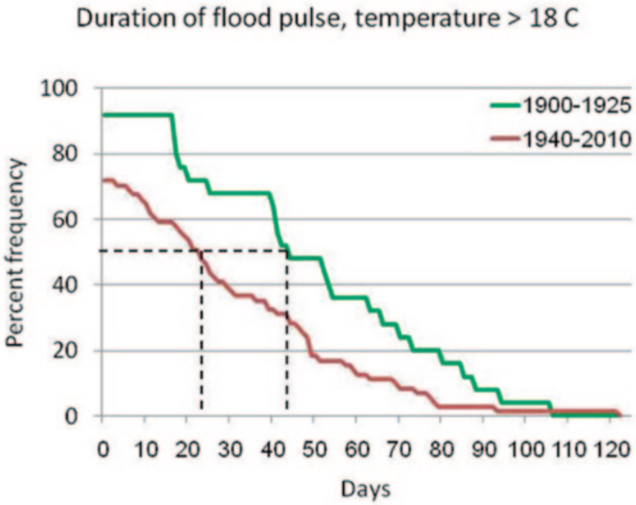

Fig. 5 Cumulative percent frequency of days when the lower Mississippi River floodplain was inundated and the water temperature exceeded 18 °C before (1900–1925) and after (1940–2010) neck cutoffs that shortened the river and the installation of tall levees. *Dashed line* denotes 42 days of inundation, an estimated time required for floodplain-spawning fishes to successfully recruit to the population

assessments of growth and year-class production are needed, it appears that the altered hydrograph may limit fish production in the lower, free-flowing reach.

3.4 Nitrogen Cycling

The Mississippi River transports large quantities of nitrogen from continental North America to the Gulf of Mexico (Goolsby et al. 1999; Meybeck 2003; Rabalais et al. 2007). With point sources (e.g. municipal and industrial wastewater) greatly reduced, contemporary efforts to reduce nitrogen loads have focused on reducing nitrogen applications on farm lands and inputs to the River. Largely overlooked, however, is the potential to manage the Mississippi River to reduce the nitrogen load as it moves through the system.

3.4.1 Upper Impounded Reach

In the upper impounded river, where the connections between the main channel and the floodplain are largely intact, nitrogen cycling is dependent on an interplay between hydrology and floodplain geomorphology. Biogeochemical cycling of nitrogen is most active in off-channel habitats, particularly in backwaters, while nitrogen transport occurs primarily in the main channel (Strauss et al. 2011).

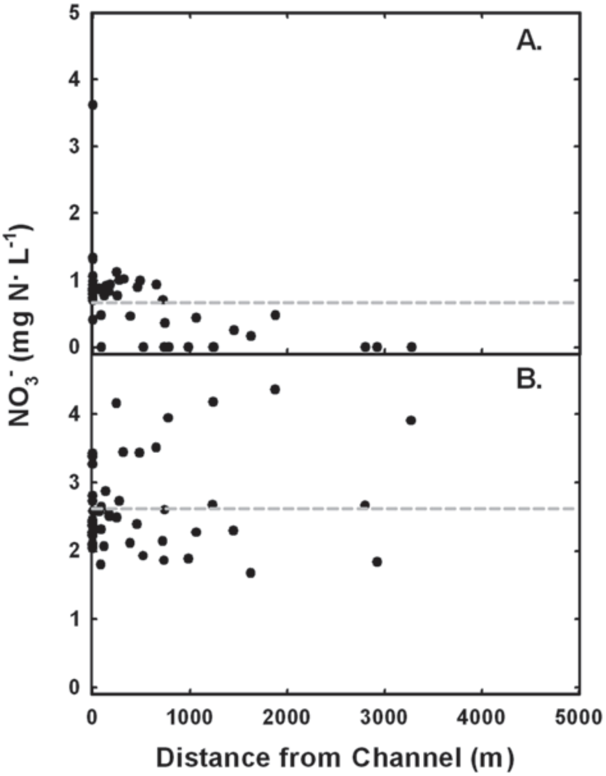

Fig. 6 Distribution of water column nitrate across Navigation Pool 8, upper Mississippi River, during **a** low (Fall 2001) and **b** high (Spring 2001) river discharge. Pool-wide average nitrate concentration was 0.7 mg N L^{-1} during fall sampling (**a**) and 2.6 mg N L^{-1} during spring sampling (**b**). Distance from channel is measured from the center point of the nearest main channel to the sample point while not crossing a land form. (Figure modified from Richardson et al. 2004)

Main channel nitrate concentrations are typically higher than in backwaters and decline as water moves from the channel (Fig. 6a). Nitrogen concentrations are greatest during spring floods when nitrate-rich water is distributed across the flood plain (Fig. 6b). Nitrate concentrations rapidly decline in the backwaters after floods subside (Houser and Richardson 2010) while remaining relatively high in the main channel. Rates of nitrate removal in Pool 8 are great enough throughout the year to remove 6.9 % (6,939 mt N year^{-1}) of the nitrate load carried in the main channel (Richardson et al. 2004). Navigation pools with greater backwater and active floodplain areas (e.g. Pools 8, 9, 13) remove more nitrate than those with smaller backwaters and active floodplain areas (Strauss et al. 2011). The total cumulative effect of nitrate loss in the navigation pools of the upper and lower impounded reaches (Pools 1–26) is the removal of 9.5 % (159,044 mt N year^{-1}) of the total nitrogen load.

Backwaters are depositional zones where fine, carbon-rich particles accumulate and provide abundant carbon for denitrifying bacteria. Backwaters also tend to contain abundant macrophytes that further contribute to the sediment carbon pool.

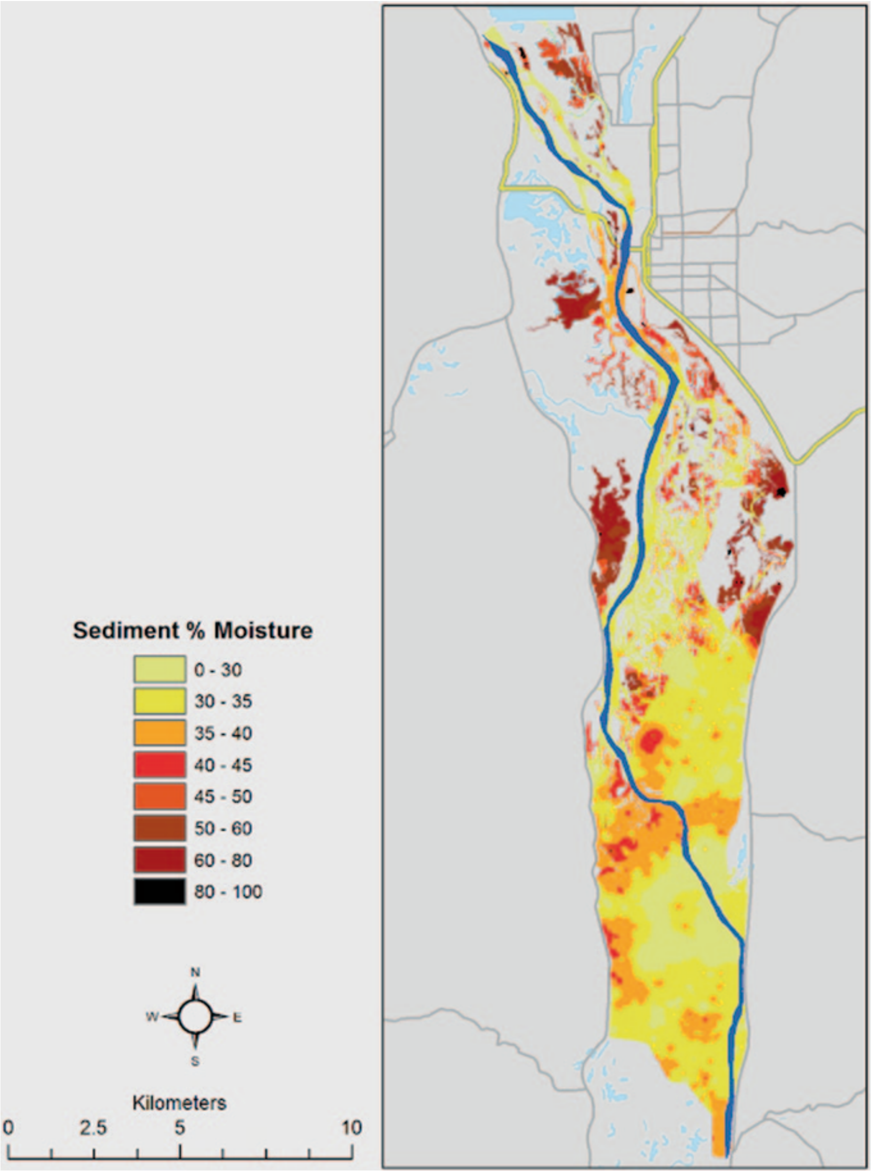

Fig. 7 Sediment moisture (as predictor of sediment carbon concentration; $r^2 = 0.61$) in navigation Pool 8, upper Mississippi River (Rogala 1996). Greatest sediment moisture occurs in backwaters with marsh vegetation (marsh areas in the 1989 coverage of Pool 8 in Fig. 3)

Sediments differ among habitats on the floodplain, and the greatest sediment carbon is found in the more isolated backwaters (Fig. 7). Further, backwater sediments tend to be anoxic due to bacterial metabolism (Wetzel 2001). These factors combine to provide environmental requirements for denitrification (Strauss et al. 2004). Yet, because nitrate is carried primarily in main-channel water, a region of the river generally characterized by oxygenated sediments with low carbon content, there is a distinct miss-match of nitrate source and nitrate removal areas. The carbon-rich backwaters are primed for denitrification, acting as a biogeochemical "hotspot" (sensu McClain et al 2003) upon delivery of nitrate.

Rates of nitrogen cycling are dependent on local river geomorphology, the timing of floods in the backwaters and the supply of nitrate. Local controls of nitrogen cycling include: (1) availability of adequate sediment carbon, (2) sediment anoxia, (3) long hydraulic retention time for enhanced contact of dissolved nitrate with bioactive sediments and (4) periodic connection to channels for replenishment of water-column nitrogen (Strauss et al 2006). While temperature is an important control of bacterial metabolism, denitrification in the backwaters of the upper impounded reach appears more strongly controlled by the four factors listed above. Strauss et al. (2006) showed that ambient denitrification was most strongly controlled by the water column nitrate concentration, while potential denitrification was most strongly controlled by water temperature. Ambient denitrification measures denitrification without the addition of potentially limiting nitrate or carbon and, therefore, is a measure of the actual, not potential, denitrication rate. Potential denitrification is measured by denitrification enzyme assay (DEA) and is measured with excess nitrate or carbon; as such, it is an indicator of the maximum possible denitrification rate and useful for cross-site comparisons of denitrification, but DEA does not estimate actual denitrification (Groffman et al. 1999). Variation in temperature strongly affects nitrogen metabolism measured by DEA because no substrate is limiting. In contrast, variation in ambient denitrification rate is primarily controlled by nitrate concentrations and, to a lesser extent, by water temperature (Strauss et al. 2006). Other studies of wetland nitrate removal also conclude nitrate concentration is the primary driver of denitrification, and water temperature, season and hydraulic retention time are secondary (e.g. Poe et al. 2003; Woltemade and Woodward 2008);

Strauss et al. (2011) expanded on data from Richardson et al. (2004) to estimate seasonal denitrification rates in the main channel, side channel, backwater and impounded areas in an upper Mississippi River navigation pool. Potential denitrification rates varied among seasons but were two to four times greater in backwaters and impounded areas than in the main channel; potential denitrification rates in the side channel habitats were similar to or slightly greater than in the main channel. Generally, potential and ambient denitrification are greater in shallow, slower-flowing habitats where water flows fast enough to replenish nitrate concentrations but not so fast as to erode carbon-rich sediments. Floodplain management to maximize nitrate removal must consider all factors affecting denitrification, particularly through manipulation of water flow; the Finger Lakes project in Navigation Pool 5, described below, is such a manipulation.

Current management of the upper impounded reach partially offsets the nitrate miss-match. Impoundment has increased the area of backwaters where denitrification rates are high, and connectivity between the backwaters and the main channel creates conditions conducive to nitrate delivery to the backwater areas. Yet, management to keep most water in the navigation channel reduces nitrate delivery to off-channel areas throughout most of the year, thereby limiting denitrification.

However, it is likely that greater denitrification occurs now than pre-impoundment due to the greater area of backwaters and greater loads of nitrate (Turner and Rabalais 2003; Belby 2009).

3.4.2 Lower Free-Flowing Reach

The biogeochemistry of nitrogen is no different in the free-flowing river than in the upper impounded river. The striking difference, though, is that the nitrate-rich water is on the floodplain, where denitrification rates are highest, for a brief period of time.

Estimates of nitrogen dynamics in the lower Mississippi River floodplain based on fundamental rate functions and aquatic ecosystem and fish bioenergetics models indicated that denitrification was dominated by soil/bacterial processes and increased from 542 kg ha^{-1} during a 2-month, cool inundation scenario to 976 kg ha^{-1} when inundation extended one additional month and water temperature warmed (Schramm et al. 2009). Sequestration of nitrogen by aquatic biota and fish was relatively minor for both 2-month and 3-month inundation scenarios. While potentially informative, these estimates require validation. Denitrification rates on the floodplain in the lower free-flowing river are less likely to be nitrate limited during the period of inundation than in the upper impounded reach because the nitrate-rich flood waters will freely flow onto the floodplain (Richardson et al. 2004); but other factors, such as water depth, distance from the main channel and the effects of inundation on soil oxygen are expected to modulate denitrification. Nevertheless, present amounts of nitrate removed will be limited by the short duration of floodplain inundation.

3.5 Achieving Ecological Services

3.5.1 Fish in the Upper Impounded Reach

Managers recognize that the constraints imposed on the ecosystem in the upper impounded reach by navigation and agriculture are not diminishing, and that the production of desirable fish and wildlife populations depend on the quantity and quality of habitat in the now permanently inundated and connected aquatic areas (River Resources Forum 2004). To this end, fish managers have mostly taken a project-centric (small-scale) approach that focuses on improving impounded areas and continuously connected backwaters as habitat for fishes rather than a broader system approach as suggested by literature on large river restoration (e.g. Stanford et al. 1996; Poff et al. 1997; Poudevigne et al. 2002; Buijse et al 2002).

A main thrust of management actions for fish in the upper impounded reach has been mitigating for the aging of the navigation pools. Centrachids are often an explicitly targeted organism for HREPs because they are important to anglers and good surrogates for other backwater-dependent fishes. A prevailing paradigm is that relatively deep (≥ 1 m) and warm ($\geq 1\,°C$), slowly flowing (≤ 1 cm s^{-1}) off-channel areas with adequate oxygen (> 3 mg L^{-1}) needed in the winter for survival of centrarchids and other backwater-dependent fishes (Gent et al. 1995; Knights et al. 1995) are limiting production of these fishes (River Resources Forum 2004). The loss of suitable and necessary off-channel habitats is a result of post-dam sedimentation in the connected backwaters (Theis and Knox 2003) and erosion of island complexes that provided backwater-like conditions (i.e. low-flow and low-fetch) in the impounded area (U.S. Geological Survey 1999).

Management techniques for backwater-dependent fishes have been specific to the area in which they occur. In the riverine and transitional areas of navigation pools, where floodplain lakes have been isolated by dams or are filling with sediments, management strategies call for introducing water via control structures or dredging to increase depth to prevent oxygen depletion in winter and summer (Theiling 1995; UMRR EMP 2010). Enough water must be introduced to offset oxygen demand by organic sediments and decomposing vegetation, yet not too much as to increase current velocities and decrease temperatures to levels harmful to fishes in winter (Knights et al. 1995). For shallow backwaters, increasing depth by dredging also offsets dissolved oxygen depletion by increasing the ratio of water volume to oxygen-demanding sediments (Gent et al.1995; Johnson et al. 1998).

Nineteen of the 27 completed HREPs in navigation pools 1–10 of the upper impounded reach have incorporated flow introductions or dredging to improve oxygen conditions and depth diversity (UMRR EMP 2010). One successful example of flow introduction is the Finger Lakes project in Pool 5. Here, managers enhanced 70 ha of centrarchid overwintering habitat by installing flow-control culverts to regulate flows of oxygen-rich water into a series of backwater lakes at a cost of US$ 1 million (Johnson et al. 1998). Post-project monitoring indicated that physicochemical criteria for centrarchid winter habitat were met in areas previously considered poor habitat, and that bluegill and black crappie (*Pomoxis nigromaculatus*) used these areas in winter.

Management actions to benefit fishes in the impounded areas of navigation pools include (1) the construction of large island complexes to replace those lost to erosion and (2) drawdowns (i.e. lowering water level about 0.3–0.6 m at the dam) in summer to partially emulate pre-dam low-water conditions. Eleven of 27 completed HREPs in pools 1–10 have incorporated island construction (UMRR EMP 2010). For example, an island complex was constructed in the impoundment zone of Pool 8 to provide about 200 ha of overwintering habitat for fish at an estimated cost of about US$ 2.5 million (UMRR EMP 2006). The project area was quickly colonized by desirable aquatic vegetation (Langrehr et al. 2007), and bluegill and largemouth bass abundance increased in the project area (UMRR EMP 2010).

Five pool-wide drawdowns have been conducted in three pools in the upper impounded reach to increase emergent vegetation in littoral habitat of the impounded areas and, to a lesser degree, in other pool areas (River Resources Forum 2007; UMRR EMP 2010). The magnitude or duration of three of these drawdowns was limited because discharge was too low to maintain adequate water levels for navigation in the upper portion of the pool during the drawdown (River Resources Forum 2007). The drawdowns had obvious ecological effects in that most dewatered areas were colonized by emergent aquatic and moist-soil vegetation (River Resources Forum 2007; UMRR EMP 2010); however, the effect of these drawdowns on fish abundance has not been assessed. Given the temporal and spatial scale of the anticipated effects of drawdowns, pool-wide, long-term monitoring will be necessary to evaluate the effects on fish.

In part, the project-centric approach described here might be thought of as making the best of the situation given the constraints and reflects the infancy of restoration efforts in large river systems (Buijse et al. 2002). In essence, managers are not trying to restore the river-floodplain ecosystem to predam conditions, but rather are attempting to enhance or maintain postdam habitat for native species, many of which are generalists that are seemingly adaptable to either natural or impounded systems. Unfortunately habitat for native lentic fishes and other desirable biota is not continually created and maintained by the post-dam system as it was by the predam system; thus, engineered intervention has been and will be necessary. A common fishery management concern of the project-centric approach is how much (habitat) is enough. This is difficult to determine because historical (baseline) data on fish and wildlife populations are limited and clear objectives have not been set. Insights from a hydrogeomorphic-features perspective might be more attainable given data and modelling approaches available for hydrologic and geomorphic features, but whether hydrogeomorphic answers directly translate into relevant biological responses is uncertain.

3.5.2 Fish in the Lower Free-Flowing River

The lower Mississippi River-floodplain ecosystem is little studied, and ecological drivers are incompletely understood. It appears, however, that the altered hydrograph and subsequent decoupling of the flood and thermal cycles adversely affect fish production. The actions to floodproof the lower Mississippi River valley—the tall levees and neck cutoffs—have been successful, as evidenced by the lower and briefer flood pulse (Fig. 4). The lower Mississippi River basin landward of the levees has remained flood free since the alterations in 1928–1940, although the river almost overtopped the levees in 2011. Natural solutions are the preferred way to restore rivers (Poff et al. 1997; Galat et al. 1998); but in the case of the lower free-flowing Mississippi River, restoring the hydrograph requires reversing the engineering works, and this is not a socially or economically viable option.

The present active and connected floodplain, however, could be modified to create a series of shallow impoundments that would allow water to be retained into warm seasons and produce the historical conditions that benefit fish production. A similar design was suggested by Sparks et al. (1998) for the upper Mississippi River and by Amoros and Bornette (2002) for several European rivers. Designed with different water-entry elevations, these modified floodplains could provide diverse conditions needed by a diversity of fishes (Amoros and Bornette 2002). Entrance of water into the downstream end of the impoundment, a process that mimics natural inundation of off-channel and floodplain waters, would minimize sedimentation

(Sparks et al. 1998; Amoros and Bornette 2002). In addition, design and operation of these impoundments has been suggested as a way to favor native species while suppressing non-natives and increasing biodiversity (Connell 1978; Gutreuter et al. 1999; Sommer et al. 2004).

Developing impoundments would be expensive. However, maintaining navigation and flood control in the LMR costs in excess of US$ 200 M per year (Ron Nassar, Lower Mississippi RiverConservation Committee, personal communication). Certainly cost is an issue, and justifying the expense may be difficult in a system that receives little fishing or recreational use. An equal, if not greater, hurdle to restoring ecological functionality of the river-floodplain ecosystem is control of the floodplain. Unlike the upper impounded reach of the Mississippi River, where much of the floodplain is under federal and state ownership, the lower Mississippi River-active floodplain is privately owned. Thus, a major challenge to modification of the active floodplain could be cooperation from landowners in potential programs that would encourage them to sell property or to participate in conservation incentive programs.

3.5.3 Nitrogen Cycling in Upper Impounded Reach

There are no management activities in the floodplain or the channels of the upper impounded reach designed specifically to reduce nitrogen. However, at least one management project designed to increase fish productivity also increased nitrate (and probably sediment) removal. In the Finger Lakes project described above (Johnson et al. 1998), increased water inputs to isolated backwaters used to stimulate fish production also increased nitrogen removal. Nitrogen carried by the inflowing river water was rapidly lost through denitrification (James et al. 2008a, b) and assimilation by periphyton (Kreiling et al. 2010). The rate of nitrate reduction in a given lake was related to the rate of nitrogen loading to the lake and the sediment surface area for nitrate uptake. During floods, when loading and flow-through rates were high, the hydraulic retention time was too short for more complete nitrate removal, and some nitrate was transported downstream. Further, the presence of dense macrophytes enhanced nitrate removal by providing a substrate for nitrate-assimilating periphyton, by increasing water retention and by promoting coupling of nitrification and denitrification (Kreiling et al. 2010). Clearly, reconnection of backwaters to channels improves nitrogen-removal rates but only up to a certain nitrogen load. Yet, this work showed the potential to calculate optimal flows needed to maximize nitrate removal. Similar patterns of nitrogen cycling have been seen on the Danube River (Hein et al. 2004) where river restoration has focused on reconnecting channels and backwaters as a way to create a more naturally functioning river.

Late-summer drawdown of the impounded area to mimic the historical hydrograph to stimulate plant growth and enhance centrarchid fish production may adversely affect nitrogen removal. In vitro experiments suggested that drying of sediments exposed by drawdown would promote nitrogen removal by nitrification of sediment ammonia and ultimately promote denitrification upon sediment rewetting

(James et al. 2004). However, in situ studies indicate drawdown may reduce nitrogen removal (Cavanaugh et al. 2006). In addition to the loss of denitrification that would occur in the formerly inundated backwaters during the period of drawdown, nitrification rates are extremely low, providing little nitrate for denitrification. Further, nitrogen is translocated from deeper sediments into tissues of emergent macrophytes (Kleeberg and Heidenreich 2004; Cavanaugh et al. 2006). These plants die and decompose in the fall when the drawdown ends, depositing organic nitrogen from plant tissues on the sediment surface. This organic nitrogen likely is reincorporated into local biomass or flushed downstream during the next flood.

3.5.4 Nitrogen Cycling in Lower Free-Flowing Reach

The limited studies on nitrogen cycling in the lower free-flowing reach (Schramm et al. 2009) are simplistic in that they only consider water temperature and duration of inundation. Other biotic, abiotic and hydrology-related conditions, especially a supply of nitrate as well as soil carbon and anoxia as described for the upper impounded reach, can be expected to affect denitrification (Kern et al. 1996). Nevertheless, it was evident from Schramm et al. (2009) that the soil accounted for most of the nitrogen removal, and that denitrification increased with temperature. Thus, any management activity that serves to retain water on the floodplain longer and during warmer water temperatures should increase denitrification. The shallow floodplain impoundments proposed to benefit fish production should, by causing soil anoxia and increasing water retention, also increase denitrification. However, as observed in the Finger Lakes project in the upper impounded reach, nitrate loading rate will affect nitrate reduction. Thus, continued input of river water to the impoundments will be needed to maximize denitrification.

Although essentially physically external to the lower Mississippi River in the sense that water flows out of the Mississippi River and does not return, two water diversion projects at the lower end of the river, Caernarvon (rkm 130) and Davis Pond (rkm 190), are the only projects in the Lower Mississippi River designed to remove nitrogen from river water (Mitsch et al. 2005; Turner et al. 2007). These projects are operated to flow Mississippi River water through the marshes of the Mississippi River delta. Although primarily intended to supply sediment to the subsiding coastal marsh and reduce seawater intrusion, these systems have the potential to reduce nitrogen loading to the Gulf of Mexico. Unfortunately, the combined diversion is only 0.65 % of the annual river discharge and results in retention of less than 1 % of the nitrogen load.

4 Synthesis and Conclusions

The Mississippi River is an example of the all-too-common irony that engineered alterations to river-floodplain ecosystems to accommodate modern human needs require an engineered solution to maintain habitats for desirable fish and wildlife communities adapted to the new conditions. A relatively new challenge is recognition that the Mississippi River is also a conveyer of about 1.2 million mt year^{-1} of land-derived nitrogen to the Gulf of Mexico (Turner et al. 2007; Meade and Moody 2010) that is a primary contributor to hypoxic conditions and loss of fisheries production in the Gulf.

We have provided evidence from two different reaches that management of the present-day Mississippi River floodplain is necessary to sustain desirable fisheries and achieve high rates of nitrogen removal. Alteration of the Mississippi River to satisfy needs for commerce and flood control has created very different conditions in the upper and lower reaches, but these differences emphasize the diversity of contemporary river-floodplain ecosystems and provide a broad view of their function. Although seemingly very different reaches with different problems and solutions, a common thread throughout the length of the Mississippi River is that management for social and economic priorities has stabilized the navigation channel, altered the hydrology and removed the dynamic ability of the river to maintain existing aquatic habitat or to create new aquatic habitat needed to replace that lost to dams, levees, channelization and sedimentation.

In the upper impounded reach, most of the historical floodplain and many floodplain water bodies are now permanently inundated and connected to the main channel. The quality of these contiguous, low-flow areas as fish habitat is degrading post dam as a result of sedimentation in the riverine and transitional areas and island erosion in the impounded area of the navigation pools. The relative importance to fish production of the active floodplain as compared to the permanently inundated and connected backwaters in this reach is unknown. In the lower free-flowing reach, an expansive active floodplain receives less frequent inundation during a briefer and colder flood pulse. As in the upper impounded reach, floodplain aquatic habitat is being lost to sedimentation, and a once dynamic and meandering river is no longer able to create new habitat. Thus, in both reaches, geomorphic changes and constrained hydrology have removed the two principle drivers that allow rivers to be self sustaining; and, therefore, engineered solutions are necessary.

The science at present is incomplete but sufficient to guide management efforts that, if implemented in an adaptive management framework, will further advance the understanding of the structure and function of the entire regulated Mississippi River and other temperate river-floodplain ecosystems. In the upper impounded reach, current habitat management for fishes focuses on degraded areas by restoring the immediate post-dam geomorphology, optimizing flow and allowing drawdowns. Management of natural resources in the upper impounded reach has been evolving from a project-centric, small-scale approach to one that considers larger scales, biotic assemblages, flow regimes and other processes (e.g. nutrient cycling and fish passage). In the lower free-flowing reach, the floodplain has not been managed as an aquatic resource, and lack of future management for ecological services could limit further advances in understanding the ecology of the lower Mississippi River floodplain ecosystem. The limited studies conducted also support the conclusion that management to benefit fisheries production will also increase nitrogen removal. The magnitude of the socio-economic consequences of nitrogen-driven eutrophication of the Gulf of Mexico coupled with the increasing need for fish-derived protein (Garvey et al. 2010) and essential nutrients (Arts et al. 2001) may create a sufficient mandate to direct attention to restoring the ecological structure and function of the Mississippi River-floodplain ecosystem.

Additional challenges including invasive species and climate change will further complicate management efforts in this large river-floodplain system. For example, Asian carp (silver carp [*Hypophthalmichthys molitrix*] and bighead carp [*Hypophthalmichthys nobilis*]) have already become biomass-dominant taxa in parts of the system (e.g. Sass et al. 2010) and seemingly little stands in the way for expansion of their range into the upper impounded reach. The silver carp is already established in the lower free-flowing reach of the Mississippi River (H.L. Schramm, personal observation). These large and prolific fishes are planktivores and, thus, their diets overlap with other keystone prey fishes (e.g. gizzard shad), invertebrates (e.g. net-spinning caddisflies), and most larval fishes in the system. Efforts are now underway to develop barriers and chemical control measures to deter their invasion into parts of the upper impounded reach of the Mississippi River (Minnesota Department of Natural Resources 2011).

How climate change might affect the Mississippi River system, including fish and wildlife resources, has received little attention in management or research. Water temperature changes will likely only be a small part of the issue. With changes in climate come changes in precipitation patterns and, in turn, changes in river flow regimes. Some projections have been offered for the Upper Mississippi River basin that may provide insight for changes in nitrogen cycling in the upper impounded reach. Climate change models suggest the Upper Mississippi River basin will experience both warming and elevated rainfall and runoff (Donner and Scavia 2007). Under this scenario of warmer temperature and increased nitrate input, denitrification rates are expected to increase in the river-floodplain ecosystem. However, nitrate loading from agricultural runoff will also increase (Randall and Mulla 2001), and modelling by Donner and Scavia (2007) and others (e.g. Justic et al. 2005) suggest elevated runoff under future climate scenarios will result in increased hypoxia in the Gulf of Mexico. Current land and river management actions to reduce nitrate flux to the Gulf of Mexico may be far too meager to offset the predicted increase in nitrate loading; significant reductions of nitrogen application and increases in wetland acreage (greater than the 10 % increase suggested by Mitsch et al 2001) may be needed for such remediation to occur. We are not aware of any projections of the effect of climate change on upper impounded reach fisheries.

Knox (2000) suggested that the frequency and magnitude of large floods in the Mississippi River Valley is highly sensitive to even modest changes in climate. However, predicting effects of climate change is especially difficult for the lower Mississippi River, which receives the drainage of 41 % of the United States and from widely different climatic regions. Changes in flow regimes probably will affect the composition of the biotic community and rates of key processes including fish production and nutrient cycling. Whether or not the current taxa and their relative abundances can persist will depend on the species characteristics and the magnitude of climate change and associated effects on flow regime and habitat

(Poff 2002). Further, the interaction of flow and temperature must be considered. Regardless, natural resource managers are just beginning to take notice of this new challenge, and taking action is likely a ways off given the uncertainty in making predictions with climate models at management-relevant scales in the Mississippi River ecosystem.

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The Role of Floodplain Restoration in Mitigating Flood Risk, Lower Missouri River, USA

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Abstract Recent extreme floods on the Lower Missouri River have reinvigorated public policy debate about the potential role of floodplain restoration in decreasing costs of floods and possibly increasing other ecosystem service benefits. The first step to addressing the benefits of floodplain restoration is to understand the interactions of flow, floodplain morphology, and land cover that together determine the biophysical capacity of the floodplain. In this article we address interactions between ecological restoration of floodplains and flood-risk reduction at 3 scales. At the scale of the Lower Missouri River corridor (1300 km) floodplain elevation datasets and flow models provide first-order calculations of the potential for Missouri River floodplains to store floods of varying magnitude and duration. At this same scale assessment of floodplain sand deposition from the 2011 Missouri River flood indicates the magnitude of flood damage that could potentially be limited by floodplain restoration. At the segment scale (85 km), 1-dimensional hydraulic modeling predicts substantial stage reductions with increasing area of floodplain restoration; mean stage reductions range from 0.12 to 0.66 m. This analysis also indicates that channel widening may contribute substantially to stage reductions as part of a comprehensive strategy to restore floodplain and channel habitats. Unsteady 1-dimensional flow modeling of restoration scenarios at this scale indicates that attenuation of peak discharges of an observed hydrograph from May 2007, of similar magnitude to a 10 % annual exceedance probability flood, would be minimal, ranging from 0.04 % (with 16 % floodplain restoration) to 0.13 % (with 100 % restoration). At the reach scale (15–20 km) 2-dimensional hydraulic models of alternative levee setbacks and floodplain roughness indicate complex processes and patterns of flooding including substantial variation in stage reductions across floodplains depending on topographic complexity and hydraulic roughness. Detailed flow patterns captured in the 2-dimensional model indicate that most

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floodplain storage occurs on the rising limb of the flood as water flows into floodplain bottoms from downstream; at a later time during the rising limb this pattern is reversed and the entire bottom conveys discharge down the valley. These results indicate that flood-risk reduction by attenuation is likely to be small on a large river like the Missouri and design strategies to optimize attenuation and ecological restoration should focus on frequent floods (20–50 % annual exceedance probability). Local stage reductions are a more certain benefit of floodplain restoration but local effects are highly dependent on magnitude of flood discharge and how floodplain vegetation communities contribute to hydraulic roughness. The most certain flood risk reduction benefit of floodplain restoration is avoidance of flood damages to crops and infrastructure.

Keywords Floodplain restoration · Flood risk · Ecosystem services · Missouri River

1 Introduction

Annual costs of flood damage in the United States have been estimated at $ 2.67 billion (Changnon 2008). Traditional policies to reduce risk and damages from floods generally combine upstream controls to reduce peak runoff and downstream controls that may seek to convey floodwaters rapidly through populated areas at a reduced stage (water surface elevation) by channelization, separating floodwaters from property by constructing levees or floodwalls, creating diversions of floodways, or minimizing risk by floodplain zonation policies that remove homes and infrastructure from floodplains. The objective of this article is to explore the common ground between flood-risk reduction and ecological restoration of large-river floodplains, using models of the Lower Missouri River, USA (Fig. 1) at a range of scales relevant to planning and restoration.

Ecological floodplain restoration projects have typically intended to restore ecological functioning of floodplains by increasing the lateral hydrological connections between the channel and the floodplain (Florsheim et al. 2006). Connections can be viewed as four-dimensional, including lateral, longitudinal, and vertical dimensions (groundwater and hyporheic flow), and the time dimension of when and how long flooding occurs (Junk et al. 1989; Tockner et al. 2000; Poole 2002). Restoration objectives for timing of connection have been set to replicate aspects of the natural hydrograph (Poff et al. 1997) or have been based on attempting to fill specific life-history requirements of riverine species (Scott et al. 1997).

How much hydrologic connectivity should be achieved in ecological restoration is a matter of debate in many river systems. Objectives range from return to a historical reference condition to implementation of connectivity designed to meet specific goals while accommodating other uses of the floodplain (Rhoads et al. 1999; Sparks et al. 1998; Gore and Shields 1995). Ecological restoration of large-river floodplains typically follows the concept of "designer ecosystems" wherein designs seek

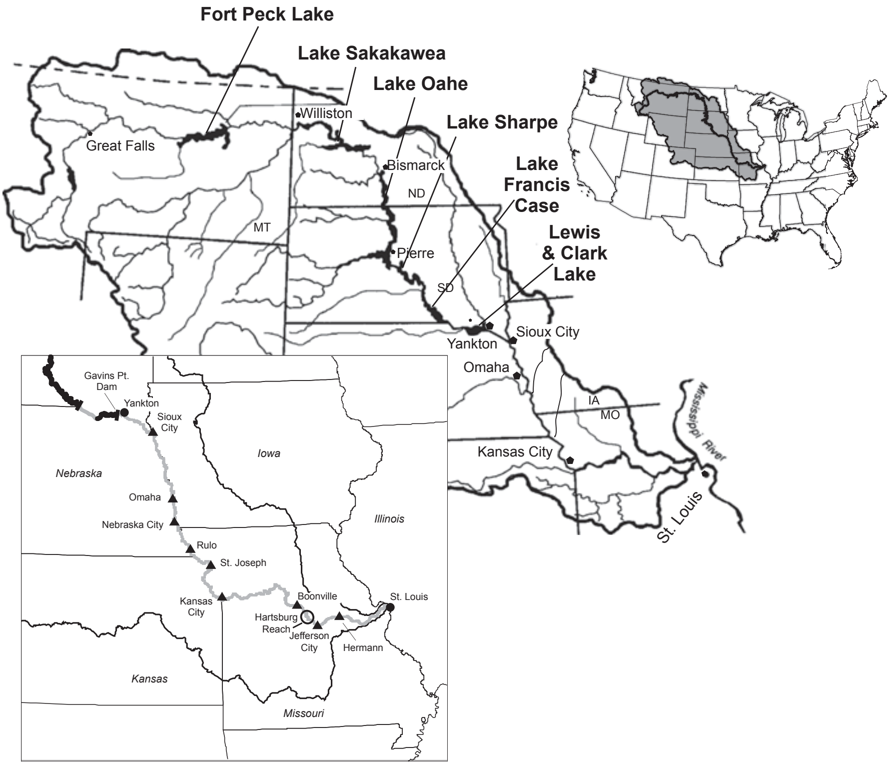

Fig. 1 Location of the Lower Missouri River, Boonville segment, and Hartsburg reach

to optimize a socially acceptable mix of ecological and socio-economic objectives (Palmer et al. 2004; Marris 2011). Design of a non-natural, sustainable, ecosystem presumes a comprehensive and quantitative understanding of ecosystem form and processes and the skills to engineer a functioning system. However, studies of the state of the art of ecological river restoration indicate that a great deal of uncertainty continues to exist in theory and practice (Palmer et al. 2005, 2010; Wohl et al. 2005; Simon et al. 2011).

Connectivity that might be beneficial to floodplain ecosystems is often viewed as destructive flooding by those who live, work, or cultivate in a floodplain. Hence the history of river management is dominated by channelization and construction of levees that seek to minimize hydrologic connectivity of floodplains (Tobin 1995). Constraining flooding with levees has been associated with "flood amplification," a process by which decreased flood conveyance results in increasing flood stages and consequent economic pressures to build levees yet higher (Pinter et al. 2002, 2010). In addition, when levees are breached due to engineering failure or overtopping, concentrated flow of high-velocity water can result in erosional and depositional damage to agricultural lands and infrastructure that is much greater than the cost of inundation alone (Jacobson 2003; Schalk and Jacobson 1997; Jacobson and

Oberg 1997). Concerns about flood amplification and future climate and land-use changes have prompted the Dutch to institute a system of engineering changes on the Rhine River to provide greater flood conveyance while maintaining traditional socio-economic uses of the channel and floodplain and, in some cases, increasing habitat benefits, the so-called "Room for the River" program (Fokkens 2007). Similar downstream approaches have been espoused on rivers of the mid-North American continent following major flood events, such as the 1993 flood in the Mississippi River basin which has been estimated to have caused as much as $30 billion in damage (Interagency Floodplain Management Review Committee 1994; National Oceanic and Atmospheric Administration Satellite and Information Service 2011). In a seminal document assessing floodplain management following the 1993 flood (the "Galloway Report"; Interagency Floodplain Management Review Committee, 1994), the committee argued for a systematic, coordinated approach to floodplain management that included the recommendation that flood-prone lands could be purchased or zoned to minimize flood risk and maximize ecological values. After extreme flooding on the Missouri River in 2011, the U.S. Army Corps of Engineers (Corps) argued that flood-risk reduction for extreme floods cannot be accomplished through upstream reservoir management alone; rather, progress in flood-risk reduction would require complementary implementation of downstream approaches, including "changing local zoning ordinances, changing existing levee alignments or setting back levees to allow more room for the river" (McMahon 2011).

1.1 Conceptual Functions of Flow Corridors

Flow corridors (or floodways) discussed here are floodplain areas adjacent to the channel that are allowed to flood periodically. Flow corridors may be geomorphically dynamic and conform to the idea of erodible river corridors (Piégay et al. 2005), or in the case of many channelized rivers, the channel and flow corridor are laterally stabilized but allow for dynamic hydrology and some vertical geomorphic change by erosion and deposition. Because of their relatively wild nature compared to leveed sections of developed floodplains, floodways provide opportunities for restoration of floodplain ecological processes.

Floodways constructed through levee setbacks or removal may provide flood-risk mitigation through three interacting mechanisms. The first of these is local stage reduction. By providing additional overbank area for flood waters, local stages are expected to decrease. Average overbank velocities are also expected to decrease as depth and hydraulic radius are decreased. This first-principles analysis is complicated by two critical uncertainties: how vegetation-induced hydraulic roughness may evolve in the overbank area and how subsequent erosion or deposition may alter the hydraulic geometry. It would not be unexpected to have increased deposition and loss of cross-sectional area in response to the growth of hydraulically rough floodplain vegetation communities, resulting in a progressive recovery of flood stages unless compensated by channel erosion. Presumably the cross sectional geometry would eventually approach a dynamic equilibrium state adjusted to the flow regime and sediment supply, but the ultimate form, and effects on stage and velocity, are difficult to predict.

The second hypothesized flood-risk benefit is flood-wave attenuation, wherein a combination of static and transient water storage in the floodplain would be sufficient to decrease peak discharge and delay downstream propagation (or celerity) of the floodwave. Attenuation can be a complex process because it depends on the interaction between the flood volume and timing, channel-floodplain geometry, and distribution of hydraulic roughness. Attenuation may be strongly affected by constructed features like levees and road embankments which create areas with very low velocities or "dead storage" at some discharges and locations, but may accelerate velocities and reduce attenuation at other discharges and locations. Timing and locations of levee overtoppings or breaches may also complicate attenuation processes, at times either decreasing or increasing downstream-directed discharge as leveed areas fill; for very large floods like the 1993 flood on the Mississippi River, all floodplain storage may be filled, thereby minimizing attenuation (Scientific Assessment and Strategy Team 1994). Previous studies of the effects of restoration of small streams on flood-wave attenuation have documented a range of potential attenuation from relatively small effects (Sholtes and Doyle 2011; Thomas and Nisbet 2007) to substantial decreases in peak discharges and celerity (Anderson et al. 2006). Few studies have addressed rivers as large as the Lower Missouri.

The effects of floodways on stage and attenuation are also coupled to groundwater in alluvial aquifers. Some alluvial aquifers are quite permeable and may recharge or drain depending on surface-water stage (Kelly 2004). Similarly, surface-water which is detained on floodplains will have a greater chance of infiltrating vertically into subsurface aquifers or being lost to evapotranspiration, both of which may contribute to attenuation under some conditions. Retention of water on the floodplain may be considered a benefit or a cost: in most cases, retention of water in floodplain wetlands would be considered an ecological benefit whereas retention ponding in agricultural floodplains would be considered a cost.

The third hypothesized benefit is that floodways may also act to decrease flood risk by removing high-value crops, land uses, or infrastructure from the areas most susceptible to flooding. The floodway may thereby act to decrease the economic consequences of flooding, with or without diminished flood stages or peak discharges (Remo et al. 2012).

The value of a floodway or flow corridor can be considered in terms of goods and services it adds (or subtracts) from the totality of goods and services provided by a river and its floodplain. In a broad sense, all these goods and services can be considered ecosystem services because they emanate from the natural capital of the river ecosystem. Conventionally, large-river corridors (channels and floodplains) have been recognized for their support of numerous ecosystem services that are of direct human value, including provision of water for public supply, navigation, hydroelectric power, development sites, recreation, and floodplain agriculture. Rivers and their floodplains also contribute ecosystem services that have not been conventionally accounted, especially in commercial markets. These can be considered natural ecosystem services (Jacobson and Berkley 2011) and include regulating services (nutrient cycling, carbon sequestration, and flood storage), and supporting services that lead to productivity and biodiversity (de Groot et al. 2002; Costanza et al. 1997). Socio-economic and natural ecosystem services can be mutually supporting (for example, nutrient cycling, primary productivity, biodiversity, and recreation). Others are less compatible, such as flood storage and development of urban infrastructure.

A fundamental challenge persists in the fact that socio-economic ecosystem goods and services are readily monetized whereas many of the natural services are poorly quantified and less amenable to monetization (Jacobson and Berkley 2011). Conceptually, the scientific challenge is to construct the trade-off between socio-economic and natural ecosystem benefits of the floodplain in various configurations, while the management challenge is to select and implement a mix of the two that optimizes total benefits. Although the necessary comprehensive and quantified accounting of ecosystem services provided by restored floodplains may not presently be possible, progress can be made in exploring the fundamental physical, chemical, and biological processes that will underlie such an accounting.

The intent of this article is to begin to address this complex challenge by quantifying the interactions of flow, floodplain morphology, and land cover that together determine the biophysical capacity of the river corridor at various scales. Our emphasis is on developing an understanding of how flow corridors may contribute to regulation of flood stage and storage, and minimize flood damages. We use the Lower Missouri River (downstream of Gavins Point dam, Fig. 1) as an example of a large, floodplain river subject to multiple management objectives.

2 Background

2.1 The Lower Missouri River

The Missouri River (Fig. 1) drains more than 1.3 million km^2 of the United States and Canada. The river has been highly altered by dams and channelization. The mainstem reservoir system managed by the U.S. Army Corps of Engineers contains over 91 km^3 of storage managed for hydropower, flood control, water supply, navigation, recreation, and fish and wildlife (Galat et al. 2005). The mainstem reservoir system has altered the flow regime substantially, decreasing spring peak flows, increasing daily flow variance in inter-reservoir area due to hydropeaking, and increasing summer low flows downstream of Gavins Point dam. Flow variability increases downstream from the dam as less-managed flows combine with the mainstem discharges (Jacobson and Galat 2008).

The mainstem reservoir system has also trapped much of the sediment flux in the Missouri River basin. Presently, annual suspended sediment load of the Missouri River downstream from Gavins Point dam ranges from nearly 0 to 17% of the earliest recorded loads (Jacobson et al. 2009; Heimann et al. 2011). The result of the downstream sediment deficit, along with other physical factors, has been channel incision (Schmidt and Wilcock 2008; Williams and Wolman 1984). Altered sediment transport capacity, channelization, tributary sediment supply, and commercial sand dredging have all contributed to downstream variation in streambed adjustments (Jacobson et al. 2009; U.S. Army Corps of Engineers 2007; National Research Council 2011).

Before European settlement, the sand-bedded Missouri River was a highly dynamic, braided to anastomosed channel characterized by rapid channel migration, complex channel morphology, and a highly connected floodplain (Jacobson and Galat 2006; Moody et al. 2003). The downstream 735 miles[1] of the Lower Missouri River have been channelized and structured for navigation, resulting in loss of two thirds to three quarters of the channel top width, a simplified channel, and stabilized banks (Funk and Robinson 1974; Hallberg et al. 1979). River-training structures (wing dikes) focus the flow and maintain a navigation channel 9 ft (2.7 m) deep and 300 ft (91 m) wide. The type, extent, and spatial density of wing dikes varies along the channel; wing-dike lengths decrease markedly upstream of the Kansas River confluence (river mile 360; river km 575). Channelization was accompanied by levee construction on adjacent and accreted lands. Although the early plans for channelization of the Lower Missouri River included management of a 3000 ft (914 m) floodway upstream of Kansas City and a 5000 ft (1524 m) floodway downstream of Kansas City (Pick 1944), the floodway was incompletely incorporated into levee alignment designs. Instead, levees along the Lower Missouri River include a mix of federal and private agricultural levees designed to a range of specifications and with a variable floodway width. Presently, confined width between levees or between levees and bluffs ranges from 240 to 26,600 m. The longitudinal distribution of levees varies from upstream near Gavins Point dam, where channel incision and a highly managed flow regime have diminished a need for levees, to downstream around urban areas in Omaha, Kansas City, and St. Louis where high federal levees and floodwalls provide protection from events exceeding the 0.2–1% annual exceedance probability floods (Fig. 2d).

Variable channel adjustment, flow-regime alteration, and channel-training engineering have resulted in variable opportunity for flood discharges to connect with and inundate of floodplain along the Lower Missouri River (Fig. 2e, f); hence the potential for ecological restoration of floodplains is highly non-uniform along the river (Jacobson et al. 2011). At the scale of individual valley bottoms, restoration potential varies with depositional history and geomorphology. Ridge and swale topography is typical of the most recently deposited sediments of the pre-engineered river, where it is not obscured by late Pleistocene loess or leveling and grading. The ridges mostly are remnants of sandy point bars and the swales are infilled channels, which tend to be composed of less-permeable, silt and clay sediments (Holbrook et al. 2006). This alluvial architecture results in juxtaposition of landscape patches

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[1] River miles are the conventional units of measurement for distance along the Missouri River and are retained in this article to facilitate communication with management agencies and stakeholders. River miles start at zero at the confluence of the Missouri River with the Mississippi River.

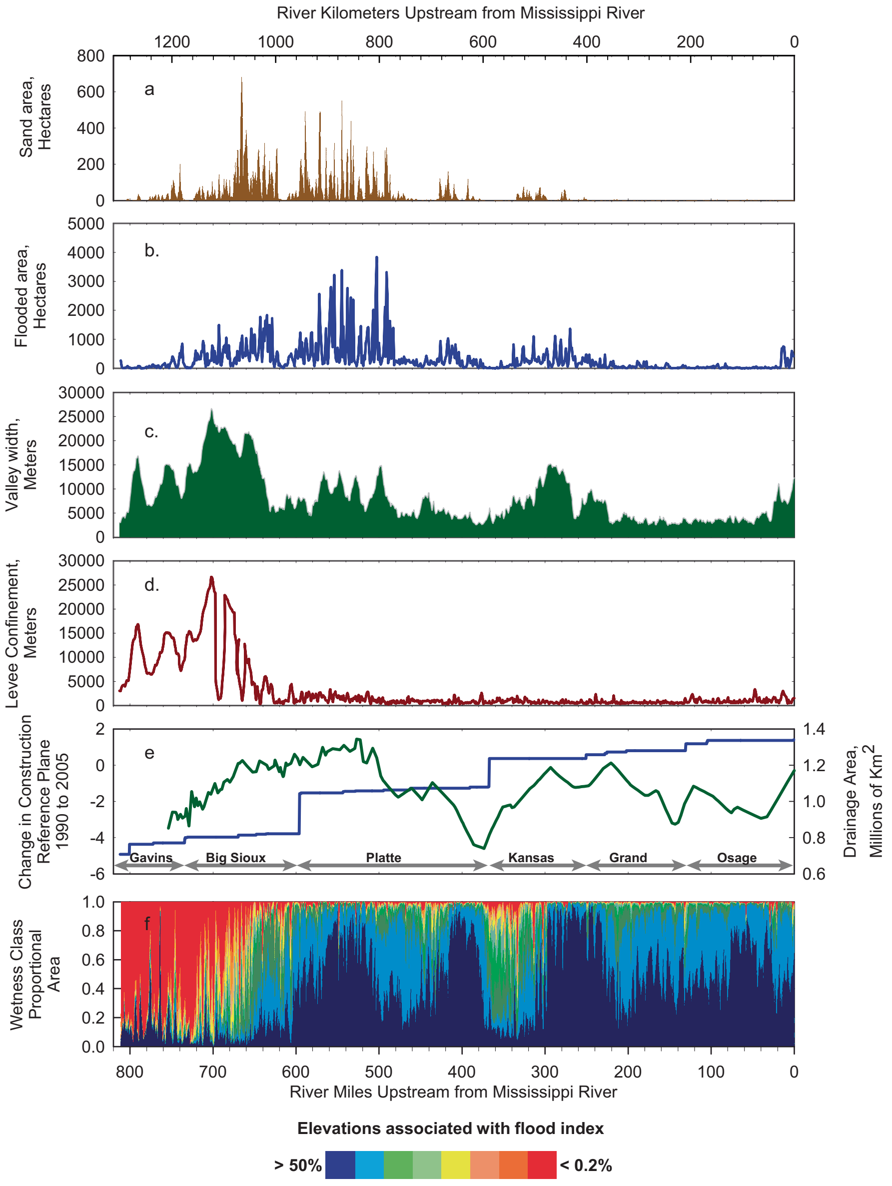

Fig. 2 Longitudinal plots of the Lower Missouri River. **a** Floodplain sand deposition, 2011 flood, **b** Flooded area, 2011 flood, **c** Valley width (includes floodplain and low terraces), **d** Confined width of channel between levees or valley wall, **e** Changes in construction reference plane (water-surface elevation at 75 % flow exceedance) from 1990 to 2005 indicating areas of channel incision and aggradation/loss of channel conveyance (Jacobson et al. 2009) and cumulative downstream increase in contributing drainage area, **f** Proportion area of the floodplain at or above elevation of indicated wetness classes. (Jacobson et al. 2011; Chojnacki et al. 2012)

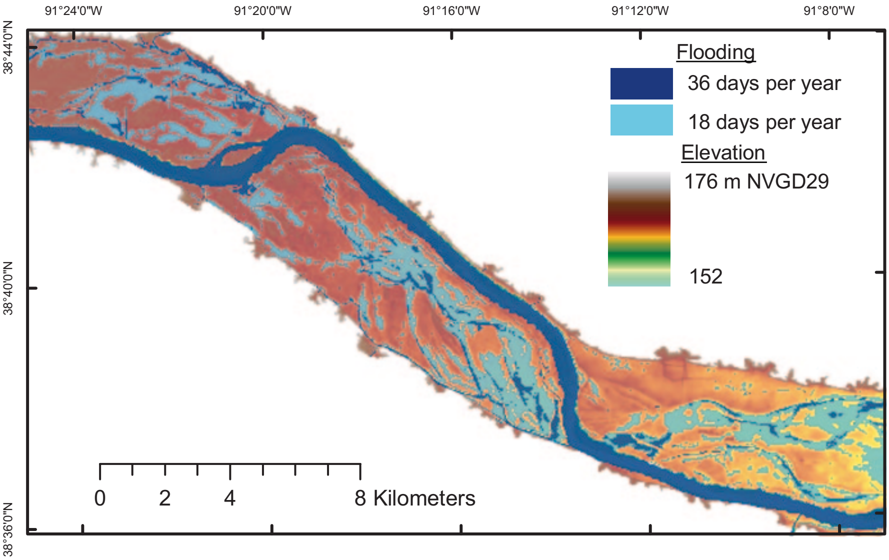

Fig. 3 Map showing inundation of a typical long bottom of the Missouri River floodplain near Berger, Missouri. 18 days per year and 36 days per year inundation are shown in shades of *blue*. Relatively frequent inundation is complex and proceeds from downstream to upstream

with varying access to surface water, interaction with groundwater, and permeability of the underlying sediment. The valley bottom width (measured from bluff to bluff) is highly variable (Fig. 2c) upstream of river mile 250, ranging up to 25,000 m. From river mile 250 to the mouth, the valley bottom width narrows to a mean of 4500 m. Here, the river bottoms have been classified as "long" and "loop" bottoms, indicative of their differing length to width ratios (Schmudde 1963). Because the valley bottoms naturally slope somewhat greater than the meandering mainstem channel, natural flooding of the bottoms proceeds from downstream to upstream, progressively backflooding swales until flow overtops the upstream bank (Fig. 3).

2.2 Flooding Processes in the Midwest

The Mississippi and Missouri rivers have experienced a series of significant floods in the late twentieth and early twenty-first century. Flooding in 1973 on the Mississippi River focused attention on the potential amplification of floods by loss of conveyance due to levees and other structures (Belt 1975). Extreme flooding in 1993 in the Mississippi and Lower Missouri Rivers prompted additional concerns that increased flood stages and associated levee breaks were responsible for a substantial portion of the overall cost of the flood, which had total damages estimated at $ 16–30 billion; as much as 50 % of the damage was attributed to agricultural lands (Interagency Floodplain Management Review Committee 1994; National

Oceanic and Atmospheric Administration Satellite and Information Service 2011). A detailed analysis of damage to agricultural lands in a levee break in the Missouri River floodplain indicated that conventional flood-damage assessments were likely to underestimate the long-term erosional and deposition damage in levee breaks by a factor of about 10 (Jacobson 2003). Extreme flooding on the Mississippi and Missouri Rivers during 2011 also resulted in extensive damages to urban, industrial, and agricultural lands over broad areas of the Midwest. The costs associated with these floods have been estimated to be in excess of $ 6 billion (National Oceanic and Atmospheric Administration Satellite and Information Service 2011).

After the 1993 Midwest flood, a series of studies was completed to address alternative floodplain management on the Mississippi and Missouri rivers. An important component was unsteady 1-dimensional hydraulic modeling with alternative levee setbacks to quantify stage reduction and flood attenuation that could be provided by connected floodplains under alternative land uses (Scientific Assessment and Strategy Team 1994). The study concluded that under conditions with no levees and extremely low hydraulic roughness (Manning's $n = 0.04$, indicative of grass meadow) the 1993 peak Mississippi River discharge of 23,800 m^3/s could experience stage decreases of 0.8–3.3 m; however, the authors believed that more realistic roughness values representing row crops and floodplain forest could result in stage decreases of 0–2.2 m. At some stations on the Missouri and Mississippi rivers, the highest roughness value explored ($n = 0.64$) resulted in increases in stage relative to the with-levee condition because increased flow resistance compensated for increased flow area.

Recent floods document the importance of flood origin in determining where floods occur along the mainstem Lower Missouri River and the extent to which they can be mitigated by the reservoir system (Fig. 4). The flood of 1993 originated from rainfall in southern Iowa, northeastern Missouri, and northwestern Kansas during the summer of 1993. Runoff accumulated downstream from the mainstem reservoirs so the reservoir system was minimally effective in mitigating the flooding (Wahl et al. 1993). Peak flow annual exceedance probability decreased from 10 to 20 % annual exceedance probability at Sioux City, Iowa to 0.2–0.5 % annual exceedance probability at Hermann, Missouri (Parrett et al. 1993; U.S. Army Corps of Engineers 2004)[2]. This flood was also very long in duration; discharge was above flood stage at Hermann, Missouri for over 2.5 months and annual probabilities for 60, 90, and 120-day discharges at Hermann were estimated to be < 1 % (Southard 1995).

Flooding in 1997 was notable because it originated in snowmelt upstream of the reservoir system, so peak flows were controlled (Fig. 4). Prior to 2011, 1997 provided the highest and longest discharge at Sioux City since the reservoir system began operation in 1967. Peak flow in April was 2745 m^3/s, a less than 5 % annual exceedance probability flood, and discharges were in excess of 1700 m^3/s for

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[2] Annual exceedance probability figures cited throughout this article are from U.S. Army Corps 2004 flow frequency study (U.S. Army Corps of Engineers 2004) and are subject to frequent updates.

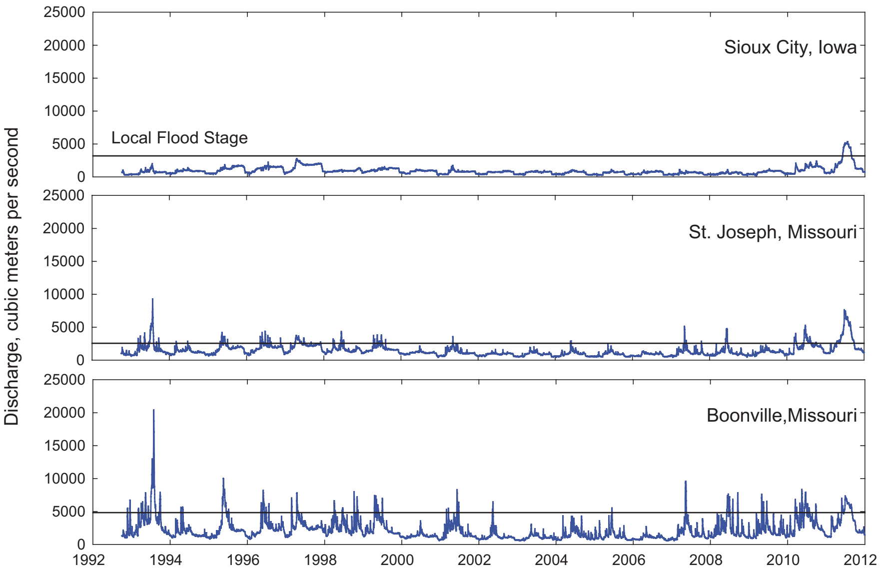

Fig. 4 Hydrographs showing daily mean discharges at three streamflow gaging stations on the Lower Missouri River, 1993–2012

8 months; as a peak discharge, 1700 m^3/s would be between 20 and 50 % annual exceedance probability.

The 2007 flood on the downstream 300 miles (480 km) of the Missouri River resulted from rainfall in eastern Kansas, Nebraska, Iowa and northern Missouri, mostly downstream from the mainstem reservoirs. Flows peaked at 9622 m^3/s at Boonville, Missouri, (between a 10 and 20 % annual exceedance probability) on May 13 and were above flood stage at Boonville for about 12 days.

The 2011 flood was caused by a combination of above-average snow pack and very rare, high-intensity rainfall in eastern Montana during May 2011, upstream of the mainstem reservoir system (Independent Post-Flood Review Panel 2011). The amount of runoff was the highest on record and overwhelmed flood-control capacity of the Missouri River mainstem system (Independent Post-Flood Review Panel 2011). Peak flow at Sioux City was 5348 m^3/s (<0.2 % annual exceedance probability, U.S. Army Corps of Engineers, 2004), the highest since dam closure and almost double the previous post-dam peak. Flow at Sioux City was above flood stage for 80 days. The peak of the flood was substantially reduced by reservoir flood stage; the unregulated peak at Sioux City has been estimated at greater than 7924 m^3/s (U.S. Army Corps of Engineers 2012). Total runoff for the Missouri River mainstem during 2011 was the largest for a 113 year period. Conventional flood-frequency methods estimated 2011 runoff to have a 0.2 % annual exceedance probability and March-July a 0.17 % annual exceedance probability (Independent Post-Flood Review Panel 2011). Because tributaries downstream of the mainstem reservoir system were contributing little discharge, flood exceedance probability decreased downstream to 0.5−1 % annual exceedance probability at St. Joseph and 20–50 % annual exceedance probability at Boonville, Missouri.

3 Approach

We address the relations between flood risk reduction and ecological floodplain restoration by focusing on hydrology, geomorphology, and hydraulics of the river-floodplain system as the primary controls on ecosystem services. To define scales, we use the general hierarchical framework of Frissell et al. (1986) and focus on system, segment, and reach scales. At the scale of the entire Lower Missouri River (system scale, 1300 km, Gavins Point Dam to the confluence with the Mississippi River), we use the Land Capability Potential Index (LCPI, (Chojnacki et al. 2012; Jacobson et al. 2007)). The LCPI was developed from intersection of water-surface elevations derived from a regional 1-dimensional hydraulic model originally developed for flow-frequency estimates with a high-resolution, photogrammetrically derived digital elevation model (U.S. Army Corps of Engineers 2004) and County-level soils data (Soil Survey Staff 2010). The LCPI is considered an index because it simply evaluates floodplain land elevations relative to modeled water-surface elevations without explicit consideration of whether surface water access to a point is prevented by the presence of a levee or natural topographic barriers. Moreover, the LCPI does not account for changing hydraulic geometry should levees be removed (Jacobson et al. 2011; Jacobson et al. 2007). At the system scale, the LCPI provides a basis for accounting for how much floodplain area is potentially available for inundation, water storage, and restoration.

Also at the system scale, we compiled information on levee constriction of the river and on sand deposited on the floodplain by the 2011 flood. Levee information was available from the U.S. Army Corps of Engineers whereas sand deposition was compiled from multispectral satellite imagery collected October and November 2011. SPOT (Système Pour l'Observation de la Terre) 4 and 5 satellites provided 26 10- and 20-m resolution multispectral images that covered the entire 811 miles (1298 km) of the Lower Missouri River at a discharge that was entirely within the banks. Sand was mapped using supervised classification of each image, and confirmed by field visits. Sandbars within the banks were excluded from the analysis. This method results in a conservative estimate of sand deposition because sand overlain by mud was excluded, and sand was undermapped when it was deposited in wooded areas. No attempt was made to relate sand area to volume; however, similar methods after the 1993 flood on the Mississippi River indicated that the minimum detectable thickness of sand is on the order of 60 cm (Jacobson and Oberg 1997).

At the segment scale (85 km), we use a 1-dimensional hydraulic model in two phases to explore the effects of alternative levee alignments on stage reductions and to compare with land availability for ecological floodplain restoration. The first phase of 1-dimensional modeling consisted of steady state models to screen potential flood-risk reduction benefits of various hypothetical changes to floodplain geometry through restoration measures such as levee setbacks and river widening. By balancing water energy and mass between cross sections, the steady-state 1-dimensional model provides average water-surface elevations and average velocities in the channel and overbank areas at each cross section for a fixed discharge. An existing 1-dimensional model originally created for mapping the 1 % annual chance floodplain and calibrated to the 1 % annual exceedance probability profile was selected for analysis (U.S. Army Corps of Engineers 2004, 2008). The steady-state 1-dimensional modeling was performed in HEC-RAS (Hydrologic Engineering Center—River Analysis System) version 4.0.0 using bathymetry and high-resolution digital elevation model contoured at 1.2 m intervals both from 1998 to 1999 data collection, but adding in habitat restoration changes such as levee setbacks and removals, created side channels and other shallow water habitats representative of approximately 2007 conditions. Overbank Manning's roughness coefficients were set to values representative of approximately 2007 overbank roughness visually using available aerial photographs. Cross sections were placed approximately every 1 km and non-conveyance areas were defined in areas such as island levees, continuous small berms, and near roadways thought to have nearly zero velocities. Steady flow was calibrated to observed peak water-surface elevations from the 2007 flood by adjusting the channel hydraulic roughness spatially throughout the model. This model is referred to as the existing conditions (2007) model. A pre-restoration geometry file (1992) was then created by adjusting existing conditions levee locations back to their pre-1993 flood configurations, setting overbank roughness values to agriculture where appropriate, and leaving out other habitat restoration changes such as created side channels, but otherwise keeping channel Manning's n and geometry consistent with the existing conditions model.

Alternative steady state model scenarios used the calibrated roughness values for channel and the 1992 floodplain but used alternative channel geometry and levee locations to test responses to hypothetical restoration scenarios with similar floodplain landcover. Floodplain roughness values were typically 0.04 for cropland and 0.09 for variable floodplain forest, while the channel roughness coefficient was calibrated to 0.022. Steady state models at a 10 % exceedance probability flood (approximately 9960 m^3/s) are evaluated to explore stage reductions relative to the 1992 condition under the following scenarios:

- Widening channel by 46 m. This increase in channel width was selected as a realistic amount of shallow water habitat that could be created with existing USACE restoration authorities to providing increases in shallow, slow water habitats within the channel assuming lands could be acquired from willing sellers.
- Widening channel by 46 m and setting levees back to 305 m. This levee setback distance was arbitrarily chosen as an example representative of a realistic amount of floodplain connectivity that could be achieved with existing USACE restoration authorities assuming lands could be acquired from willing sellers. The levee setbacks were from 1992 levee locations, resulting in a variable flow corridor width that averaged 934 m.
- Levee setback, 305 m, no channel widening.

- No-levee condition, no channel widening. Though highly unlikely to occur, this condition was modeled to test the upper limit of flood risk reduction that could occur through restoration. However, for simplicity groundcover was assumed to remain consistent.

The second phase of 1-dimensional modeling was conducted to test potential attenuation and local stage reduction benefits of the existing conditions (2007) and hypothetical no-levee restoration scenarios of variable floodplain land-use with overbank Manning's roughness coefficients 0.05 and 0.1. The steady-state HEC-RAS model geometries were cropped upstream of Boonville, Missouri and downstream of Jefferson City, Missouri and run in unsteady mode using a daily discharge hydrograph from the May 2007 flood that achieved a peak flow just less than a 10 % annual exceedance probability flood.

Existing-conditions (2007) unsteady HEC-RAS (version 4.1.0) models were calibrated to 2007 water-surface elevations and, where available, to measured overbank and side channel velocities, primarily through spatially varied adjustment of Manning's n. For comparative purposes, 15-min flow data were also input at Boonville to test intra-day attenuation potential of restoration scenarios.

Finally, at the reach scale (15–20 km) we developed a 2-dimensional, depth averaged model using TUFLOW (BMT Group Ltd., Brisbane, Australia[3]) which solves the full free-surface shallow-water equations to provide water-surface elevations, depths, and depth-averaged velocity vectors throughout the modeled domain (WBM Oceanics 2005). This model was compiled for two loop bottoms of the Missouri River, nested within the 1-dimensional model. TUFLOW uses a static topographic boundary condition but editing routines within the Surface-water Modeling System (SMS, Aquaveo, Inc., Provo, Utah) interface allow for rapid updates of topographic elements including alternative levee alignments and wing dikes (Aquaveo LLC 2011). Steady state flows for the 2, 5, and 10-year recurrence intervals and the 2007 unsteady flood hydrograph were used as the upstream boundary condition, while a constant water-surface slope was used as the downstream boundary condition. Measured and modeled water-surface elevations were used to calibrate the model to existing channel conditions under steady state flows. River-training structures were accurately incorporated in the computational mesh in order to capture their potential hydraulic effects. Alternative levee alignments were developed as infinitely high levees so as to not allow overtopping at modeled discharges. Existing levees were removed from the topography by assigning elevations equivalent to adjacent non-leveed areas. Alternative floodplain roughness coefficients were used to test sensitivity to various floodplain vegetation communities. We used Manning's n coefficients ranging from $n=0.05$ (to model low-resistance conditions from fallow agricultural fields) to $n=0.2$. The 0.2 roughness coefficient was selected to represent very high vegetation-induced roughness representative of dense "dog-hair" thickets of young willows and cottonwoods (Flippin-Dudley et al. 1998), although most floodplain forest might be expected to have n values 0.1–0.15 (Arcement and

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[3] Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government

Schneider 1984). The model domain is approximately 20 km along the stream centerline and extends across the entire floodplain from bluff to bluff. The computational grid is 20 m × 20 m and consists of 311,000 cells. Although such models can be used to explore many aspects of hydraulic roughness, channel geometry, and levee alignment, we limit our analysis in this article to illustrating the additional complexities in velocity, depth, and stage distributions that are evident in 2-dimensional model representation, and to evaluating effects of alternative setbacks and typical roughness on water-surface elevation. For setback alternatives we use 1992 levee alignments (levees close to the banks, average confined distance between levees or levees and bluff = 629 m), a 1143 m corridor, a 1524 m flow corridor (equivalent to the 5000-foot Pick-Sloan floodway), and a no-levee scenario where flows have full access across the 3200 m floodplain.

4 Results

Analyses at three scales emphasize the importance of scale in understanding restoration potential and flood-risk reduction. By focusing sequentially at finer resolutions we document how different levels of analysis present useful information at each scale.

4.1 System Scale—Lower Missouri River

Total area and relative area of floodplain lands at or below flood indices vary substantially along the mainstem Lower Missouri River as a result of variation in floodplain width, flow regime, channel engineering, and geomorphic adjustments (Fig. 2e–f). Channel incision and aggradation in the post-dam, post channelization time period have resulted in substantial longitudinal variation of hydroperiod and flood hazard. Aggradation in the Lower Missouri River generally involves the variable distribution of deposition in the channel and in the overbank areas, thereby reducing flood conveyance and increasing stages relative to historic conditions. Channel incision downstream of Gavins Point Dam has been attributed to diminished sediment load and incision near Kansas City has been attributed to a combination of diminished sediment load, including commercial sand and gravel extraction, in the mainstem river, diminished load from the Kansas River, and channelization (Jacobson et al. 2009; U.S. Army Corps of Engineers 2009). The combination of geomorphic adjustment (incision and aggradation) and flow regime determine flood hazards along the mainstem. Although the LCPI dataset (Fig. 2f) is not intended to map flood hazard, it does document longitudinal variation in the area of floodplain lands susceptible to flooding over a range of exceedances, and therefore documents the longitudinal distribution of floodplain lands that are amenable to restoration of connectivity (Jacobson et al. 2011).

The effects of longitudinal variation due to flood hydrology and geomorphic adjustment are evident in maximum flooded area and floodplain sand deposition area associated with the 2011 flood, a flood that originated mainly from upstream of Gavins Point Dam, resulting in discharges with unprecedented duration upstream of the Kansas River (Fig. 2a, b). Most of the flood inundation and sediment-deposition damage to agricultural fields occurred approximately between river miles 450 and 700 (river km 768 and 1120) where discharges were relatively high and aggradation allowed floodwater easier access to the floodplain.

The spatial distribution of floodplain potential is illustrated in Fig. 5, by flood-index category and hydrologic river segment (Fig. 2e) (Jacobson et al. 2010). Based on present-day hydrology and land-surface elevations, little floodplain land is available for restoration or flood storage in the Gavins and Ponca segments; most of the floodplain (or valley bottom) land base is at elevations greater than the 0.2 % flood index elevation. The Big Sioux segment still has a lot of land base at relatively high elevations, but more is available in the elevation ranges of the > 50 % annual exceedance probability to 10–20 % annual exceedance probability floods. Downstream in the Platte, Kansas, Grand, and Osage segments the distribution of floodplain elevation classes is dominated by the 20 to > 50 % exceedance probability classes, indicating greater proportions of floodplain lands amenable to wetland restoration and flood-risk reduction (Fig. 5).

LCPI data also provide a means to calculate floodplain storage volumes relative to flood volumes, an indicator of whether flood-wave attenuation would be likely. In the Platte segment (Fig. 2e), average discharges for 0.2–50 % annual exceedance probability peak discharges (U.S. Army Corps of Engineers 2004) were used to calculate discharge above flood stage, averaged among three streamflow gaging stations in the segment (Nebraska City, Nebraska, Rulo, Nebraska, and St. Joseph, Missouri). The available storage volume in the floodplain was calculated by taking the additional area that could be flooded (assuming no levees) by each additional flood-index class and multiplying by the incremental change in water-surface elevation as determined from rating curves at the three gages. This calculation results in an estimate of cumulative storage volume available as peak stage increases over bankfull. That potential storage volume can be compared to the total volume of the index floods by calculating the volume of water that would be available overbank if the peak discharges were maintained for a series of days. Fig. 6 illustrates the resulting relations of the ratio of potential floodplain storage volume to flood volume, by flood duration and peak discharge exceedance probability.

The graph shows that the Platte segment provides potential floodplain storage that can be as much as 3.2 times the volume of water in a 1 day flood held at the 20 % exceedance probability discharge (about 3760 m^3/s). In general, the proportion of a flood that the floodplain may store decreases rapidly with increasing magnitude and increasing duration. The floodplain would have only 50 % of the volume necessary to store 1 day of the 0.02 % exceedance probability flood (about 9820 m^3/s) and only about 8 % of the volume necessary to store a 20 % exceedance probability flood for 40 days. To place Fig. 6 in real context, the actual discharge at the Nebraska City streamgage in 2011 was equivalent to about a 0.5 % exceedance

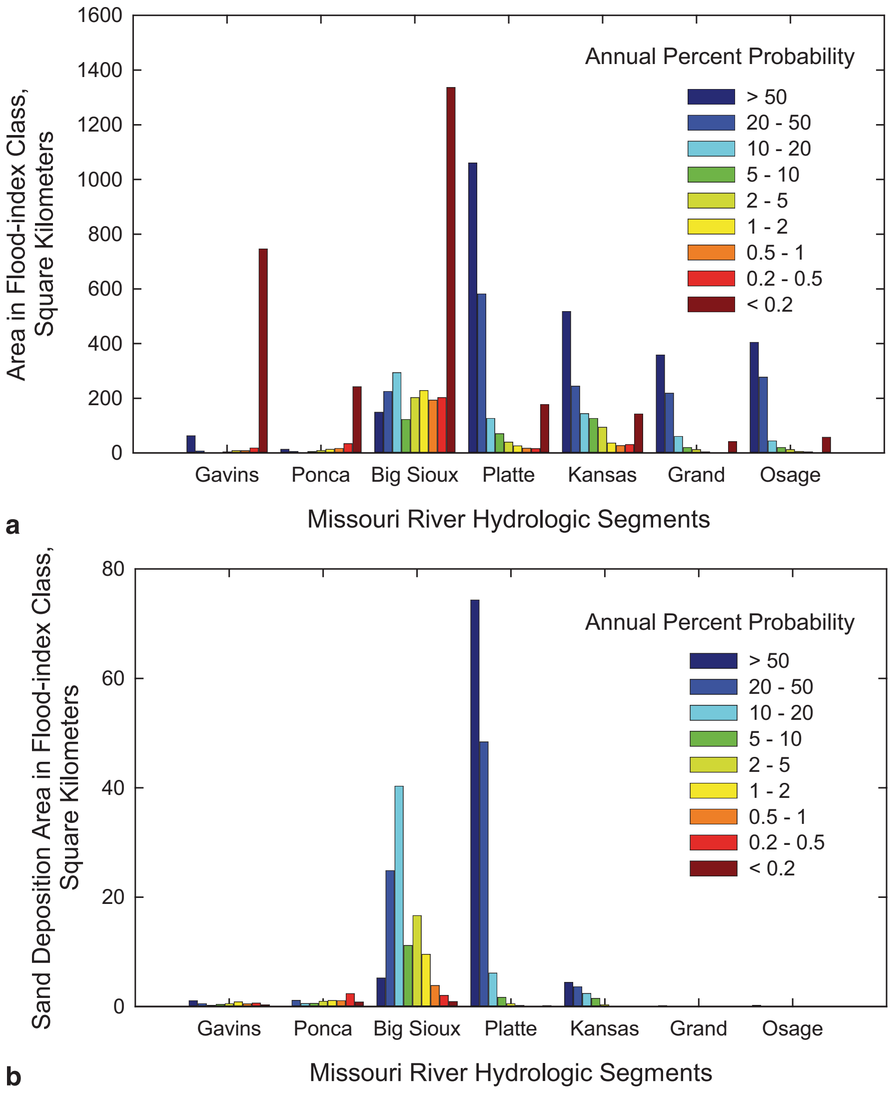

Fig. 5 **a** Floodplain land in flood-index classes by Missouri River hydrologic segments, **b** 2011 floodplain sand deposition in flood-index classes by Missouri River hydrologic segments

probability flood (8120 m^3/s) lasting for about 40 days, (shown by the circled area), indicating that the floodplain potential for storage was only about 2 % of the total flood volume.

Figure 2a also shows flood damages as indicated by deposition of mappable thicknesses of sand outside the channel. The longitudinal distribution of sand deposition reflects the longitudinal variability in flooding. There was little floodplain deposition in the Gavins and Ponca segments; deposition was concentrated in the

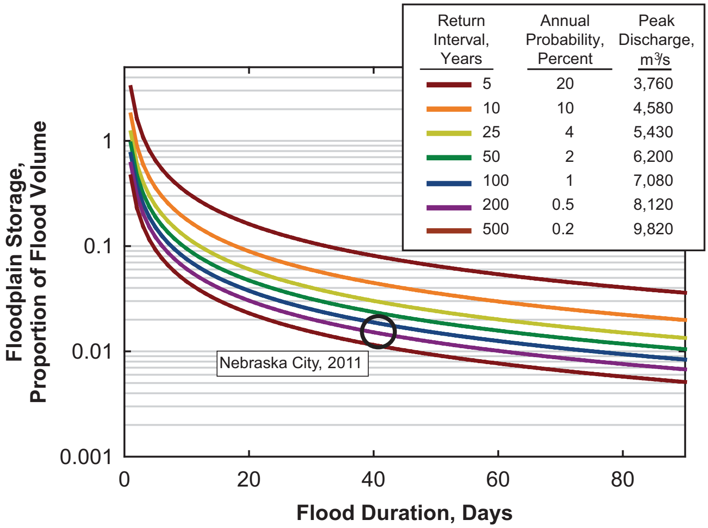

Fig. 6 Relation between available storage on the floodplain of the Platte segment, Lower Missouri River compared to the flood volume by the flood duration and flood peak magnitude. The approximate position of flood volume and duration at Nebraska City, Nebraska in the 2011 flood is shown for comparison

2–20 % annual exceedance probability classes in the Big Sioux segment; and in the Platte and Kansas segments deposition was concentrated in the 10–50 % annual exceedance probability classes (Fig. 5b).

4.2 *Segment Scale Results*

At the segment scale, we explored interactions between floodplain restoration and flood-risk reduction by applying HEC-RAS 1-dimensional modeling. These efforts included scenarios of channel widening and levee setbacks between river mile 197 (river km 315) at Boonville, Missouri and river mile 144 (river km 230) at Jefferson City, Missouri (Fig. 7), a 53 mile (85 km) reach with a significant amount of existing public conservation lands. This segment is also relatively narrow compared to much of the Lower Missouri River, with a mean floodplain width of 4400 m compared to 8188 m for the entire river. For the Grand segment as a whole, 50 % of the valley bottom is at or below the 50 % annual exceedance probability index elevation and 80 % is at or below the 20 % annual exceedance probability elevation (Table 1).

Hypothetical changes to river geometry were compared to the 1992 condition. In 1992, the entire segment was bordered by levees with 5–20 % annual exceedance probability protection. The mean distance between the levees (or between levee and the valley wall) was 629 m while the mean channel bankfull width was 348 m. The 1992 period predated extensive restoration and also was prior to the 1993 flood

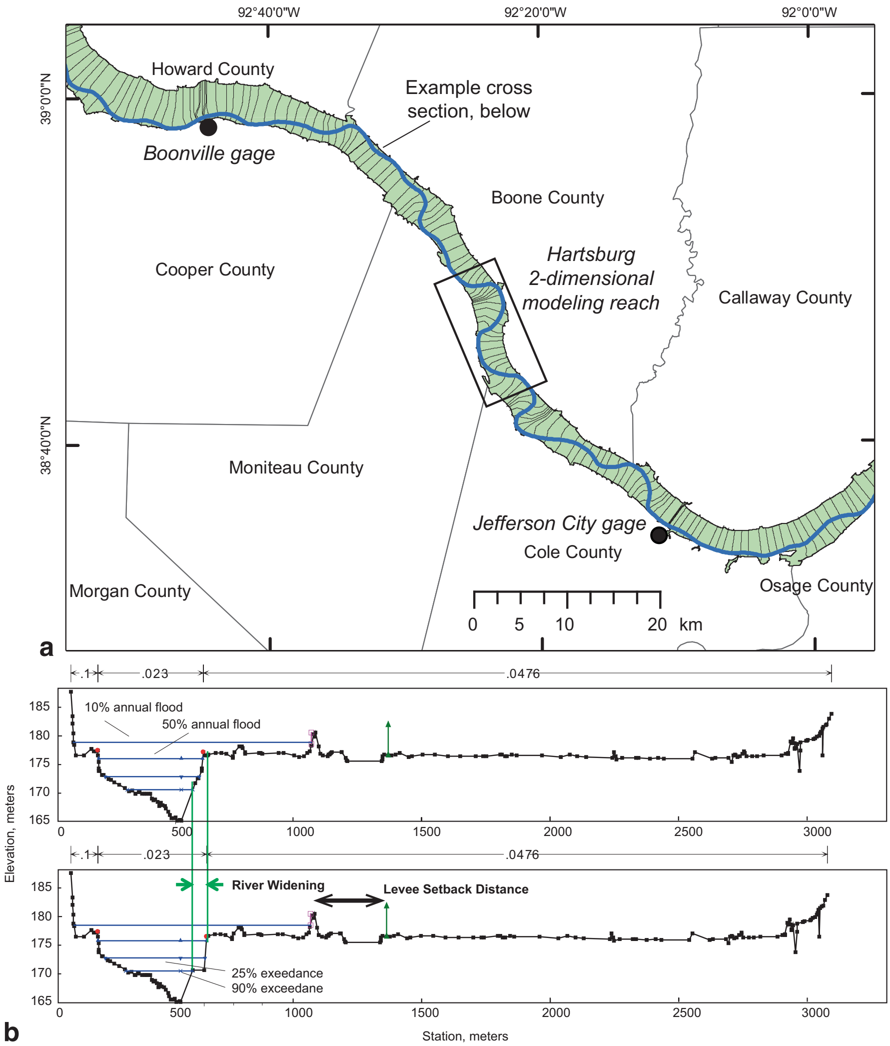

Fig. 7 **a** Map of 1-dimensional modeling reach on the Lower Missouri River showing cross section spacing, **b** Representative cross section of the model showing scale of channel widening and levee-setback alternatives

which breached many levees in the area; some of the levee breaches were repaired subsequently but some were not, especially where land was purchased for conservation.

Channel widening and levee-setback scenarios both were effective in decreasing stages on a cross-sectional average for the steady state 10% annual exceedance flood (Fig. 8). Channel widening of 46 m resulted in an average of 0.30 m of elevation decrease whereas channel widening plus levee setback of 305 m resulted in an average of 0.39 m decrease. The levee setback without widening was effective in

Table 1 Valley width and areas at or below indicated annual exceedance probability flood index by hydrologic segment, Lower Missouri River

	Valley width, meters			Cumulative area at or below indicated flood-index annual chance elevation, square kilometers								
Segment[a]	Mean	Minimum	Maximum	>50 %	20–50 %	10–20 %	5–10 %	2–5 %	1–2 %	0.5–1 %	0.2–0.5 %	<0.2 %
Gavins	9,554	3,013	16,834	63	70	72	74	78	86	95	113	860
Ponca	11,647	8,028	15,094	13	19	22	27	36	49	66	100	342
Big Sioux	15,243	5,158	26,653	149	374	668	790	993	1,222	1,415	1,618	2,954
Platte	7,075	2,536	14,869	1,061	1,643	1,769	1,839	1,879	1,905	1,922	1,939	2,116
Kansas	8,562	2,848	15,181	517	762	906	1,033	1,127	1,163	1,190	1,221	1,364
Grand	4,400	2,423	9,962	359	577	638	658	671	675	677	680	722
Osage	4,527	2,676	12,339	404	682	726	746	758	764	768	770	828

[a] Missouri river segments are defined based on changes in hydrology at major tributary confluences or other factors affecting channel processes (Jacobson et al. 2010), Fig. 2

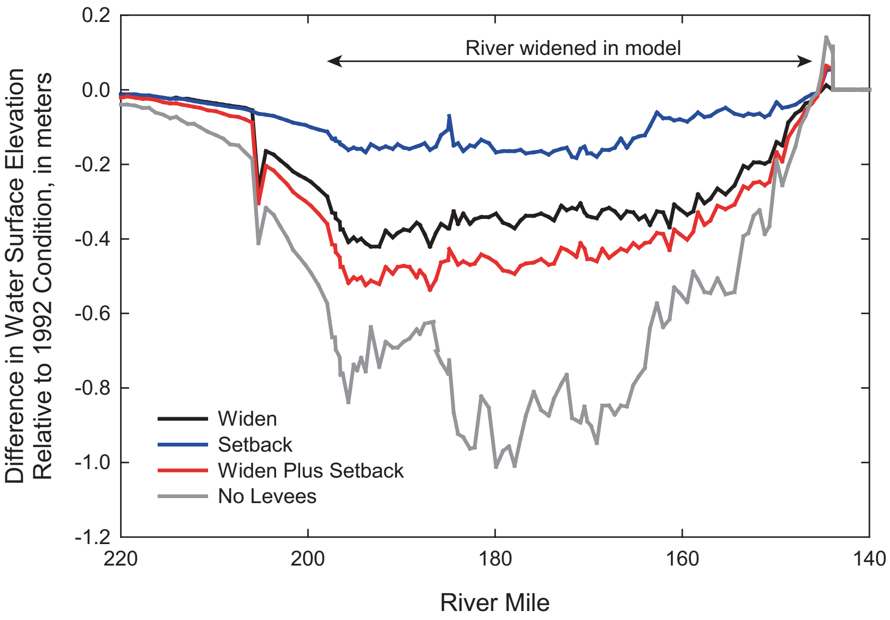

Fig. 8 Longitudinal plots of difference in water surface elevation (scenario minus existing 1992 condition) by 1-dimensional model cross section through the study segment. Flow is from left to right

decreasing stages by approximately 0.12 m. The greatest water-surface decreases resulted from the hypothetical no-levee condition where cross-sectional water-surface elevation decreased by an average of 0.66 m and as much as 1.0 m. The water surface elevation difference plots (Fig. 8) show anomalies at the upstream and downstream ends (river miles 205 and 145; river km 328 and 232) where the sudden imposition of widening created depressions and elevations in the water surface. These scenarios did not look at the effects of changing land use and hydraulic roughness on the floodplain; instead they assumed that floodplain land use would remain in the 1992 condition, a mix of row crop agriculture and successional bottomland hardwood forest.

The unsteady flow model used the 2007 flood as a reference (Fig. 9), routed daily flows through the segment under 2007 levee configuration, 1992 levee configuration, and a hypothetical non-leveed condition. During 2007, 78.3 km^2 of the floodplain (approximately 33.2 %) was in conservation status and approximately 38.2 km^2 was connectable to the river through levee breaches or removal (approximately 16.2 %). The non-leveed condition would allow inundation over approximately 236 km^2 for all floodplain lands. For this unsteady flow analysis, the 2007 flood under 1992 levee configuration peaked at 9588 m^3/s at the downstream end of the modeled reach at Jefferson City, Missouri (Table 2; Fig. 10). The same flood hydrograph under the 2007 levee configuration (partial conservation) peaked at 9584 m^3/s (0.08 % decrease). Under the hypothetical no-levee situation, the un-

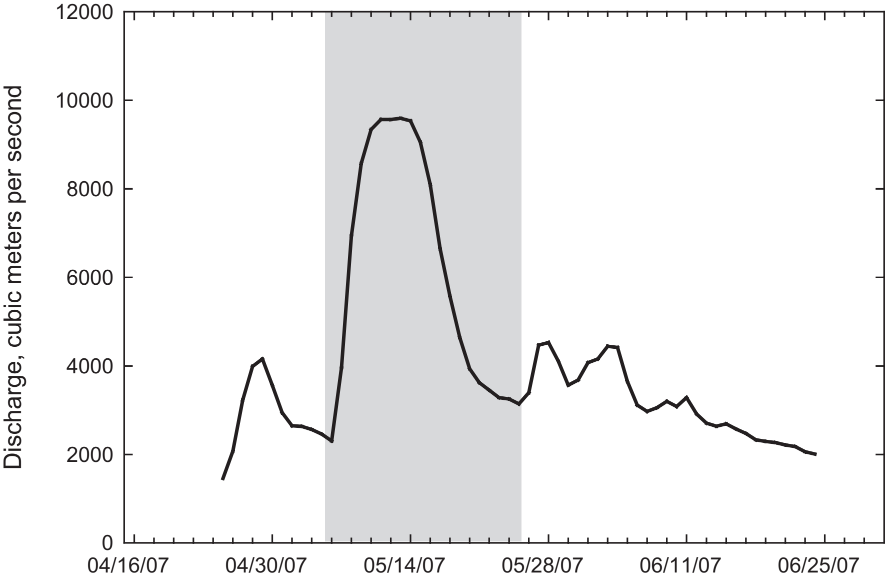

Fig. 9 Discharge of Missouri River at Boonville, Missouri during the spring and summer of 2007. The *shaded box* delineates the portion of the hydrograph used in unsteady flow modeling

steady 1-dimensional model with roughness values of 0.05 and 0.1 resulted in 0.1 % and 0.13 % decrease in peak discharges (Table 2). These changes to peak discharge are subtle and arguably within the range of error of the model. Although peak discharges were not appreciably affected, setback scenarios and roughness had measurable effects on flood-wave celerity, delaying timing of the hydrograph by several hours. Celerity was most pronounced for no-levee scenarios although there was a minor difference in celerity between the roughness scenarios, with faster celerity being associated with lower roughness (Fig. 10). Models with 15-minute flow data (not presented here) showed similar results as routing daily flows, decreasing peak discharges by 0.2 % for partial restoration and 0.5 % for full restoration scenarios; however, restoration appeared to smooth out and reduce the within-day variability of flow and stage at Jefferson City, making the river less responsive to smaller within-day peaks while the hydrograph was at its crest.

4.3 Reach Scale Results

Two-dimensional hydraulic modeling using the TUFLOW model presents opportunities to evaluate the spatial complexity of floodplains and improve on understanding of velocity and water residence time. We selected the Easley-Hartsburg reach from river mile 161 to 174 as a representative of loop bottoms of the Lower Missouri River (Fig. 11). We calibrated the model to a 1-dimensional steady state water-surface elevation for a 10 % exceedance probability flood (9962 m^3/s) with

Table 2 Changes in peak discharge for 1-dimensional unsteady flow model, daily mean discharges, 2007 flood hydrograph

Scenario	Peak discharge at Boonville, Missouri	Peak discharge at Jefferson City, Missouri	Decrease relative to 1992	Percent decrease relative to 1992 (%)
1992 geometry, 2007 roughness	9593.7	9587.5	NA	NA
2007 geometry, 2007 roughness	9593.7	9584.2	−3.4	−0.04
No levee hypothetical, floodplain 0.05 roughness	9593.7	9577.5	−10.0	−0.10
No levee hypothetical, floodplain 0.1 roughness	9593.7	9575.3	−12.2	−0.13

NA not applicable

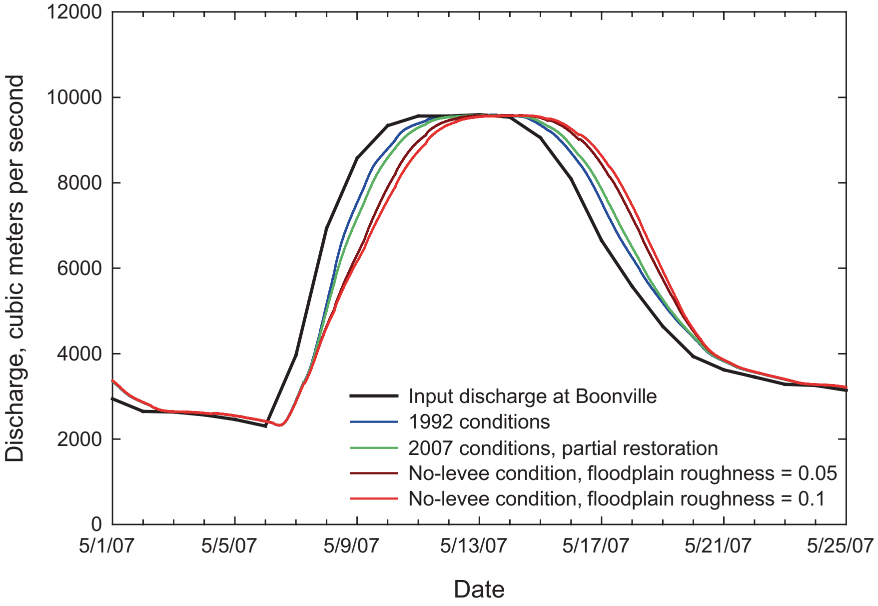

Fig. 10 Unsteady input and output 2007 hydrographs of the 1-dimensional model for 1992 condition, 2007 partially restored condition, and two hypothetical no-levee scenarios with floodplain roughness of 0.05 and 0.1. The input hydrograph (*black*) is at Boonville, Missouri; the other hydrographs are discharge at Jefferson City, Missouri 85 km downstream

non-breaching agricultural levees (U.S. Army Corps of Engineers 2004). Calibration under the leveed condition was insensitive to floodplain roughness because the little overbank area outside the channel was flooded. We limit this analysis to (1)

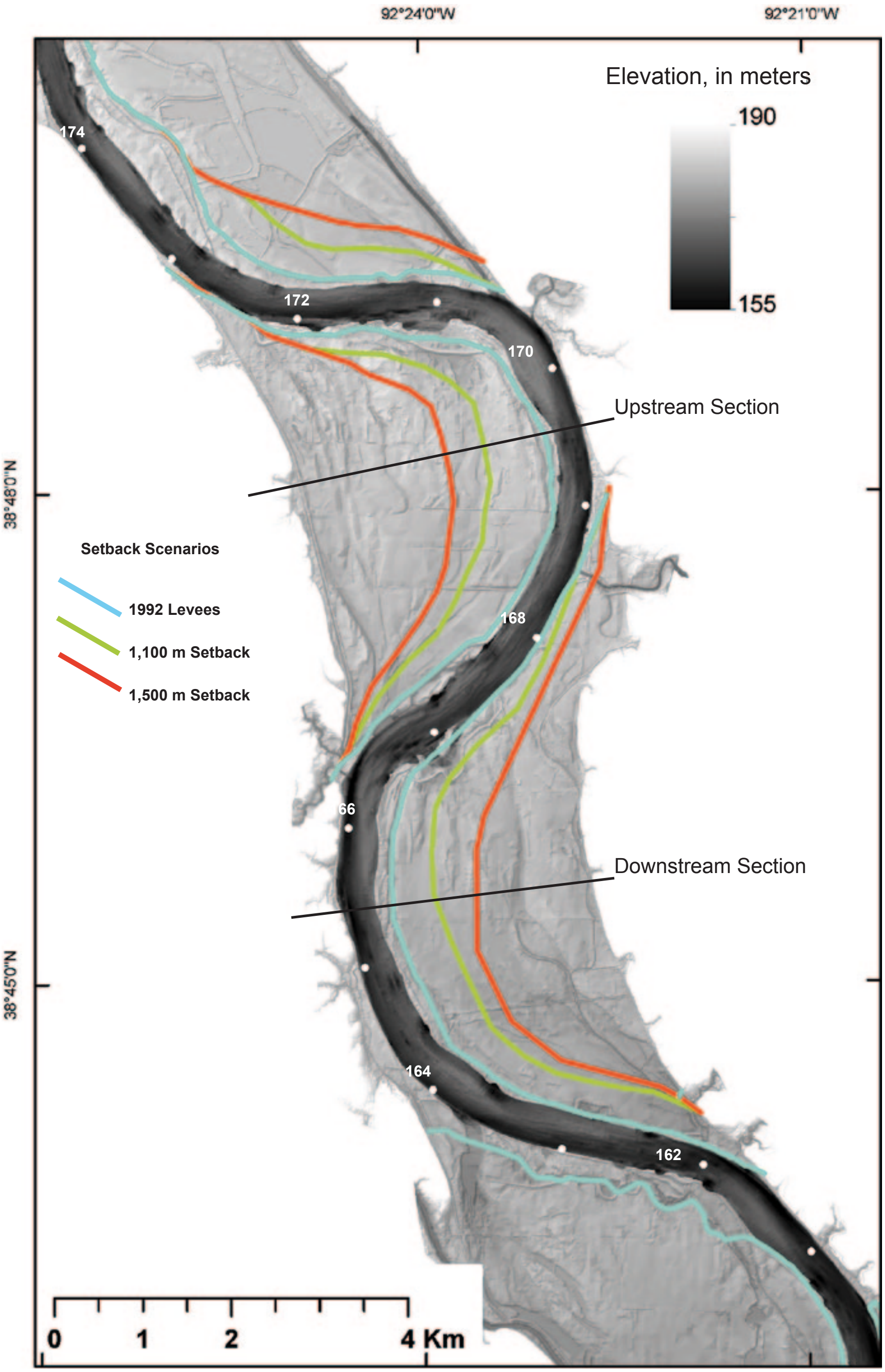

Fig. 11 Location of the Hartsburg 2-dimensional modeling reach

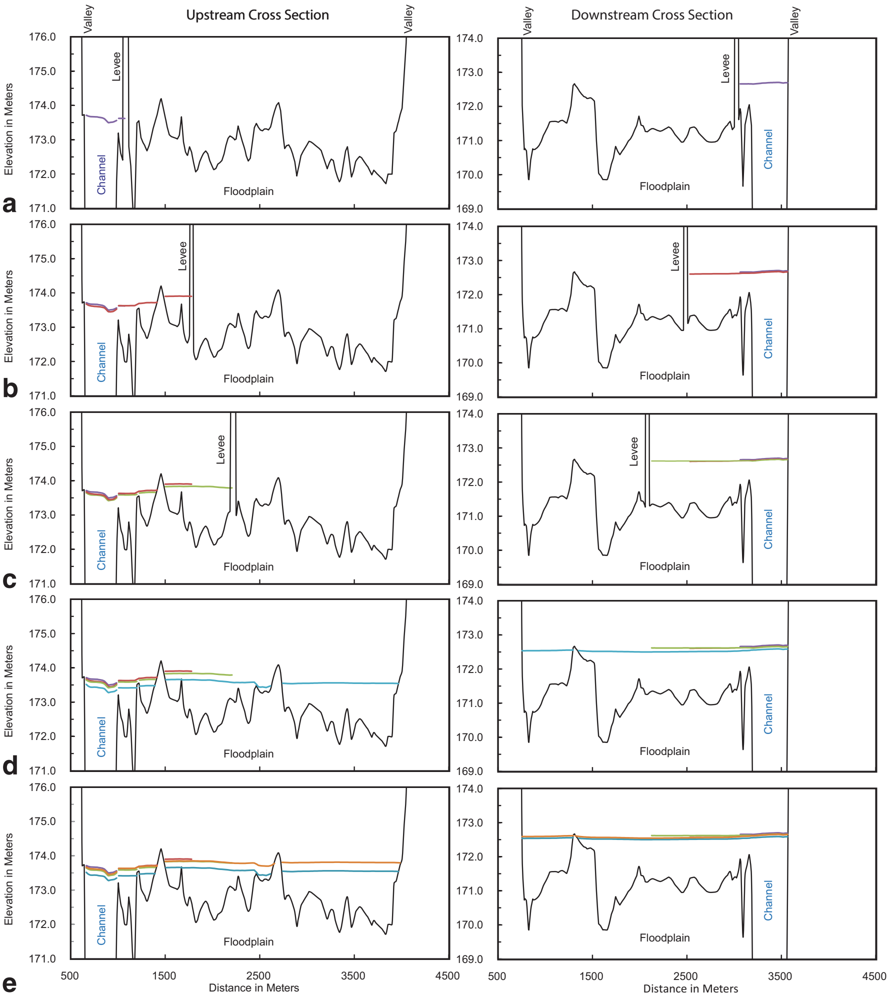

Fig. 12 Steady state 2-dimensional model results showing effects of flow corridor and roughness on estimated water-surface elevations. View looking downstream and cross section locations upstream and downstream shown on Fig. 11. **a** Low floodplain roughness (0.05), 1992 levee, **b** Low floodplain roughness, 1100 m setback, **c** Low floodplain roughness, 1500 m (Pick-Sloan) setback, **d** Low floodplain roughness, no levees, **e** High floodplain roughness (0.2), no levees. Note approximate 400 times vertical exaggeration

an illustrative example of sensitivity of steady discharge to floodplain roughness and levee setback scenarios at approximately a 20 % annual exceedance probability (8320 m^3/s) and 10 % annual exceedance probability (9962 m^3/s), and (2) initial unsteady flow modeling that documents the spatial dynamics in floodplains.

Water surface elevations for the 20 % annual exceedance probability discharge on two representative cross sections of the valley bottom near river mile 169.2 (river km 270; Fig. 12) illustrate lateral and longitudinal variability captured in

Table 3 Average water surface elevation of restoration scenario minus average water surface elevation of 1992, with-levee condition. Positive numbers are increasing stage, negative numbers are decreasing. Values are in meters and were calculated from gridded water-surface elevations for entire model domain

Scenario	Floodplain roughness	
20% annual exceedance probability flood	0.05	0.2
1143 m corridor	0.00	0.10
1524 m corridor	−0.01	0.12
No levee	−0.14	0.01
10% annual exceedance probability flood		
1143 m corridor	−0.01	0.13
1524 m corridor	−0.02	0.14
No levee	−0.16	0.04

the 20-m computational mesh. Even under the leveed condition, the water surface elevations show decimeters of lateral variability resulting from elevation differences from inside to outside and bends and local effects of wingdikes (Fig. 12a, upstream and downstream). With a levee setback to create a 1143-m flow corridor and using a floodplain roughness coefficient typical for grassland or a fallow agricultural field (0.05), additional lateral variability is evident. Although water surface elevations decreased within the channel, some of the additionally flooded areas in the overbank had increased water-surface elevations because of the interaction of complex flow paths and local topographic highs (Fig. 12a, b, compare upstream and downstream cross sections). Averaged throughout the model domains, water surface elevations showed a negligible change (Table 3). With a levee setback to create a 1524-m flow corridor (the Pick-Sloan floodway) and using roughness of 0.05, water-surface elevations continued to decline in the channel, but overbank water-surface elevations were variable (Fig. 12c). Comparison of the upstream and downstream cross sections indicates the variability of hydraulic responses on the floodplain; on average, the water-surface elevation is 0.01 m less than the 1143-m setback (Table 3). In the non-leveed alternative and low floodplain roughness scenario substantial decreases in water surface elevation are evident across the entire floodplain and in the channel, although downstream effects are less than upstream (Fig. 12d, Table 3). Increasing floodplain roughness to 0.20 (indicative of very dense floodplain forest that would likely be rare or transient on the Missouri River), however, would predict an increase in average water surface of 0.01 m above the with-levee condition (Fig. 12e, Table 3). Average results for 10% annual exceedance probability floods are similar but predict somewhat lower water surface elevations under low-roughness conditions and somewhat higher water-surface elevations under high-roughness conditions (Table 3).

Floodplain roughness may also affect velocities in the main channel even when levees do not impede flow across the floodplain. Increases in floodplain roughness from 0.05 to 0.1 were associated with about a 9% increase in peak velocity in the

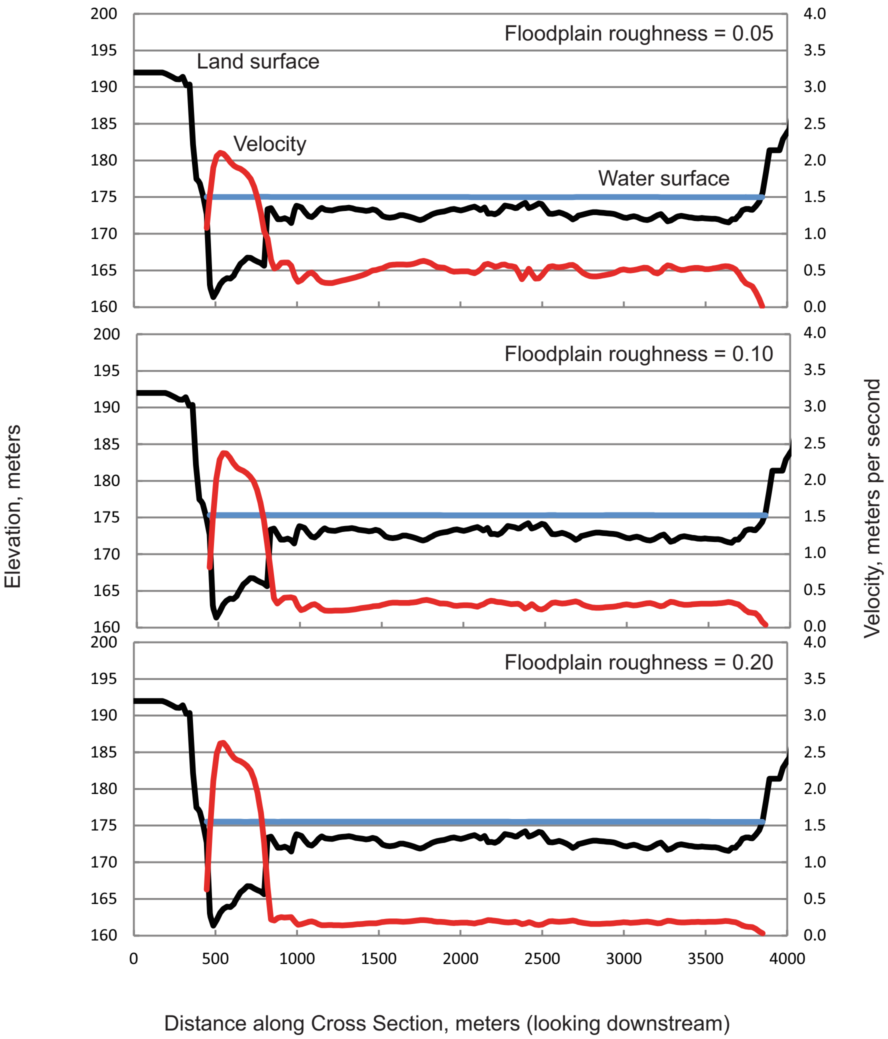

Fig. 13 Cross sections of water-surface elevations and water velocities for no-levee scenario, floodplain roughness = 0.05, 0.1, and 0.2, showing an increase in velocity in the main channel as floodplain flow resistance increases

main channel and an increase in roughness from 0.05 to 0.2 increased peak velocity by about 30 % (Fig. 13).

We additionally analyzed floodplain dynamics using the 2-dimensional model in unsteady mode using daily discharges for the 2007 flood hydrograph with and without levees and with moderate floodplain roughness (n = 0.1). The unsteady 2-dimensional model without levees illustrates a complex pattern of flooding (Fig. 14). During the rising limb of the hydrograph the bottom floods with low-velocity water in topographically preferential areas at the upstream and downstream margins. While

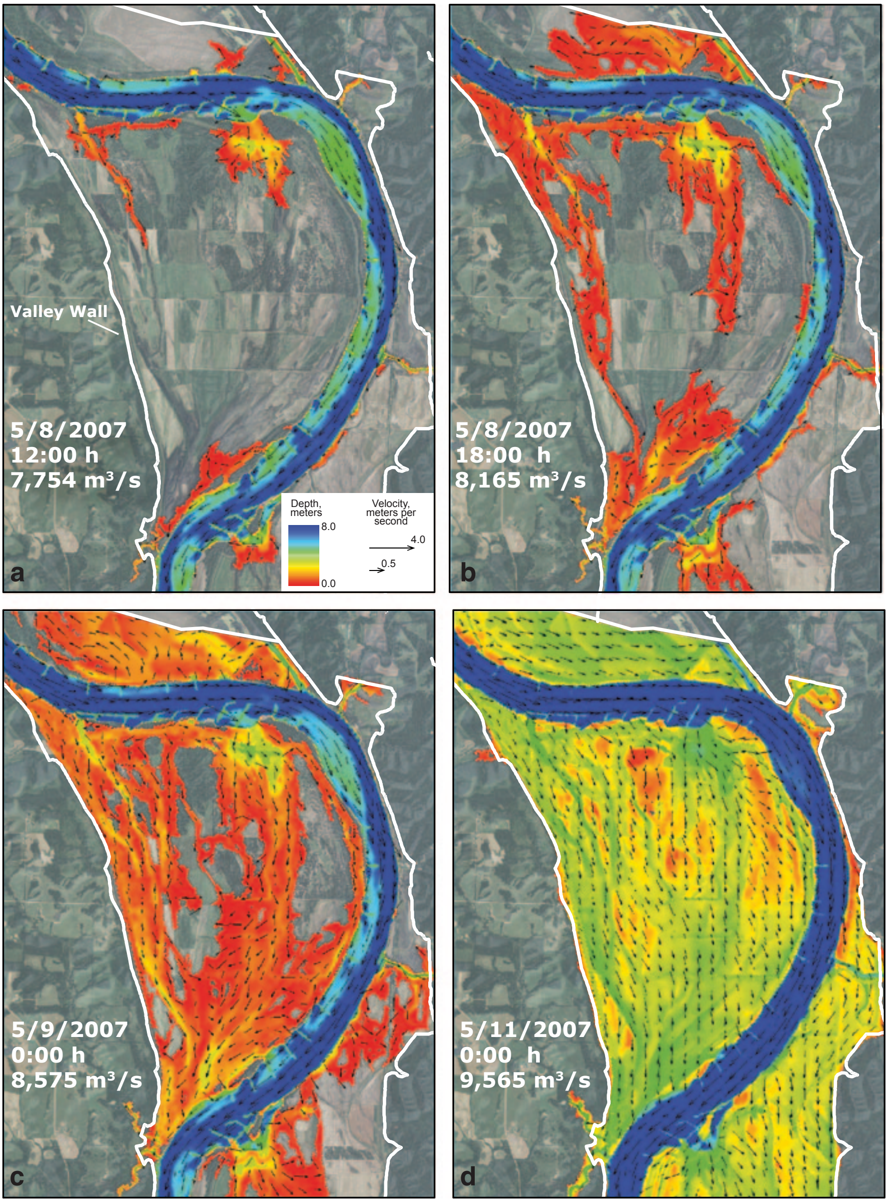

Fig. 14 Maps of unsteady flow model for the upper one half of the 2-dimensional model domain showing complex inundation of the floodplain. **a** May 8, 2007 12:00 h 7754 m^3/s, **b** May 8, 2007 18:00 h, 8165 m^3/s, **c** May 9, 2007 0:00 h, 8575 m^3/s, **d** May 11, 2007 0:00 h, 9565 m^3/s

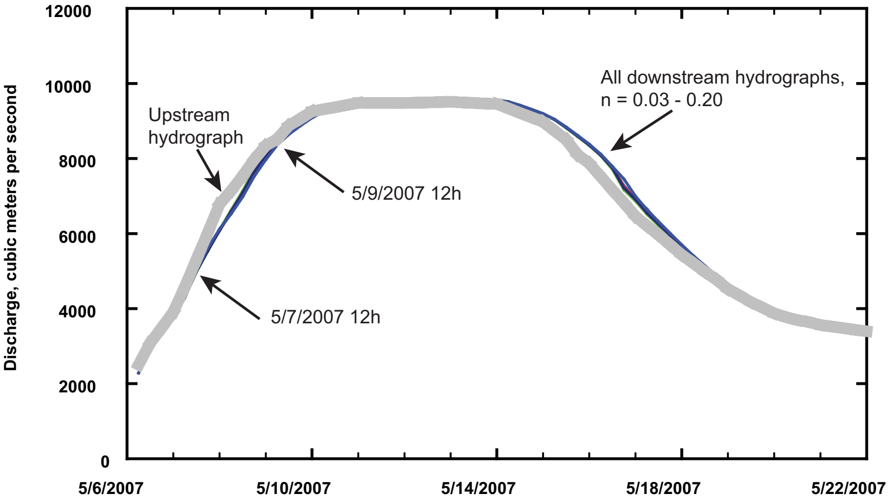

Fig. 15 Inflow and outflow hydrographs for the 2007 flood for varying floodplain roughness *ni*= 0.03–0.20. Attenuation is not discernible at this scale and all roughness scenarios overlie one another. The change in shape of the rising limb between May 7 and May 9 is indicative of filling and storage in the floodplain. After May 9 storage was full and all flow was being conveyed

they are initially flooding, these swales are essentially dead storage with low velocities directed into the floodplain. As the flood progresses, the floodplain fills and is finally overtopped from upstream, resulting in continuous conveyance through the bottom indicated by uniform downstream-directed velocity vectors. At this stage of the flood, the initial dead storage is gone and conveyance or retardation depends mostly on floodplain roughness.

Finally, to explore whether the relatively small non-leveed area would have a discernible effect on attenuating the 2007 flood under a variety of roughness scenarios, we ran the unsteady model with floodplain roughness values 0.03 to 0.2. Identical input hydrographs were applied at the upstream end of the 20 km reach (at river mile 173). Differences at the downstream end of the reach (at river mile 162) between the leveed and non-leveed alternatives are small and difficult to discern graphically (Fig. 15), a result that is consistent with the 1-dimensional modeling results. There is no appreciable change in peak discharge or flood celerity with increasing roughness. Deformation of the shape of the rising limb between about 5000 and 8500 m^3/s indicates that the range of discharges when water is effectively stored on the floodplain is relatively small compared to the size of the flood.

5 Discussion

5.1 System Scale Restoration Potential

Spatial variability is a dominant factor in understanding the potential for restoration and flood-risk reduction at all scales illustrated on the Missouri River. In contrast to river continuum concepts (Vannote et al. 1980), many geomorphic characteristics of the present-day channel and floodplain do not vary monotonically in the downstream direction (Fig. 2). The system scale illustrates the broad-scale spatial variation in persistent geomorphic and flow-regime characteristics that determine flooding potential. Geomorphic adjustments to sediment deficits and channelization have resulted in variable channel incision and channel aggradation (Jacobson et al. 2009). Understanding of the system-scale distribution of floodplain lands provides decision makers with an understanding of where investments in floodplain land restoration have the most potential to meet restoration goals and to realize flood-risk reduction objectives.

The system scale also indicates the spatial distribution of flood risk, and where flood-risk reduction might be most effective. In general, reaches characterized by stable or increasing stage trends at flood flows are those where it may be more feasible to improve flood conveyance while also maximizing opportunities for floodplain connections. For example, reaches at river miles 25–76 (km 40–122), 227–296 (363–474), 376–414 (602–662), and 510–567 (816–907) have over 50 % of the valley bottom within reach of high-frequency floods, and therefore show greater promise of increased floodplain connectivity, ecological restoration, and flood-risk reduction compared to other locations. Ecological restoration can also reduce risk by removing agricultural land and infrastructure from high-risk areas. The 2011 flood resulted in the most flooding and sand deposition in segments of the river upstream of the Kansas River where flow magnitudes were the greatest and where long-term geomorphic adjustment has resulted in loss of flood conveyance, allowing more land to be affected by the flood due to higher river stages during flood flows (Figs. 2, 5). The >50 % and 20–50 % annual exceedance probability flood index classes in the Platte River segment contained 93 % of the segment sand deposition and 45 % of all the floodplain sand deposition downstream of Gavins Point Dam. These classes would provide the most potential for restoring floodplain wetlands (Jacobson et al. 2011), and if in conservation status, would have avoided substantial flood damage.

The system-scale analysis also allows flood volumes to be compared to the area available for flooding for broad-scale assessment of how floodplain lands could contribute to flood-risk reduction by temporarily storing flood waters. In the Platte segment, the rapid decrease in proportion of flood volume compared to floodplain volume as flood duration increases (Fig. 6) indicates that significant storage is likely to exist only for smaller, more frequent, and short floods. The interquartile range of flood durations in this segment is 30–50 days indicating that the floodplain has a maximum volumetric capacity to hold only 6–10 % of a 20 % annual exceedance probability flood. This capacity decreases with decreasing annual exceedance probability and increasing duration. Hence, design of floodplain restorations for the purposes of increasing flood storage and attenuation are likely to be most successful when targeted toward a higher exceedance probability, short-duration flood.

5.2 Restoration, Stage Reductions, and Flood Attenuation

At the segment scale, 1-dimensional hydraulic modeling provides a computational basis for assessing how stages and peak discharges may be affected by alternative channel-floodplain geometries and hydraulic roughness. The modeled decreases in water-surface elevations with increasing levee setbacks confirm the intuition that increasing the channel width and the distance between levees should result in decreased stages. The results also indicate that channel widening has a high relative contribution compared to levee setbacks. The greater contribution from channel widening presumably results because higher velocities in the channel provide substantially increased conveyance for each increment of widening compared to increments of widening of the overbank areas. This indicates that restoration designs should account for the interaction of channel and floodplain conveyance. A comprehensive analysis would therefore need to account for potential lagged geomorphic responses of the bed and floodplain as a reaction to channel widening; there is therefore some uncertainty as to how long and to what degree model results would remain valid in the future as channel and floodplain morphology change.

The greatest stage decrease for the alternatives modeled was for the case of no levees and no channel widening. This is a highly hypothetical alternative because it would require significant changes to the floodplain economy. More realistic future scenarios might have reaches with no levees managed for conservation lands interspersed longitudinally with leveed floodplains with variable setbacks.

Although these models predict some stage reduction for all alternatives, the effects of setbacks on attenuation are less clear, especially in a system that might be characterized by variable setbacks and land uses. The unsteady models at the segment scale address the potential for attenuation over an 85 km segment using a flood with a peak magnitude of nearly a 10 % annual exceedance probability and a 22-day duration. Peak discharges for the no-levee situation would be decreased less than 0.04 to 0.13 % (Table 2). This small effect may be attributable in part to the relative lack of floodplain storage in this narrow segment of the Missouri River valley relative to the size of the flood. In the 1-dimensional model, increasing overbank roughness is associated with increased attenuation of peak discharges, indicating the slowing effect of floodplain land cover. Similar results were obtained from modeling synthetic and actual river restoration projects in North Carolina (Sholtes and Doyle 2011); the results indicated that small to intermediate floods (2–50 % annual exceedance probability) were more likely to be attenuated by restoration compared to larger floods. The authors concluded that effective attenuation would require restoration of long segments of a river in order to involve sufficient storage. In contrast, other modeling studies have suggested that forested floodplain restoration could have significant effects in terms of decreasing peak discharges and flood celerity, using both 1- and 2-dimensional models (Anderson et al. 2006; Thomas and Nisbet 2007). We attribute the relative lack of attenuation of peak flows in the Missouri River case to the large scale of the Missouri system, including discharges ranging 10–600 times the peak discharges modeled in other studies. While attenuation of peak flows seems insignificant, models indicate potential for restoration activities to provide measurable delay in timing of peak flows by approximately 0.2 and 1.1 days for partial and full restoration scenarios, and also some ability to dampen within-day peaks when the flood is at or near its peak.

Two-dimensional modeling at the reach scale provided complementary insights to the 1-dimensional modeling. The 2-dimensional modeling demonstrates the influence of floodplain topography on the spatial and temporal distribution of water on the floodplain, insights that cannot be gained from cross section averages from a 1-dimensional model. Because topography serves to channelize floodplain flow into preferential pathways, effects of restoration on stage are variable across the floodplain (Figs. 12, 13, and 14), indicating the importance of adequate assessment of topographic variability in restoration designs. A levee alignment might be chosen, for example, to take the advantage of topography to provide increased conveyance in floodplain channels, or alternatively, to maximize retention time to support other ecosystem services. Restoration designers may also utilize 2-dimensional model results to recognize where altering topography, for example by targeting topographic highs for borrow material, could avoid local backwater effects to offset the possibility of inadvertently raising water-surface elevations. In addition, the significant effects of hydraulic roughness in altering conveyance and stage reductions, suggests that the spatial distributions of vegetation communities with variable hydraulic resistance would be an important part of a design to optimize restoration benefits as well as flood risk reduction.

Differences in 1- and 2-dimensional model predictions of stage reduction for nearly comparable discharges and scenarios indicate the varied perspectives that come with different scales of restoration, model resolution, and assumptions about floodplain roughness. The results in Table 3 summarize changes in average water-surface elevations across the model domains relative to the with-levee scenario. The cross-sections in Fig. 12 illustrate some of the localized variation in water surface elevations that would likely not be detected with 1-dimensional models. In the most direct comparison between the two models—the steady state, no-levee scenario with low floodplain roughness, 10 % annual exceedance probability flood—the 2-dimensional model predicts 0.16 m of average reduction and the 1-dimensional model predicts 0.66 m. We hypothesize that the discrepancy is largely due to scale effects. Notably, the downstream 15–20 km of the 1-dimensional analysis shows a 0.17 m average stage reduction, a comparable result to the 0.16 m reduction in the 2-dimensional analysis, although in a slightly different geographic area. In addition, the 2-dimensional model stage reduction averages higher variability of stages on the floodplain which may result from local backwater effects due to topography or slower velocities due to roughness.

Increases of the stage with roughness values that might be associated with very dense forest (Fig. 12) are indicative of a general trade-off between ecological restoration objectives and flood-risk reduction objectives. The lowest roughness and greatest local stage reduction would be achieved through maintenance of low-resistance vegetation such as conventional row crops or perhaps some biofuel crops. Native grasses, an important component of pre-settlement Missouri River floodplain vegetation communities (Weaver 1960), would also provide low hydraulic resistance to flow compared to floodplain forests, and may be a viable restoration option. However, the low floodplain roughness may also result in high velocities and erosional damages to agricultural levees as observed on several federal and non-federal levee systems upstream of Kansas City in 2011. The greatest ecological value would be achieved through the maintenance of a diverse mosaic of native plant communities including a range of successional communities resulting from periodic flood disturbance. Although some of the wetland plant communities could have relatively low hydraulic roughness (see Jacobson et al. 2011 for the discussion of native plant communities), many will be substantially higher than agricultural plantings. In particular, early successional stages of willow and cottonwood create "doghair" thickets that are extremely effective in retarding flow until the communities age, thin, and thereby present less total cross-sectional area to the flow (McKenney et al. 1995). Designing floodplain vegetation communities to optimize ecological restoration benefits while providing flood-risk reduction will be a substantive challenge, and may require more sophisticated parameterization of roughness than provided by application of Manning's n values in hydraulic designs. An optimal vegetation mix could conceivably provide increased flood conveyance, decreased potential for levee erosion, and increased biodiversity while also providing a source of agricultural revenue.

Two-dimensional unsteady modeling results generally confirmed the 1-dimensional result that removal of levees would have little effect in attenuating an approximate 10 % annual exceedance probability flood. It should be noted, of course, that the modeled reaches were a small overall area compared to those assessed at the system and segment scale, so it is not surprising that attenuation was not more measurable. Smaller floods would presumably experience a relatively larger attenuation. Notwithstanding the small attenuation effect, the 2-dimensional modeling illustrates important aspects of dynamic flooding processes. As recognized by Schmudde (1963), valley bottoms on the Missouri River flood from the bottom up (backflooding) as well as from the top down, due to the increased slope directly down the floodplain compared to the slope around the bottom (Fig. 3). This is illustrated in the excerpts from unsteady models (Fig. 14). Backflooding has the potential to be particularly important in flood-wave attenuation because the flow is temporarily stored in the backflooded areas, extracting flow from the rising limb of the flood wave. If the discharge continues to increase, however, velocity vectors in these areas rotate as flow is conveyed completely through the floodplain. Therefore, the area of low-lying floodplain lands at the downstream ends of bottoms, compared to flood volume, will regulate the degree of attenuation. Moreover, these backflooding areas are likely to be ecological hotspots, providing access for fishes, long retention times, and low velocities directed onto the floodplain to deliver nutrients, carbon, and fine sediment. In the floodplain explored here, backflooding is prominent at discharges between the 10 % daily flow exceedance (approximately 4018 m^3/s) and the 20 % annual exceedance probability flood (approximately 8320 m^3/s; Figs. 14 and 15). It would follow that the maximum ecological restoration benefit, measured in terms of ecosystem regulating services, may be achieved for relatively small floods with return intervals up to 5 years.

5.3 Applying Floodplain Information at Useful Scales

Each of the three separate scales of analysis presented provides specific information that can be applied to understanding, planning, and design of flow corridors. Moving from system to reach scales, the analyses employ increasingly complex methods with analytical investments commensurate with decisions that would have to be made at that scale.

The system scale analysis is based primarily on the LCPI (Jacobson et al. 2007; Chojnacki et al. 2012), which integrates relatively low-resolution, steady-state flood models with floodplain topography to provide an index of how much floodplain area is within the ranges of flood elevations. Because the LCPI does not route flows hydraulically across the floodplain, it serves only to show an index of potential connectivity. In the case of the Lower Missouri River, however, this information is available for the entire 811 river miles (1298 river km) and serves to document at the segment scale where and how much floodplain would be amenable to restoration alternatives (Jacobson et al. 2011). The system-scale analysis shows that geomorphic adjustments of the channel to upstream dams and channel engineering, and the effects of tributary influxes, have had a substantial effect on connectivity potential in the Lower Missouri River. The dataset also can be used for first-order calculations of how much floodplain storage volume exists and how the available storage compares to flood volumes. Even in parts of the Lower Missouri River that have extensive floodplain at elevations within reach of 20–50 % annual exceedance probability floods, the floodplain volume is a small percentage of flood volumes, suggesting that flow corridor planning for flood attenuation would need to focus on low-magnitude, short-duration floods, or alternatively, implementation of floodplain storage through hydraulic structures.

The segment-scale analysis uses 1-dimensional hydraulic modeling to address the details of how changes in levee alignments and floodplain roughness are likely to affect local stages and flood attenuation. This level of analysis adds in explicit hydraulic computations to increase the realism of floodplain routing within restoration scenarios based on levee setbacks and channel widening. The segment scale nests within the system scale and can be usefully applied in sections of the river characterized by specific combinations of hydrology and floodplain geomorphology. In the analysis presented here, the 1-dimensional segment scale approach shows that cross-sectional average stage reductions could be significant, although they are sensitive, as expected, to the hydraulic roughness of vegetation communities within the flow corridor. The 1-dimensional analysis in unsteady mode also indicates that the segment scale floodplain storage is unlikely to significantly attenuate peaks of 10 % annual floods, but can measurably delay timing of peaks and reduce responsiveness to smaller variations of flow and stage resulting from upstream rainfall or levee break dynamics while the river is at or near its flood crest. This type of information would be useful in planning and optimizing levee alignments at the segment scale.

The reach-scale 2-dimensional hydrodynamic analysis provides additional insight, albeit at greater cost in data needs and computational time. The 2-dimensional results greatly increase understanding by illustrating spatial variability that is not captured in 1-dimensional, cross-section based analysis. In particular, the 2-dimensional view shows the importance of floodplain topography in creating strong lateral gradients in depth, stage, and velocity, effects that would be augmented by spatial variation in hydraulic roughness variations due to varying vegetation communities. These results show the interaction of floodplain roughness and channel velocities, and in unsteady mode, they show the sequence of flooding patterns and water residence times that are likely important in regulating floodplain ecosystem processes. Hence, this scale provides information that is useful in exploring how patterns and processes of flooding would affect ecological processes, how material is exchanged with the main channel, and how feedbacks with floodplain communities may affect hydraulics. This scale would also be practical for design of reach-scale restoration projects that might include levee realignments and vegetation community restorations.

5.4 Linking Floodplain Dynamics to Ecosystem Services

The multiscale analysis presented here provides insights to how ecological restoration of floodplains may be designed to complement flood-risk reduction strategies. Some important processes, however, have not yet been addressed. Among these are the roles of groundwater and hyporheic exchange in mitigating surface-water connections, although modeling studies on other rivers indicate that vertical infiltration from the floodplain is usually small relative to total discharge (Krause et al. 2007). Rate of drainage from flooded surface depressions into the alluvial aquifer is an important variable controlling the residence time of water as floods drain from a floodplain. Water ponded in surface depressions is likely to increase ecosystem regulatory services by providing enhanced nutrient cycling, denitrification, and productivity. Hydrologic losses due to evaporation from flooded restoration areas also have been explored and could be a contributor to flood attenuation during hot summer days.

There has been a great deal of research on roughness and various ways to parameterize it in hydraulic models (Griffin et al. 2005; Kean et al. 2009; Anderson et al. 2006; Corenblit et al. 2007; Thomas and Nisbet 2007; Larsen and Harvey 2011) and the approach used in this modeling exercise has been very simple, assuming non-depth varying roughness values. Because of the large effect that vegetation roughness can have on flood dynamics, there is a need to explore whether the simple roughness parameter approach is sufficient to describe hydraulics of these vegetation communities at scales applicable to restoration decisions, or whether more sophisticated parameterizations are needed especially for bendable/breakable vegetation like agricultural crops, biofuels, or native grasses.

Floodplains are dynamic over timeframes longer than individual floods. Once a floodplain is opened to connections to the main channel the potential exists for the floodplain morphology to change due to episodes of erosion and deposition as sediment and large woody debris are exchanged with the channel. The morphological changes may interact with flow patterns to create feedbacks, either negative or positive, resulting in ongoing morphological adjustments. Rates and patterns of geomorphic change on restored floodplains are challenging to predict and remain a critical unknown, particularly as those processes interact with successional changes in floodplain vegetation communities. These changes may be of great practical importance if deposition in the restored flow corridor progressively decreases overbank conveyance. Additionally, a comprehensive assessment of the common ground between restoration and flood-risk reduction would require a complete socio-economic analysis that addresses benefits of all ecosystem services that may be gained in restoration projects and balances those benefits with potential losses of conventional socio-economic benefits presently provided by floodplain agriculture and development.

6 Conclusions

This assessment of the common ground between floodplain restoration and flood-risk reduction on the Missouri River indicates potential for support of both objectives, but also considerable uncertainty. Our modeling and other studies show that floodplain restoration has potential to result in significant local stage reductions, but the magnitude and persistence depend on the details of the size of the floodway relative to flood size, the evolution of vegetation communities and associated hydraulic roughness in the floodway, and related changes in sedimentation and erosion. The magnitude of attenuation of peak flows accompanying floodplain restoration was subtle and less certain. Uncertainty in attenuation includes all the elements of uncertainty for stage reduction, and adds uncertainties associated with total flood volume relative to floodway area, potentially complex flow paths that determine the degree of persistence of storage relative to conveyance, and variability in rates of flood rise and fall. Floodplain restoration will certainly contribute ecosystem benefits in terms of nutrient processing, productivity, and habitat availability, but the magnitude of these processes and their dependencies on flood characteristics, floodplain configuration, and vegetation communities are not well understood. In particular, the regulating ecosystem services supplied to society by restored floodplains need to be quantified in terms that can be compared directly with alternative land uses, including conventional agriculture and urban/suburban development. The least uncertain socio-economic benefit of flow corridors is the avoidance of flood damages that would otherwise occur on developed floodplains.

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Post-dam Channel and Floodplain Adjustment along the Lower Volga River, Russia

Hans Middelkoop, Andrei M. Alabyan, Dmitry B. Babich and Vadim V. Ivanov

Abstract The Volga River in the Russian Federation has been regulated by a cascade of reservoir dams since the 1950–1960s. This chapter presents an overview of the main hydrological and morphological responses of the Volga River downstream of the Volgograd reservoir dam. Regulation caused a decrease in magnitude of the spring peak flow, an earlier start and peak of the flood and a considerably steeper rise and fall of the flood. Morphological responses include a considerable channel incision in the river stretch downstream of the Volgograd dam. Furthermore, the reduction in peak flow magnitude results in a general tendency of silting up of secondary channels, and promotes vegetation colonisation along the active parts of the floodplain. Restoring the natural flow regime and morphodynamics will be problematic, particularly in view of the potential hydrological impacts of climate change.

Keywords Volga River · Regulation · Dams · Hydrological regime · Channel morphology · Flood plain

1 Introduction

The Volga is among the largest rivers in Europe and, as many of these rivers, it has been heavily modified by humans (Tockner et al. 2009). The most dramatic impacts have been imposed by the construction of a cascade of 13 large dams and reservoirs constructed during the 1950–1960s. The most downstream reservoiris located near the city of Volgograd. Downstream of Volgograd the lower Volga retains the natural channel morphology, with active bank erosion and bar formation, while the river borders a large floodplain that is seasonally inundated. The construction of the reservoirs and subsequent regulation has considerably disturbed the natural discharge

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regime of the lower Volga. This in turn has affected sediment transport, channel morphodynamics, while also the annual flood pulse of the floodplain ecosystem has been impacted. When compared to many other European rivers (e.g. Tockner et al. 2008) the lower Volga is a unique example in the sense that its lower course has remained in a relatively natural state, allowing the 'natural' response to damming to be studied. Over the past years much data on these effects has been collected by scientists and government agencies, and is awaiting investigation and communication by researchers to a wider international audience.

In this study, we investigate the hydrological and morphological changes that occurred in the lower Volga River downstream of the Volgograd dam after the establishment of large main-stem reservoirs. We illustrate these changes for the entire lower Volga, and then focus on the Volgograd reach immediately downstream of the dam, and on the development of a point bar at about 100 km downstream of the dam. We conclude by providing a long-term perspective on the future development of the lower Volga river system.

The work presented in this study is a synthesis of long-term research conducted by Moscow State University (MSU), followed by joint projects with Utrecht University and the Netherlands Institute for Inland Water Management and Wastewater Treatment (RIZA—now Deltares) and the University of Volgograd over the past decade (Middelkoop 2005). The results are based on a combination of (1) field surveys on channel morphology and deformation and bar development using depth sounders, sonar-echo instruments, leveling-instruments and GPS (Ivanov et al. 2006; Korotaev et al. 2009), (2) Remote Sensing image analysis of channel and floodplain morphology, including US CORONA satellite of 1960s and early 1970s and LANDSAT TM, (3) analyses of time series of navigation maps (1914–2003) indicating channel depth, position of channel banks, bars, islands and shore vegetation and (4) observation records of river discharge, water levels and discontinuous records of sediment load available at MSU. The latter data source is increasingly becoming accessible through public web-portals (www.waterinfo.ru/33/Rivers/index.php).

2 The Lower Volga

The Volga River drains an area of 1.36 million km^2 of the Eastern European Plain within the Russian Federation (Fig. 1a). The main river and most of its tributaries flow from the north to the south through several different geographical and vegetation zones, including taiga, hard- and softwood forests, steppes, semi-arid and arid zones. The major tributaries are the Oka, the Belaya, the Vyatka and the Kama Rivers, each of which is longer than 1000 km and have catchments exceeding 100,000 km^2. The total annual discharge of the lower Volga at Volgograd is about 260 km^3. Downstream of Volgograd there are no tributaries to the Volga and instead the Akhtuba, a minor distributary branch, separates from the lower Volga (Fig. 1b). Both distributaries enclose a 20–30 km wide x ~ 400 km long natural floodplain that is embedded in a 30–40 m deep valley, incised in Pleistocene marine sandy and

Fig. 1 **a** The Volga river basin (source: UNEP/DEWA/Grid-Geneva), **b** The lower Volga and western part of the Volga-Akhtuba floodplain

clay deposits of the former Caspian Sea (Goretski 1966; Korotaev et al. 2009). The Volga debouches in the Caspian Sea at about 28 m below global mean sea level. The Volga-Akhtuba floodplain is dissected by numerous small channels and thousands of lakes occur scattered within the floodplain. Only the sections that border the present main channels are active. The central portions comprise Early to Late Holocene complexes of inactive channels and pointbar ridges, with neither lateral erosion or overbank deposition.

The main course of the lower Volga is a typical lowland river, with an average gradient of about 6×10^{-5} (Fig. 2). Channel width varies between ~ 800 m and ~ 2 km. Maximum cross-channel depths during summer flow conditions vary along the river course between about 5 m in riffle zones and over 30 m in the deepest pools at the outside of bends. The grain size of the channel bed sediment of the Volga River is remarkably fine: downstream the Volgograd dam the bed sediment is currently dominated by sands with average median grain sizes between 0.15 and 0.50 mm. This is because of the fine-grained character of the marine deposits in which the river is embedded. Further downstream, local occurrences of increased grain size of the channel bed sediment occur, mainly due to the contribution of sediment from bank erosion of valley sides and some bedrock exposures. At some sections the channel bottom is formed by exposed marine clays, and almost devoid of coarse bed load. Under average flow conditions ($Q \sim 8000\ m^3\ s^{-1}$) specific stream power of the lower Volga is in about 3 Wm^{-2}, and Shields parameter ~ 0.6.

Annual discharge of the Volga River is about 259 $km^3\ yr^{-1}$ at the Volgograd dam, and about 253 $km^3 yr^{-1}$ at the delta apex. The discharge regime of the Volga is characterized by a clear snowmelt peak in spring and a low-flow period in late summer—winter (Fig. 3). Peak flow occurs by the end of April to early May, and on average reaches up to 26,000 $m^3\ s^{-1}$. In this period the Volga discharges about one third of its total annual discharge volume. During peak flow, the large floodplain between both branches inundates to a large extent for a period of several weeks (Górski et al. 2011).

The Volga River has major economic functions for the Russian Federation. It forms an essential component of Russia's transportation network of rivers and canals, linking the North (White Sea, Baltic Sea) to the South (Black Sea, Caspian Sea). The river is navigable over a distance of about 3200 km, and it carries about two-thirds of all navigation traffic of the country. In the 1950s, a cascade of reservoirs was established in the Volga basin (Fig. 1a), of which the largest are the Gor'kovskoe (1955–1957), Kuibeshevskoe (1955–1957), Kamskoe (1954–1956), and Volgogradskoe (1958–1960), the latter being the last and most downstream reservoir. There are eight hydroelectric stations on the Volga River and three on the Kama River that together have a power production capacity of about 40 billion kWh (Demin 2005). This requires about 50 km^3 water storage. Reservoir regulation provides sufficient navigation depth in the lower Volga during low-flow periods (i.e. > 4000 $m^3 s^{-1}$ which requires an annual volume of 47.3 km^3). The reservoirs also have an important role in the provision of freshwater for irrigation, industry and domestic use. Water from the Volga is currently used to irrigate about 200 million ha of agriculture. Before 1955 3–6 km^3 was annually diverted (1–2 % of total water runoff). To date, this is 24 km^3 per year, which is10 % of the natural water runoff reaching the Volga delta.

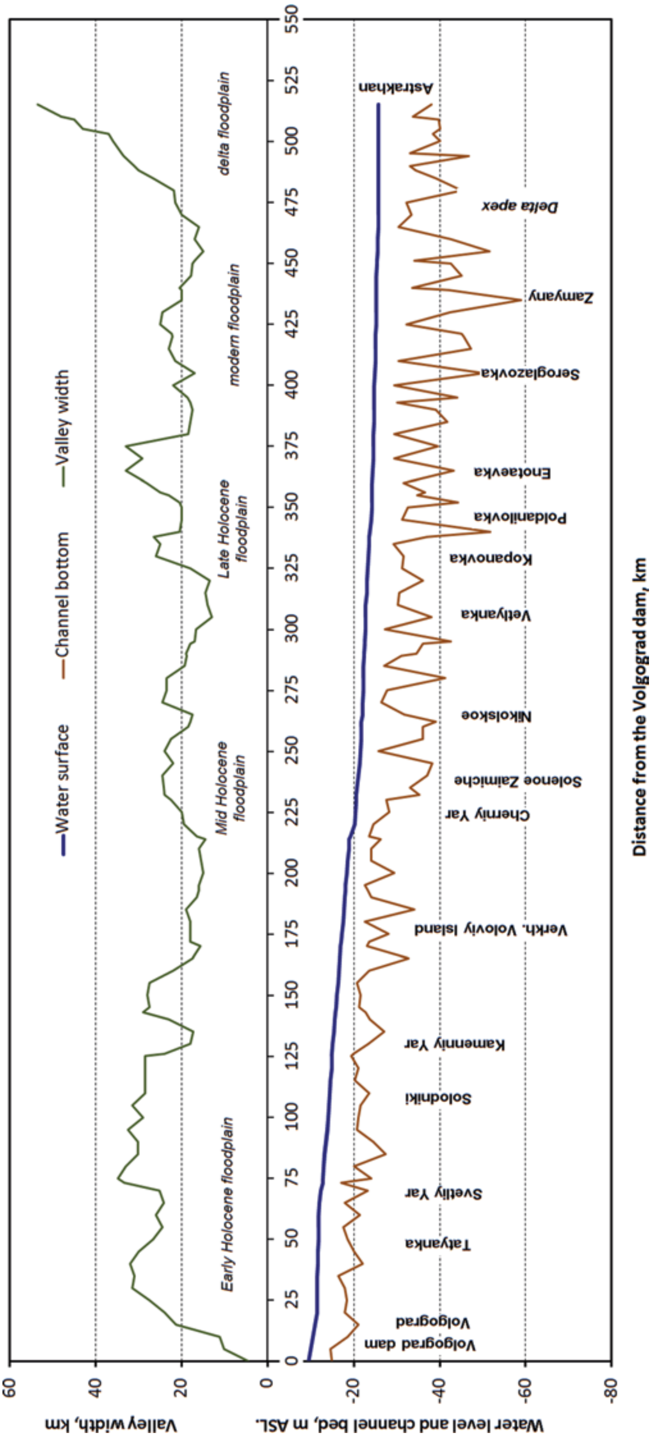

Fig. 2 Water level, channel bottom and valley width of the Lower Volga. (Modified from Korotaev et al. 2009)

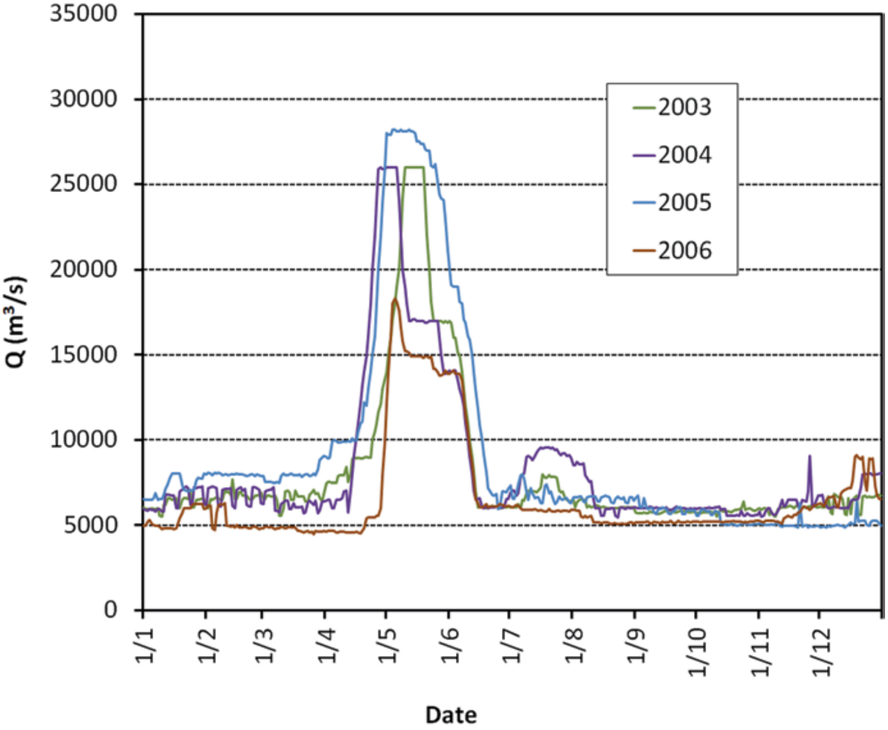

Fig. 3 Annual hydrograph of the Lower Volga at Volgograd for recent years. The figure shows the variation in regulated peak flows

3 Impacts of the Reservoirs and Dams

3.1 Hydrology

Before the construction of the reservoirs, the spring flood period started early May and reached its peak discharge in the first decade of June. The flood lasted on average for about 74 days. During this period, the lower Volga discharged about 32–35 % of its total annual discharge. The contribution of winter flow was generally less than 13 % of the total annual Volga River discharge. Figure 4 shows these typical discharge characteristics of the Volga at Volgograd for the year 1936.

Although the present-day regime still demonstrates a spring peak flow, several characteristic changes occurred (Fig. 5). Firstly, the average discharge downstream of the reservoir decreased from 8380 to 7240 m^3s^{-1}. Further, the duration of the peak flow decreased from about 74 to about 51 days. Most significant was the reduction in maximum discharge. While the unregulated mean peak discharge was about 34,500 m^3s^{-1}, with the extreme of 51,900 m^3s^{-1} in 1926, the average regulated peak discharge in the 1959–1999 period is about 26,800 m^3s^{-1}. The highest post-dam peak flow was 34,100 in 1979 (Korotaev et al. 2004). The regulated spring flood

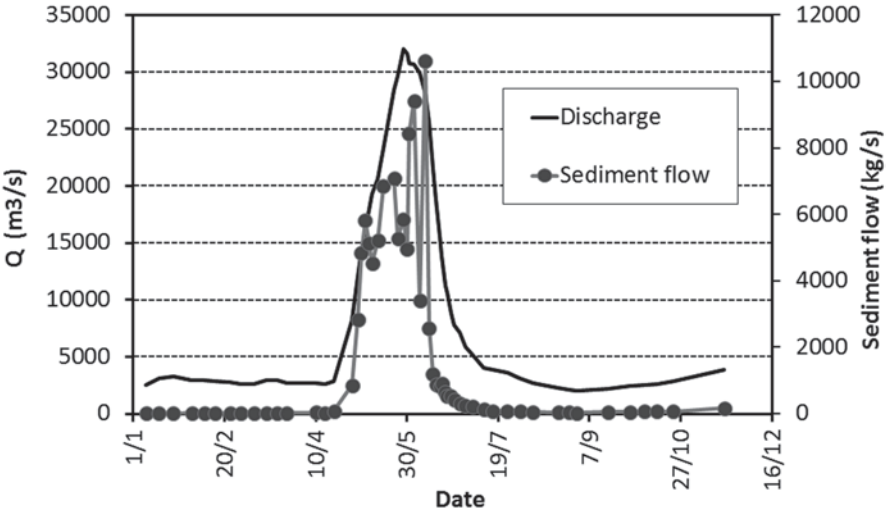

Fig. 4 Discharge and sediment load of the Volga in a pre-dam year (1936)

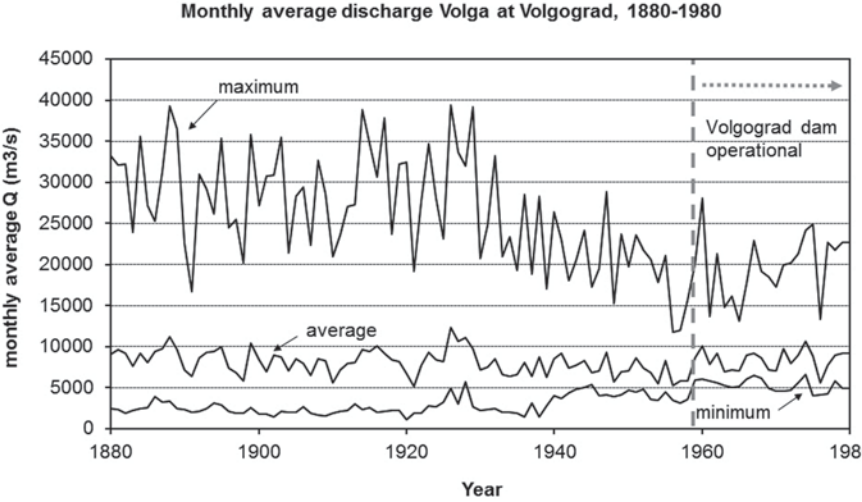

Fig. 5 Average, maximum and minimum monthly discharges of the Volga before and after construction of the reservoir dam

period starts and peaks a few weeks earlier and shows a considerably steeper rise and fall of the flood. The regulated discharge peak is followed by a period in which a relatively constant but increased discharge is maintained before the recession to low flow is achieved. Discharge during low flow periods has increased by almost 50% because of regulation, and contributes an average of 26% of the annual discharge. At a finer temporal resolution, the Volga discharge varies daily and weekly because of differences in electricity demand.

The Akhtuba branch carries a small proportion of the total Volga discharge. Pre-dam (until 1955) average annual water discharge Akhtuba's was 211 m^3s^{-1}. The reduced peak flows under the regulated regime, in combination with a new artificial entrance of the Akhtuba constructed a few km downstream from the dam, resulted in a dramatic decrease of discharge into the Akhtuba. The average annual discharge reduced by almost 50 % to about 100 m^3s^{-1}, while the channel be completely dry during the summer-autumn low flow period, as it did in 1973. Subsequent siltation-of the Akhtuba entrance has further reduced discharge into the Akhtuba. At present, maximum discharges through the Akhtuba are in the order of 2000–2500 m^3s^{-1}, which is about 10 % of the total Volga discharge. During peak flow, only 1–2 % of the total amount of water discharged by the Volga enters the floodplain.

3.2 Sediment Regime

The largest contribution to the wash load in the Volga is from soil erosion in the central portions of the drainage basin, with estimated soil erosion rates between <1 and >20 t ha^{-1} yr^{-1} (UNESCO/IRTCES 2011). A few tens of km upstream of Volgograd the average annual sediment loads were 12–18.5 Mt yr^{-1} during the period from 1934 to 1953 (Baidin et al. 1956). At higher discharge years the vast majority of suspended sediment is mainly transported during the high flow period, such as in 1936 when nearly 95 % of the total sediment load of 25.2 Mt was discharged during the spring peak flow (Fig. 4). The estimated annual suspended sediment load discharged through the delta to the Caspian Sea during the pre-dam conditions is up to 26 Mt yr^{-1}. Average suspended sediment transport at the delta apex was about 400 kg s^{-1}, with maxima up to 3870 kg s^{-1}.

The reservoirs form major traps of sediment transported to the lower Volga, and all bed load is presently trapped by the reservoirs. After the reservoirs became operational the wash load initially decreased to 11.5 Mt yr^{-1}, and then further decreased in subsequent years to 7.4 Mt per year. The period of lowest average wash load of 4.5 Mt yr^{-1} occurred during from 1961 to 1977, and was associated with relatively low peak flows. At the delta apex the annual suspended sediment reduced by 50 % after damming, to an average of 7.9 Mt yr^{-1} from 1961 to 2006 (211 kg s^{-1}). Annual maximum transport rates decreased to 2100 kg s^{-1}, while maximum average suspended sediment concentration decreased from 56 to 34 g m^{-3}. Both the reservoir trapping and the reduced water discharge resulted in the wash load of the Akhtuba branch to decrease to about 0.13 Mt yr^{-1}, with an annual average suspended sediment concentration of 30 mg l^{-1}.

It is evident that the dams and reservoirs have dramatically reduced sediment transport to the lower Volga valley and delta. To date, sediment released by channel incision and lateral bank erosion within the lower Volga reach downstream of the Volgograd dam forms a substantial source of Volga sediment, which is available to be further transported to the delta. A net increase in annual suspended sediment load of 7.3 Mt is found between Volgograd and the apex of the delta.

3.3 *Channel Morphology*

3.3.1 Larger-Scale Channel Dynamics

Based on the channel planform shown on the 1914–2001 navigation maps and satellite imagery and field surveys, the lower Volga can be subdivided into three main reaches characterized by distinct changes in morphodynamics and channel geometry (Fig. 6). These reaches display varying response to dam construction: (1) Sect. 1 to the first section of 3, km 0-~100 (Fig. 5); (2) Sects. 3–8 from km ~ 100 to 340, and (3) Sects. 8–11 from km 340 to the delta apex at km 357. The varying response of the river can be appreciated by considering the adjustment of eleven sections, including annual erosion and accretion rates per km of river (Fig. 7), and channel bars (Fig. 8) during the pre-dam period (1914–1944) and the post-dam period (1965–1982) and thereafter until 2000.

The pre-dam Volga channel reaches downstream from Volgograd had a 1.5–2 km wide, low-sinuosity, single thread channel that displayed only minor channel deformation. Average pre-dam lateral erosion rates were 5–8 m per year, which is less than 0.005 times the channel width. In the 1914–1944 period, floodplain erosion rates were in the order of $3–7 \times 10^3$ m^2 km^{-1} per year, with lateral accretion rates being slightly less. Channel bar accretion rates were about 12×10^3 m^2 km^{-1} per

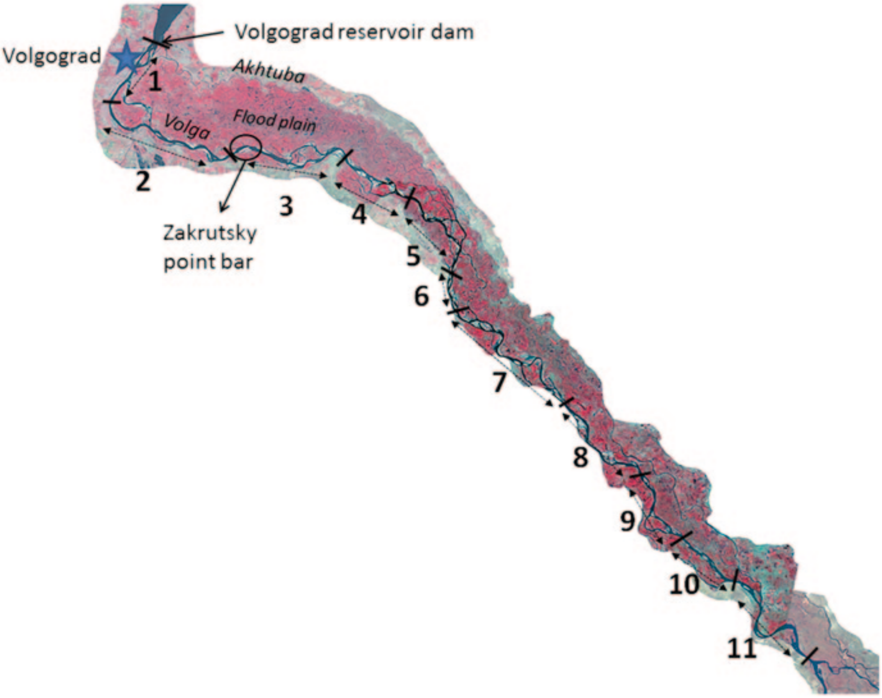

Fig. 6 River sections of the Lower Volga between the Volgograd reservoir dam and the delta apex

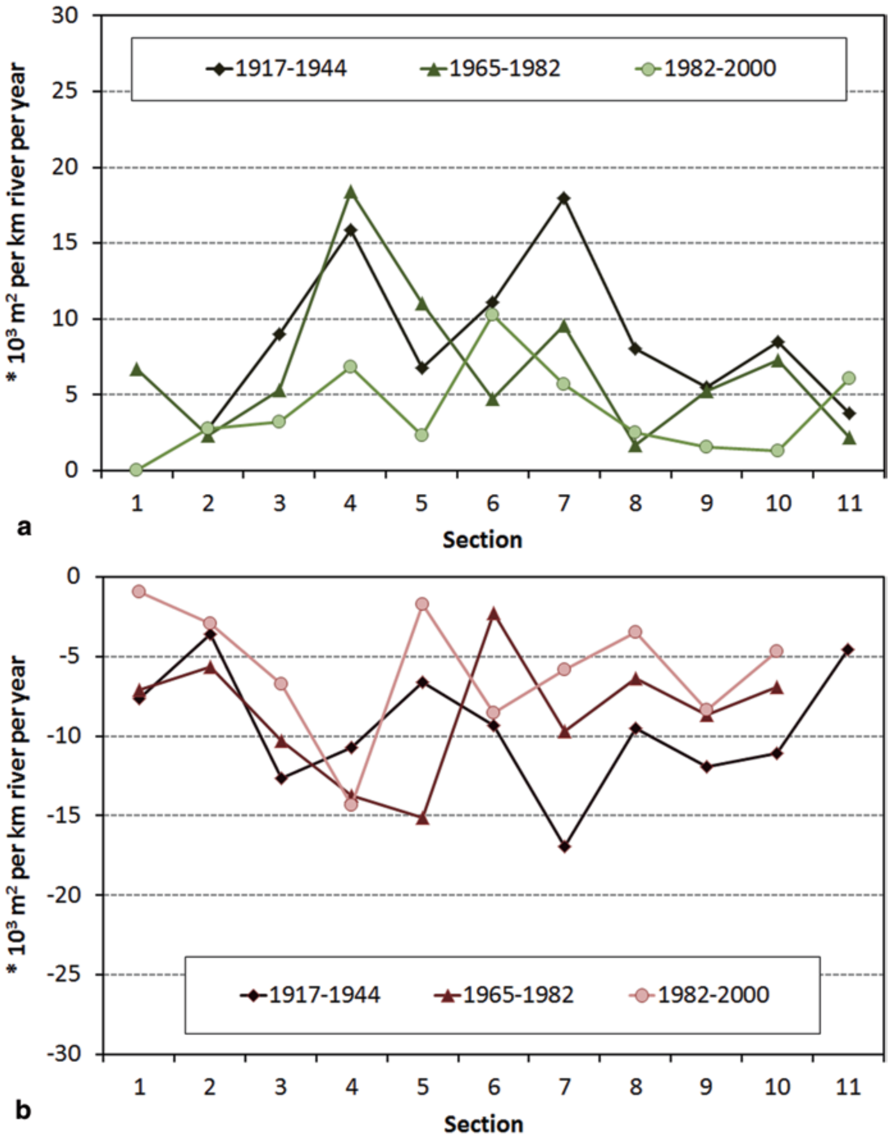

Fig. 7 **a** Bank erosion, **b** Lateral accretion rates along different sections of the Lower Volga before and after dam construction. Values are averages per km per year

year, while erosion rates were less than half this rate. In the first two decades after dam construction, rates of lateral bank erosion and accretion changed little, and in the most recent decades considerably decreased. Many channel bars were initially eroded after dam construction and in recent decades bar erosion has increased, while new bar formation rates are lower than in preceding decades. Erosion and accretion during the period 1986–2000 in the first 150 km clearly demonstrate a

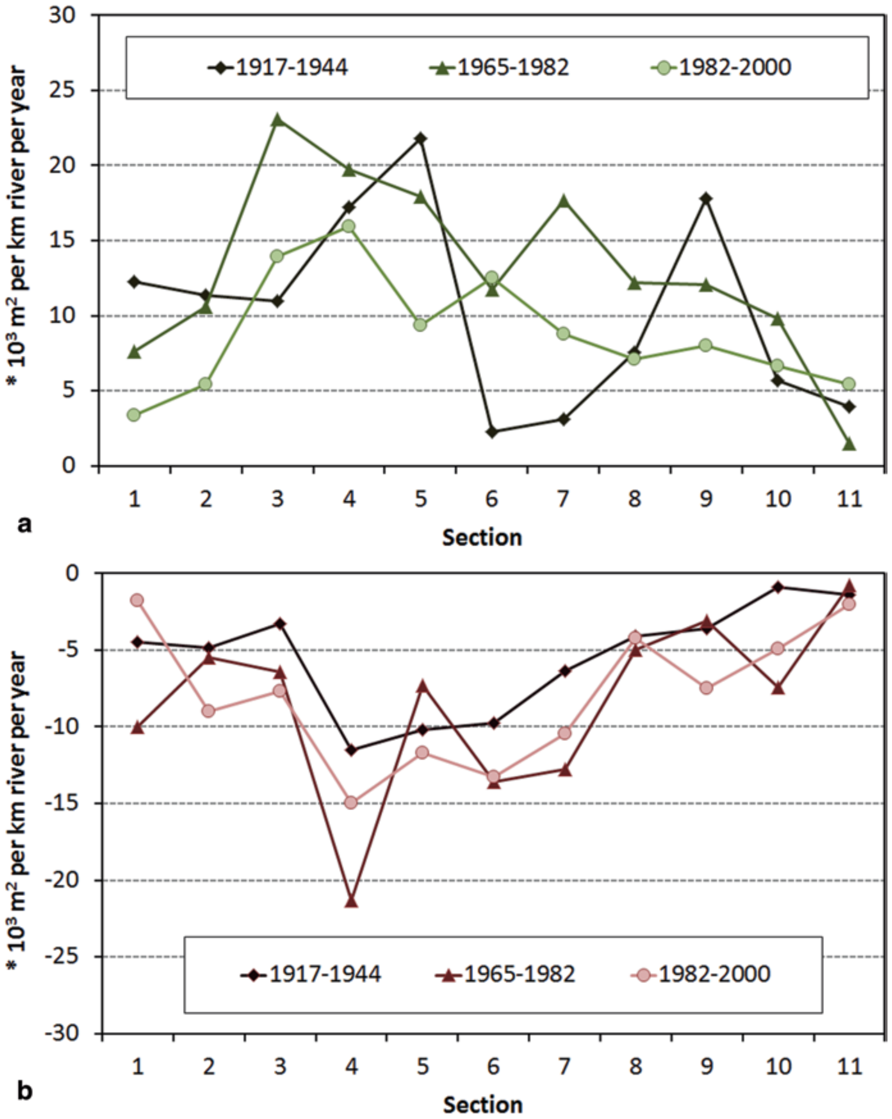

Fig. 8 **a** Channel bar erosion, **b** Deposition rates along different sections of the Lower Volga before and after dam construction. Values are averages per km per year

gradual downstream shift of the main channel in Sects. 1 and 2, and more complex changes in Sects. 3 and 4 (Fig. 9). The decrease in peak flows has also reduced flow amounts and velocities through secondary (residual) channels. This generally resulted in a more rapid silting-up of these channels, occasionally with the deposition of over 5 m thick sand plugs at their entrances, further obstructing flow. This has resulted in an overall increase in-channel stability, but perhaps at the expense of secondary or abandoned channels.

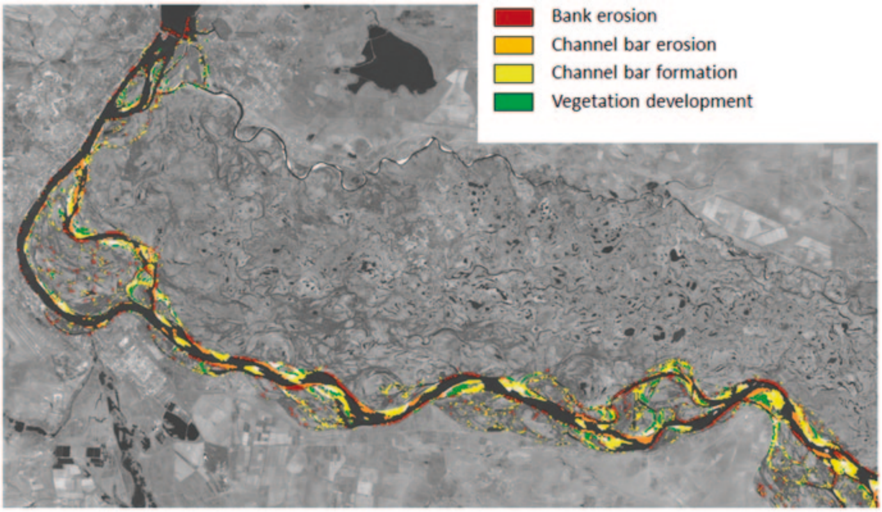

Fig. 9 Bank erosion and lateral accretion in the upper reach of the Lower Volga between 1986 and 2000 derived from Landsat TM imagery

In the subsequent ~ 250-km reach, comprising Sects. 3–8 (Fig. 6, 7 and 8) displays more complex adjustment. Here, major channel adjustments have occurred, characterised by the formation of large river bends, and active development of channel bars. Particularly after the river became regulated in the 1960s major meanders developed and were subsequently cut-off. Average bank erosion rates ranged from 15 to 20 m per year. Pre-dam floodplain accretion and erosion rates were between ~ 7 and ~ 17×10^3 m^2 km^{-1} per year, while bar accretion rates were highly variable between ~ 2 and ~ 22×10^3 m^2 km^{-1} per year. Following dam construction, bank erosion and floodplain accretion rates have decreased and have become less variable. Channel bank accretion has particularly increased in Sects. 6 and 7 (km 200–300), and bar erosion rates show an overall increase in the post-damming period.

The final 50-km reach, before the apex of the delta, is much more stable and is primarily a single-thread meandering channel. Meander bends display little displacement with decreasing erosion and sedimentation rates towards the apex because of reduced stream power associated with a decreasing channel gradient. Lateral floodplain erosion and accretion rates have also decreased, particularly in the most recent period.

The 20–30 m high cliff of resistant bedrock and Pleistocene deposits forming the right bank of the Volga channel has been a major factor in preventing major lateral channel shifts, especially over Sects. 1, 2, 6, and 8. Erosion of the left (floodplain) bank is promoted by the saturation of the floodplain soils during the spring flood period, following the peak flow, when the Volga river stage has receded to average heights. Receding alluvial groundwater draining from high saturated banks, however, results in bank instability and subsequent collapse by mass failure.

3.3.2 Local Changes: Volgograd Region

Until the 1950s the Volga Riverat the location of the present dam had a relatively straight, single thread channel, that was 2–2.5 km wide, and with a low gradient (300-km average downstream of Volgograd $\sim 0.03 \times 10^{-5}$). At ~50 km downstream from this location the main channel is divided into two branches that merged about 20 km further downstream, enclosing two main islands.

The construction of the dam and sluice complex caused major morphological changes to the river channel near Volgograd (Fig. 10). In addition to the engineering construction, a new entrance of the Akhtuba channel was created because the dam was located across the natural bifurcation. Also, major dredging was required to create sufficient discharge capacity to spill the reservoir water. A navigation channel was also created to connect sluices along the eastern side of the dam to the river channel.

Dam construction resulted in about 6.5 million m^3 of sediment to be removed from the active system. Until 1960 the total amount of sediment eroded at the dam area was, about 26.5 million m^3. This extensive sediment production induced considerable deposition in the first tens of km downstream of the dam within several years of dam construction. After the dam had become operational, active channel erosion was progressively initiated immediately downstream of the dam. Channel deformation rates were highest during the first 10–15 years after the dam construction. Massive erosion occurred within a few tens of km downstream of the dam.

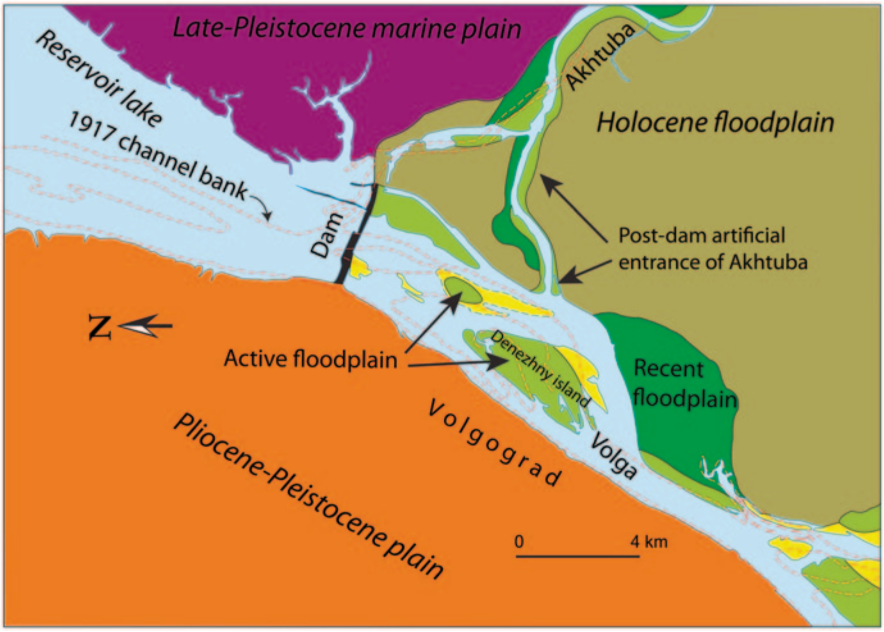

Fig. 10 Morphological overview map of the Volgograd area—situation 1980. The *red line* indicates the channel banks of the Volga before reservoir construction

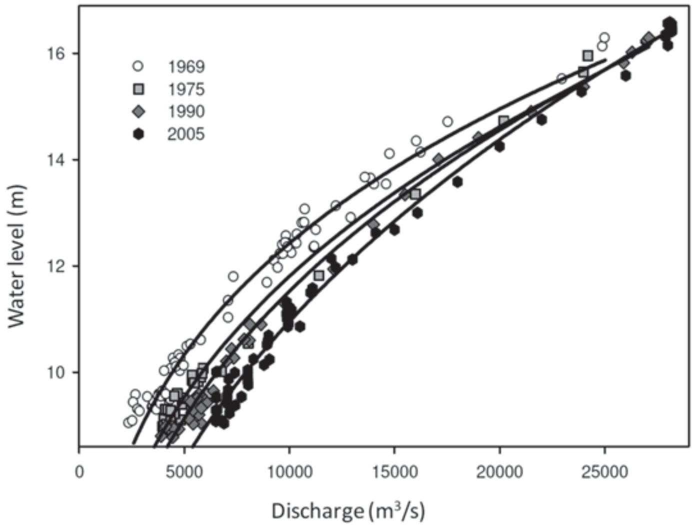

Fig. 11 Stage-discharge relationships for the Volga at Volgograd in different years after completion of the reservoir dam

Some braid bars disappeared, and the right branch around the Denezhny island 5 km downstream of the dam widened by 500 m. Braid bars moved downstream at rates between 50 and 120 m yr^{-1}. The increase of low-water levels resulted in bank erosion along a large secondary channel adjacent to the large Sarpinski island complex, immediately downstream of Volgograd. The progressive channel incision reduced annual high water stages at Volgograd by about 1.3 m over the period 1953–1998 for discharges equal to 10,000 m^{3}s^{-1}, 0.93 m for Q = 20,000 m^{3}s^{-1}, and by 0.70 m for Q = 30,000 m^{3}s^{-1}. This channel degradation still continues, as can be seen in stage-discharge relationships from different time periods at Volgograd (Fig. 11). Since the reservoir has become operational, total channel incision at Volgograd has been almost 2 m. Channel bottom erosion is especially promoted by the artificially high velocities and associated with the abrupt release of the spring discharge wave from the reservoir, which results in the river stage to increase by up to 2.5 m per day. Water flow velocities near the channel bottom may accordingly increase to over 1 m s^{-1}, causing rapid degradation of the 0.3–0.4 mm fine channel bottom sediments.

3.3.3 Local Changes: Zakrutsky Pointbar

Post-dam channel morphodynamics are displayed in greater detail for the Zakrutsky reach, a 10 km long low-sinuosity meander bend located about 90 km downstream from the Volgograd reservoir and dam (Figs. 1b and 6). The reach is located in the upstream reach of Sect. 3. Morphological changes were reconstructed utilizing satellite imagery, old and recent navigation maps, complemented by field surveys of the channel, point bar and floodplain. Figure 11 shows a bird's eye view of the present-day situation.

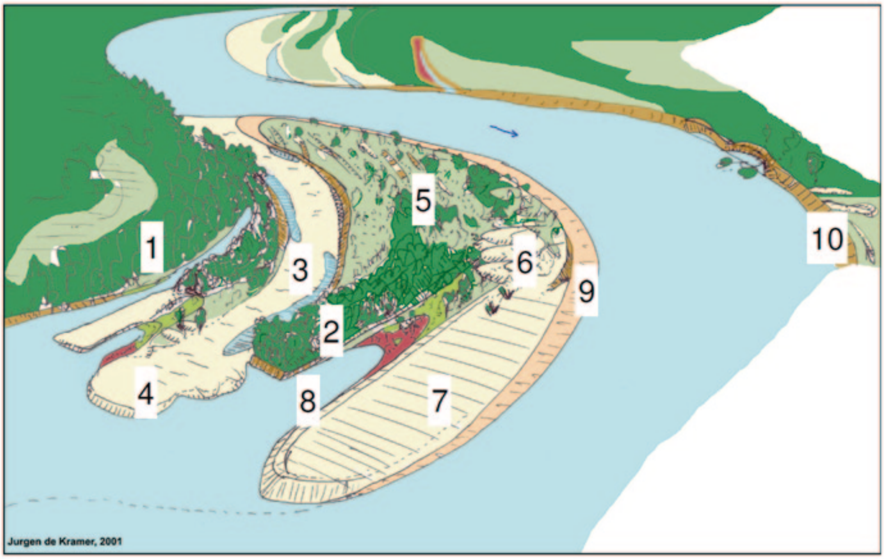

Fig. 12 Zakrutsky pointbar from a bird's eye view. Flow is towards the reader. 1 = older floodplain bar with mixed softwood-hardwood forest; 2 = oldest part of point bar with willow forest; 3 = chute channel; 4 = chute bar; 5 = central point bar with open vegetation; 6 = overbank sand bars; 7 = scroll bar; 8 = swale channel; 9 = inner bank, channel bars; 10 = erosive outer bank

The channel thalweg in 1914 crossed from the southern bank in the upstream meander to the northern bank in the west, forming a riffle at the present-day location of the Zakrutsky bar, which only existed in a rudimentary form (Fig. 13). In the subsequent period until the 1960s, the channel bend migrated by several km in a downstream direction, while the Zakrutsky area developed as a sandy point bar along the southern bank. After 1962 (Fig. 14) downstream migration rates decreased. Lateral bank erosion of the northern bank occurred at a rate of 15–50 m per year (relative erosion rates after dividing by the channel width: 0.01–0.025 yr^{-1}). The point of maximum erosion of the outer bank opposite the Zakrutsky bar shifted slowly in a downstream direction, particularly after the 1980s, with annual rates of 30–140 m. Remarkably, the knick-point to the next bend did not shift downstream, as the left bank downstream the Zakrutsky bar was minimally impacted by lateral erosion. Consequently, between 1962 and 2003 the bend radius of the meander decreased from about 11.6 km to 6.75 km, and the relative bend radius—obtained by dividing by channel width—decreased from 13.0 to 7.5. This might be the result of the artificial reduction of peak flows caused by the Volgograd dam (Van den Berg and Middelkoop 2007), which also decreased the adaptation length of the flow to bends. Along with the channel migration, the Zakrutsky bar at the inner bend gradually increased in size. This is revealed by examination of the planform geometry afforded by examination of 1960s Corona images. These data suggest that the bar formed as a sequence of individual bars, successively developing at the downstream point of an older bar. After 1986 a new scroll bar developed at the downstream tip

Fig. 13 Zakrutsky section according to a 1914 navigation map. The *dashed line* is the navigation thalweg. (Source: MPS 1917)

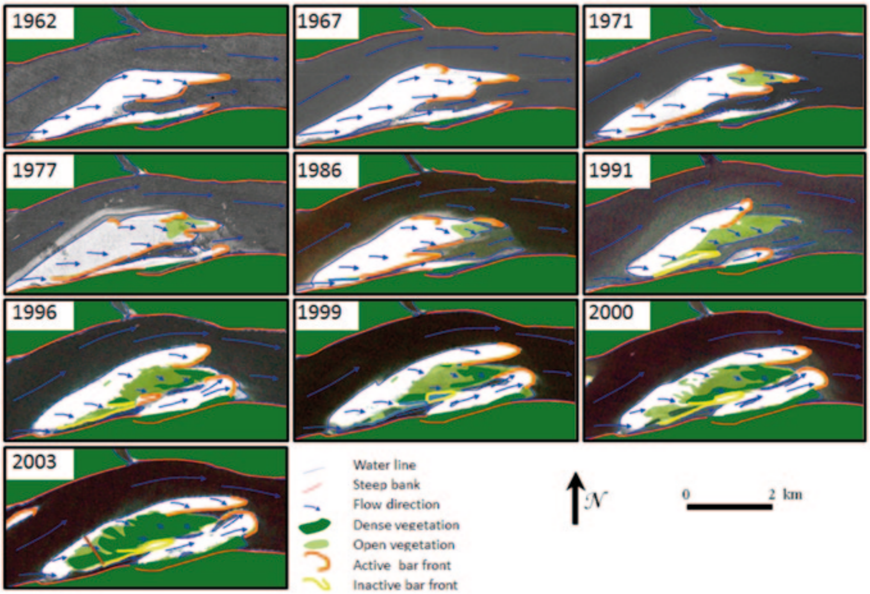

Fig. 14 Development of the Zakrutsky pointbar 1962–2003 derived from Corona and Landsat imagery

of the existing complex, which had evolved into a large bar with top bank heights of 5 m. The Zakrutsky pointbar complex, meanwhile, had become separated from the older floodplain by a chute channel.

Satellite images and tree ring counts indicate that in 1970 *Populus* colonised large portions of the northern and eastern Zakrutsky point bar, and survived vertical accretion by subsequent floods. Apparently, sedimentation rates at the proximal sides remained high, as each year young shoots from annual seedlings became buried under a new layer of sandy flood deposits. Analysis of sedimentary structures in sand pits on the northern part of the vegetated point bar revealed clear 10–20 cm thick cycles of sand layers deposited from annual floods, covered by clay drapes representing recessional flood stages. The scroll bars on the Volga point bar thus experienced rapid vertical accretion, which in large areas suppressed vegetation development for over a decade. Flow retardation within vegetated areas leads to a strong reduction in sediment transport capacity of the flow. Within the vegetated section of the Zakrutsky pointbar, annual deposition layers are considerably thinner (5–10 cm). After 1991, trees started to survive also in more upstream parts of the point bar, turning much of the area to a savannah type of landscape. Over the past 20 years the hydraulic roughness of the vegetation on the Zakrutsky bar has caused separation of the flow during flood stages, with increasing flow passing through the chute channel. This channel therefore has become more active and a large, up to 6 m thick, fan-shaped chute bar has developed at the downstream end of the bar (Fig. 12).

We contend that these processes reflect the impact of the dam construction along the Volga River, and the inherent decrease of peak flows. The reduction in peak flows was associated with a reduction in rates of lateral bank erosion, and may have also resulted in a change in planform channel geometry, specifically a reduction in meander radius rather than the progressive downstream shifting of meanders. Decreasing amounts of overbank deposition has resulted in a change in vegetation succession, from the typical bottomland floodplain vegetation of poplar and willow trees to more upland species of ash and oak which may influence flood flows. At the Zakrutsky pointbar the vegetation increasingly influenced the flow and promoted the formation of a chute, which thus effectively countered the general tendency of silting up of secondary channels as observed at other locations along the river.

4 Conclusions and Prospects

The impacts of the reservoir and dams along the lower Volga River had local and longer downstream impacts, over short and decadal-scale periods. Obviously, the major channel reconstruction at the dam site resulted in an abrupt change to local channel morphology. The enhanced peak flow velocities, combined with the sediment trapping of the reservoir, resulted in major changes which are continuing to unfold. In the course of decades after dam building this effect extended in a downstream direction over tens of kilometers. Importantly, the main channel and its banks have become the major sources of sediment transported downstream to the delta.

Morphological changes along the lower Volga comprise continued channel bank erosion, with differences between the three major river reaches remaining to exist. In the upper 100-km reach bank erosion and scroll bar deposition will continue. Within the more complex central reach, cut-off of meanders and bar accretion and erosion will remain active, while in the lowest single-thread reach meanders will continue to erode at low rates. The reduction in peak flows is reflected in two remarkably opposite responses in the development of secondary (chute) channels. Abandoned secondary channels generally tend to be in-filled with sediment, while a reduction of sediment deposition allows pioneer vegetation to colonize point bars. As a result of the inherent increasing hydraulic roughness of the vegetation, the difference between flow velocities over the vegetated pointbar ridges and those in chute channels is enhanced, leading to deepening and activation of chutes, and the formation of chute bars.

The persistent regulated discharge and lack of sediment will thus lead to a continuation of morphological changes that have been observed over the past decades. Because of the lower peak flows, vegetation is likely to colonize and develop and stabilise channel bars, and ultimately form islands. Residual channels and chute channels will further close as sand plugs develop at their entrance and are no longer eroded during peak flow. Only the deepest side channels might survive when vegetation development on the bars causes flow separation and enhances flow.

The key for water management to respond to these impacts is in the release schemes from the reservoirs, and to acknowledge the inevitable existence of reservoirs rather than consider their removal. Restoring sediment transfer from the reservoirs to the downstream reaches as e.g. occurs in the upper Rhine (Frings et al. 2014) may be considered as unfeasible because of the great size and length of the reservoirs. Moreover, polluted sediments accumulated in the lakes are suspected to become mobilized and may contaminate the lower Volga and Caspian Sea (Malik et al. 2000). This leaves the release schemes as the remaining management instrument. The degree to which more ‘natural’ release regimes, with higher peak flows and a different timing of the start and duration of the peak flow can be achieved obviously depends on the total amount of water available, economic demands of hydropower, irrigation and navigation and the storage capacity of the reservoirs. In this respect, future climate change becomes relevant, as this is a major control of water availability, as well as water demand for irrigation. A scenario study by Sperna Weiland (2011) evaluated for the IPCC A1B scenario shows that climate change may have considerable impact on the discharge regime of the Volga (Fig. 15). A 12-GCM average projected to the year 2080 shows that summer runoff will decrease by the order of 10–20 %, winter runoff will slightly decrease, while early spring runoff will likely increase. Remarkably, the total annual amount of water decreases only by 2 % according to this scenario. However, a larger difference between summer and winter runoff may pose major limitations to re-establish more natural flow regimes. Reservoirs storage capacity will be increasingly important to fulfil the increased demands for water during summer months, with less water available in this period.

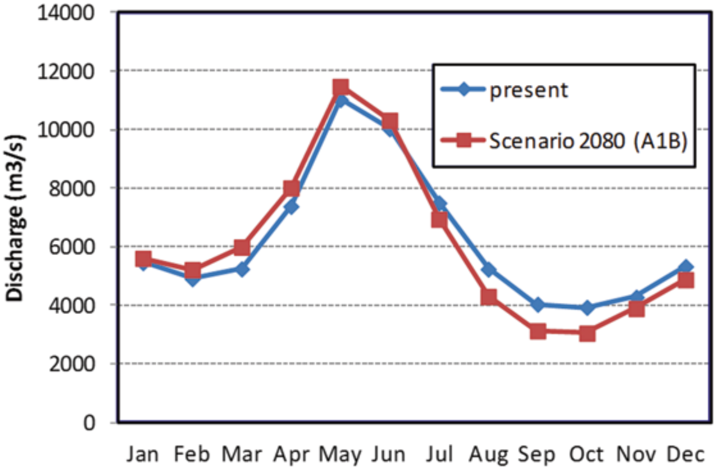

Fig. 15 Unregulated Volga runoff at Volgograd for present day and A1B scenario projected to the year 2080; multi-GCM ensemble. (Source: Sperna Weiland 2011)

This strategy will likely be at the expense of allowing larger peak flows during spring months, in spite of the larger runoff.

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Embanking the Lower Danube: From Natural to Engineered Floodplains and Back

Ştefan Constantinescu, Diana Achim, Ioan Rus and Liviu Giosan

Abstract Anthropogenic intervention along the Danube floodplain has occurred in various degrees since ancient times. Early in this history, small and localized changes were linked to fishing as floodplain lakes and channels constituted a permanent and trusted source of fish. Large scale, intense changes occurred primarily during the communist period when most of the floodplain was used for agriculture. As a result of this phase, 3250 km of artificial levee were constructed on the main course of the Danube, of which more than 1100 km are located in Romania. By the end of the 1980s, the area affected by anthropogenic intervention in the floodplain amounted to 433,957 ha, represented by 56 embanked enclosures. Only a small part (79,943 ha) remained under natural conditions, primarily the mouths of tributaries and the "Small Islet of Brăila". In time, the narrowing of the streambed by anthropogenic levees led to an increase in current velocity and significant erosion of the riverbed. The damming of Danube at the Iron Gates Gorge and of its major tributaries led to the creation of 340 artificial lakes along their courses and lowered drastically Danube's sediment discharge that feeds the current floodplain. In addition, fertilizer-aided intensive agriculture on the floodplain has fundamentally changed its soil regime.

Our study examines the recent history of the Lower Danube's floodplain, using a comparative cartography approach. Maps published in the late nineteenth century (1880–1884) show no significant human influence upon the river system. By the mid twentieth century the shift from a natural regime to a human controlled system has reached its peak as evident from contemporary maps (1960–1980). Recent satellite and aerial images (2005) continue to exhibit extensive human impacts, 30 years after the large Iron Gates I and II dams were built. Islets along the Danube course have directly reflected all these hydrological changes over time.

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Many of the artificial levees along the Lower Danube are currently severely damaged and require restoration works. In April 2006, the Danube levels reached historical values and caused significant damage. Floods occurred downstream of Iron Gates Dam not because water overtopped the levees but because of their natural failure through piping. An optimal solution for navigation and economic use should take into account many factors: the reduction of solid discharge over the entire Danube basin, the narrowing the stream bed, the need for a buffer zone for floods, as well as agricultural and fishing activities, the natural ecosystem and the services it provides. As the human-controlled transformation of the Lower Danube floodplain suggests, changing the functionality of a system could be a one-way route and as a return to the initial, natural state may be impossible.

Keywords Danube · Floodplain · Embankment · Anthropogenic intervention

1 Introduction and Context

Floodplains are important and unique ecosystems along lowland rivers and process large fluxes of energy and materials transferred from upstream sources (Hughes 1997). The dynamic nature of alluvial rivers is a function of flow and sediment regimes interacting within geologic, physiographic, and land use and land-cover controls (Ward and Stanford 1995). Economic development and expansion has strongly affected river and floodplain hydrology and associated ecosystems in many temperate and tropical areas to a larger degree than most other natural systems (Bayley 1995). Embankments and dams have led to rapid and drastic changes to floodplain and riverine ecosystems, impairing biota and abiotic processes (Hintz 2011; Ward and Stanford 1995; Clawson et al. 2001). From the standpoint of this substantially altered condition, the adaptation of floodplain ecosystems to the new context of climate change and greater human pressure represents a substantial challenge for floodplain managers and society.

Long-term adaptation consists of a series of complex processes involving climate change, river regulation and community responses (Martens and Chang 2010; Jenkins et al. 2012). Some impending threats acting upon these fragile ecosystems include potential increases in drought frequency and duration, temperature increases, sea-level rise and changes in rainfall regimes. From a historical perspective over the past century, anthropogenic intervention in the Danube basin has been the most important influence on floodplain dynamics. The potential to modify the floodplain to mitigate against further climate change and human pressure is constrained by the narrower embanked floodplain and modified hydrologic regime. The presence of dams has been associated with a reduction in sediment loads, as well as increased channel velocity. Combined, the effect has been to increase river bank erosion. The EU Water Framework Directive represents a fundamental guide for conducting floodplain restoration projects. According to Moss and Monstadt (2008), important restoration schemas were already undertaken on the Rhine, Elbe, Garonne and Long Eau Rivers.

The purpose of this study is to document the history of human impacts to the lower Danube floodplain in the context of water resource control and floodplain management. By emphasizing the interaction of fluvial processes with human development, the study represents an important baseline to management and restoration efforts—along the Danube as well as other large European rivers.

The Danube is among Earth's most international rivers and is the largest fluvial system within the European Union in terms of length, drainage area, discharge, and sediment load (6470 m^3/s and 1555 kg/s, respectively; McCarney-Castle 2012). As it flows over 2870 km from its headwaters in Germany and Switzerland to its delta at the western Black Sea coast, the Danube River flows within 10 nations and its basin drains 19 nations within an area of 817,000 km^2. The variation in river stage is large (10.5 m), among the highest stage variations of temperate zone rivers (Vidraşcu 1921), and historically was associated with a distinctive floodplain pulse and lateral hydrologic connectivity. Downstream of Iron Gates Gorge (Fig. 1), an extensive natural floodplain bordered the Danube along its lower course, which included numerous lakes rich in fish and other forms of aquatic wildlife. Historically, for example, the Balta Brăilei floodplain region upstream of the delta was associated with one of the most productive freshwater fisheries in Europe (Antipa 1910). After the 1960s, however, an extensive reclamation program converted the floodplain wetlands and lakes into predominantly an agricultural region, and is considered the most devastating and abrupt anthropogenic transformation of a fluvial wetland in post-war Europe (Botnariuc and Vădineanu 1982).

Like many large temperate zone rivers, the sediment load of the Danube River has been substantially reduced because of dam and reservoir construction. The Danube basin has many hundreds of dams and reservoirs, which were constructed primarily after the World War II. Over 150 dams were constructed within the Romanian portions of the basin, which have reservoirs that can store up to 22 billion m^3 of water. Several dams were built on local rivers in Romania (Fig. 3) and considerably reduced downstream sediment loads by trapping sediments within the reservoirs. The Jiu, Olt, Argeş, Ialomiţa and Siret rivers previously provided about a third of the Danube's annual sediment load. Because of the erodible loess deposits in upstream basins, the sediment discharge was naturally high within this section of the basin, and increased by ~37 % between Orşova and the Danube delta. This increase in sediment load was associated with only a 16 % in stream flow (Mihăilescu 1969). Along these tributaries, many small dams were built after 1950 and as a result, available measurements indicate considerable sediment load reductions along the Danube, including ~69 % reduction from the Jiu River, ~67 % reduction from the Argeş River, and a ~48 % reduction from the Siret and Prut Rivers (Rădoane 2008).

In addition to larger dams within Romania, during about a 30 year period following World War II over 600 small dams were also built on Danube tributaries in Bulgaria. These dams considerably reduced sediment discharge to the lower Danube, from 4.4 million t/year to only 0.4 million t/year (Levashova et al. 2004). Overall, Danube tributaries are currently contributing ~60 % less suspended sediment than under pre-dam conditions (McCarney-Castle 2012).

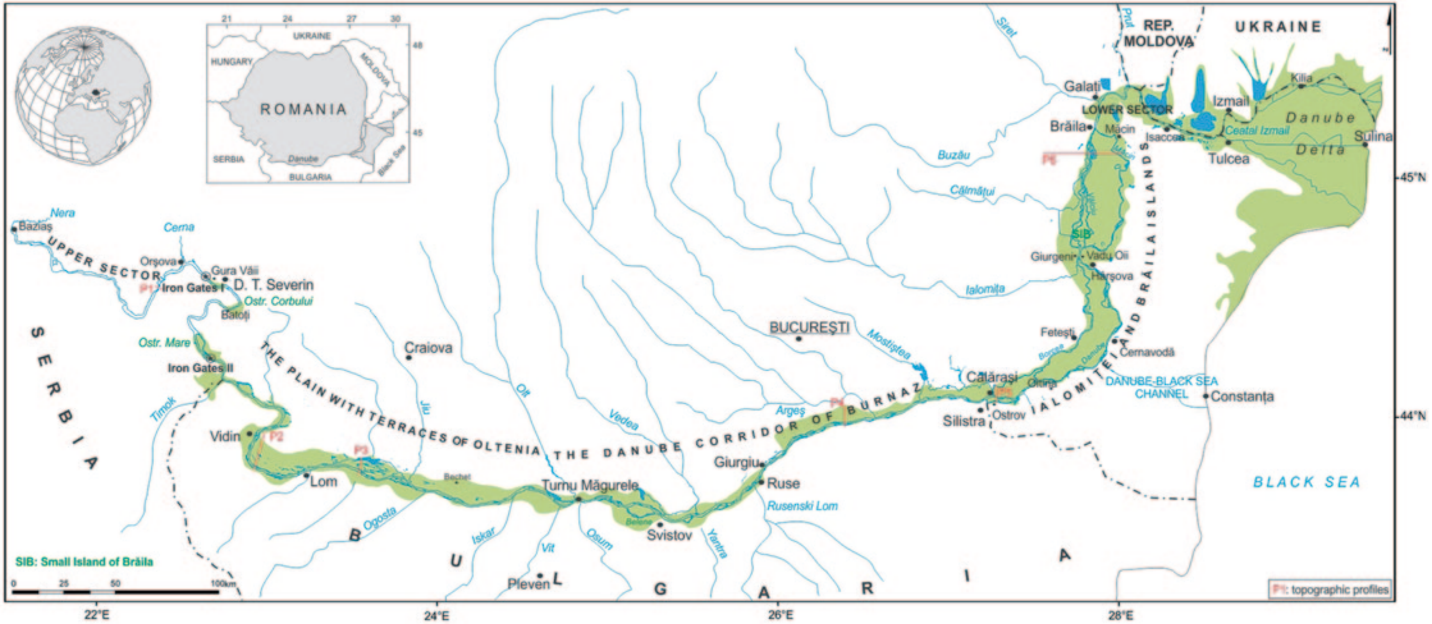


Fig. 1 The lower course of the Danube River with its main tributaries together with the floodplain segmented into morphological sectors. The map reflects the situation prior to 1960. P1 to P6 represents the location of profiles from Fig. 5

The Danube River course comprises 56 permanent main-stem reservoirs, amounting to 4.8 billion m^3 of water storage (Stanciu et al. 2008). The construction of the Iron Gates I and II Dams (Fig. 1) was a major contributor to the sediment reduction in the lowermost reaches of the Danube. Combined, the sediment load reduced by 53 % at the entry to the delta (1846 kg/s between 1840 and 1970 and 962 kg/s between 1971 and 2000) (Bondar 2008).

2 Motivation

The first debates regarding the agricultural development of the Danube floodplain occurred early in the twentieth century with proposals from the Romanian polymath Grigore Antipa (1867–1944) and his collaborator, engineer G. Vidrascu. Antipa's ideas were well advanced for their time: ecologically-oriented and grounded in the flood pulse concept with minor negative effects to be expected on the fluvial ecosystem. In contrast, the reclamation of wetlands for agriculture after 1950 during the Communist period completely transformed the floodplain. Consequently, its current heavily degraded state requires massive restoration efforts (Vădineanu 2001).

Prior to 1950's, the river dynamics greatly influenced the livelihoods of floodplain inhabitants along the lower Danube. Rare, exceptional hydrologic events, whether floods, droughts, or river course changes left deep imprints in the collective memory of residents of wetland communities, leading to a rich collective knowledge of the fluvial environment. The subsequent transformation of the region, however, and the new sense of security brought in by reclamation of wetlands caused the riparian communities to turn their thoughts from nature. Engineering the river has fulfilled an insidious double role of flood protection, but also to irreversibly isolate floodplain residents from their natural environment. Protection structures have thus become a symbol not only for the artificial state of the environment, but also of the state of the human spirit. Future efforts of floodplain restoration and development should include not only a return to the idea of a minimal developmental footprint as originally proposed by Antipa and Vidrascu, but also to a reconstruction of the cultural dimension of the way of life for floodplain inhabitants. Our contribution to these recovery efforts is the present paper that surveys and discusses the morphology of the floodplain under natural and anthropogenic conditions.

3 Mapping Methods

Following the Treaty of Berlin in 1878 that recognized its *de facto* independence, Romania began to systematically collect spatial data pertaining to topography and hydrolologic features as it strove to map its entire territory. These efforts between 1880 and 1899 enabled cartographers from Romanian Army's Institute for Cartography to produce maps of the entire lower Danube valley. The spatial data were drafted to maps using a Lambert-Cholesky projection, and is further described in Bartos et al. (2007). A transition to a Gauss-Kruger system in 1951 required considerable effort to update the cartography for the entire nation at a 1:25,000 scale. The latest updates to these maps occurred in the 1980s and utilized new field measurements and aerial images. Since the 1980s satellite and aerial images have become available, and in this study are utilized for the period of analysis spanning from 2005 to 2008. All spatial data were processed and transformed into a unique Stereo-70 projection, the official projection used in Romania.

4 Background and Terminology

The all-encompassing term "Danube floodplain" includes the entire surface subject to flooding from the modern hydrologic regime, as well as higher alluvial terraces (Posea 2005). The common Romanian term for this region is *baltă* (loosely translated as "the water realm" but meaning interchangeably "pond", "wetland", "lake", "river"; (Conea and Badea 2006)), which was previously used in the local scientific jargon (e.g., de Martonne 1902; Munteanu-Murgoci 1907). The term *lac* (English: lake) is not used in the local informal language. To avoid confusion between its multiple meanings, Antipa introduced the notion of *flooding zone*, a phrase that was later adopted by Vidraşcu. The purpose was to distinguish between the larger geomorphic units composed of low terrains near the river and its components such as the riverbed or the floodplain proper. After the communist reclamation program, the term *baltă* faded away from the local collective memory being replaced by *luncă* (English: floodplain), which was preferentially employed in official documents. The new term was more convenient for communist authorities as it signified a new reality, a transformed space, whereas the popular name referred to a past quickly forgotten.

The Danube floodplain varies in extent along it lower course. Downstream of the Iron Gates I Dam, most islets and the surrounding small floodplain areas located within the upstream gorge were completely inundated (Fig. 2). Immediately downstream of Iron Gates Gorge, which is considered the formal upstream boundary to the lower Danube River, the floodplain is narrow and sporadic. At Ostrovul Mare the floodplain begins to broaden preferentially on the left bank (Romania), and here the floodplain width varies between ~ 200 m near Calafat and ~ 30 km in Balta Brăilei. On the right bank, in Bulgaria, the floodplain is a narrow fragmented strip that was largely embanked before World War II (55,000 ha reported by Hâncu and Dan 2008; 88,000 ha reported by Ioaniţoaia 2007). In Romania, along the 993.5 km long course of the Danube from the Nera River tributary down to Ceatal Izmail at the entrance to the Danube delta, the Danube floodplain extends over 573,000 ha. About 75 % of the floodplain is currently embanked. Within this embanked region, the surface covered by water amounts to 11,143 ha and is dedicated to fisheries, while the remaining area is used for agriculture (Maria 2008). The total length of the embankments along the main course of the Danube is 3520 km, of which 1158 km are located in Romania.

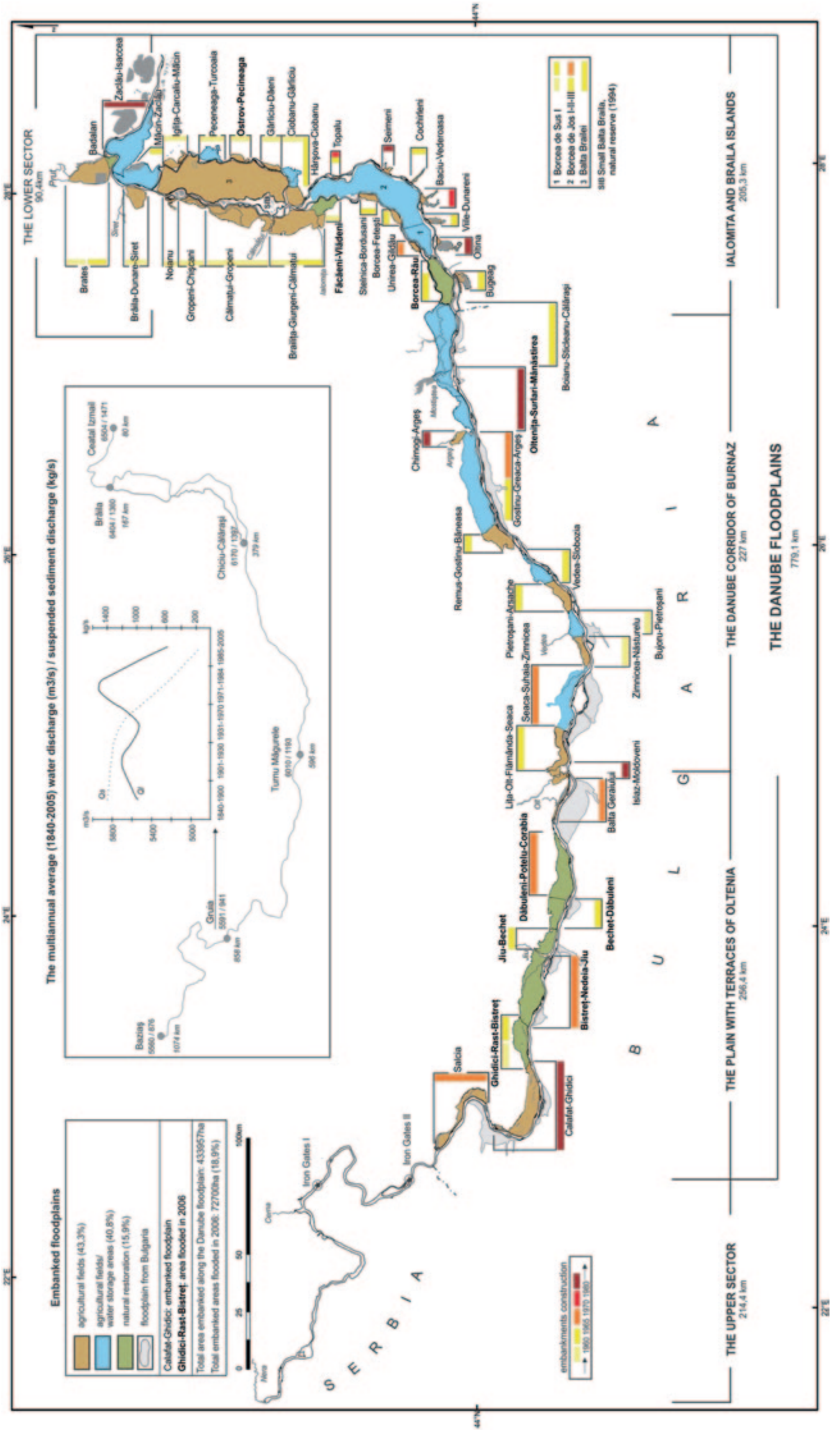


Fig. 2 The lower course of the Danube floodplain with its main floodplain enclosures

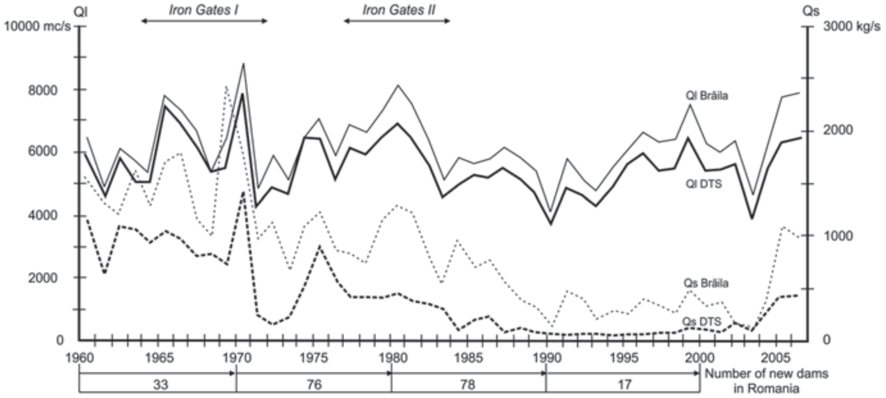


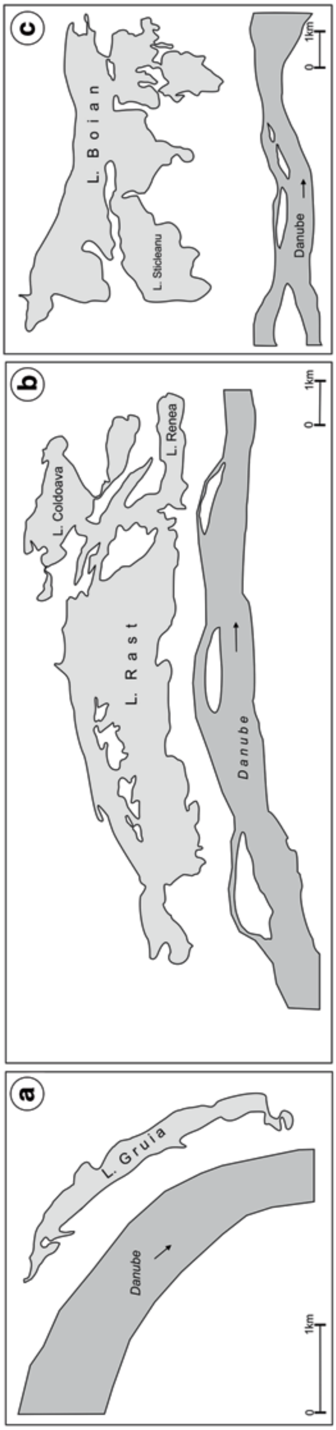
Fig. 3 Water (Q_l) and sediment (Q_s) discharges at the Drobeta Turnu Severin (DTS) and Brăila gauges between 1960 and 2007 (in solid and dashed lines respectively). Note changes in discharge after the Iron Gates dams construction

Flood basins including lakes and marshes are the most important parts of the floodplain in terms of habitat and fauna diversity. They previously served as storage basins and represented safety valves during floods, a feature noted in studies at the beginning of the last century (Vidrașcu 1921; Antipa 1921). Along the Romanian side of the floodplain, before reclamation, there were ca. 2050 floodplain basins. Following drainage and engineering works they were reduced in surface and many disappeared altogether. In natural conditions, three types of lake environments occurred (Fig. 4): (1) between Severin and Calafat only partly infilled single cut-off oxbow lakes were present, (2) between Calafat and Giurgiu large single lake basins were more common, but were rarely associated in complexes, and (3) downstream of Giurgiu, lake complexes become instead common (Posea 2005).

5 Danube Floodplain Reaches

Based on geomorphological features the lower Danube floodplain was classified into several reaches (Vidraşcu 1921; Mihăilescu 1969; Posea et al. 1974, 2005). The absolute elevation of the floodplain is of 65–70 m before the Iron Gate dam, 35 m at Drobeta Turnu Severin, 20–22 m at the Olt confluence, 15 m at the Argeş confluence, and 10 m at Călăraşi and 5 m at Brăila. The elevation gradually decreases and reaches 2 m at Ceatal Izmail. The 134 km long gorge, or the upper sector, extends from Baziaş to Gura Văii and is characterized by small floodplain patches (Fig. 5 P1). Following the construction of the Iron Gates I Dam, most floodplain patches were inundated. The Corbul Islet, a 4 km wide sector from an artificially straightened meander, is the largest floodplain patch downstream of Iron Gates II and comprises a 1700 ha enclosure separated by a 5.7 km long embankment. Another enclosure, of only 264 ha, was built on Ostrovul Mare.

Fig. 4 Morphology of Danube floodplain lakes. **a** oxbow lakes, **b** single lakes infrequently associated in complexes, **c** lake complexes



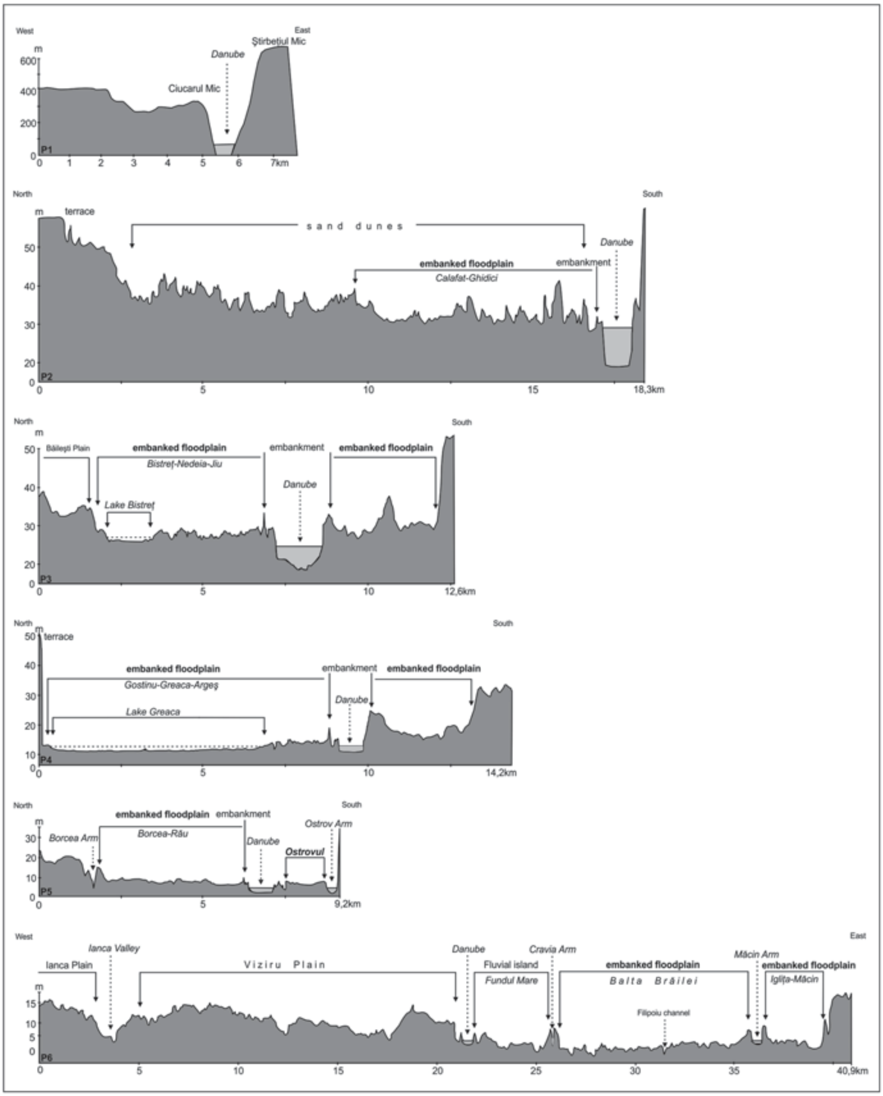


Fig. 5 Cross-sectional profiles of the Danube floodplain (see Fig. 1 for locations)

Downstream of Ostrovul Mare, the floodplain widens and reaches a maximum span of approximately 30 km, primarily on the left bank down to Brăila (Fig. 1). The Oltenia terraced plain sector (256 km) and the Burnaz Danube Corridor (227 km) are separated by the Olt valley. The first is characterized by a sequence of terraced plains with sand dunes between Batoţi and Bechet, followed by a 50–150 m escarpment of the Pre-Balcanic Plateau (Fig. 5 P2, P3). The Burnaz Corridor, east of the Olt River appears as a long valley with particularly active geomorphic processes and floodplain bottlenecks controlled by alluvial fans at tributary junctions

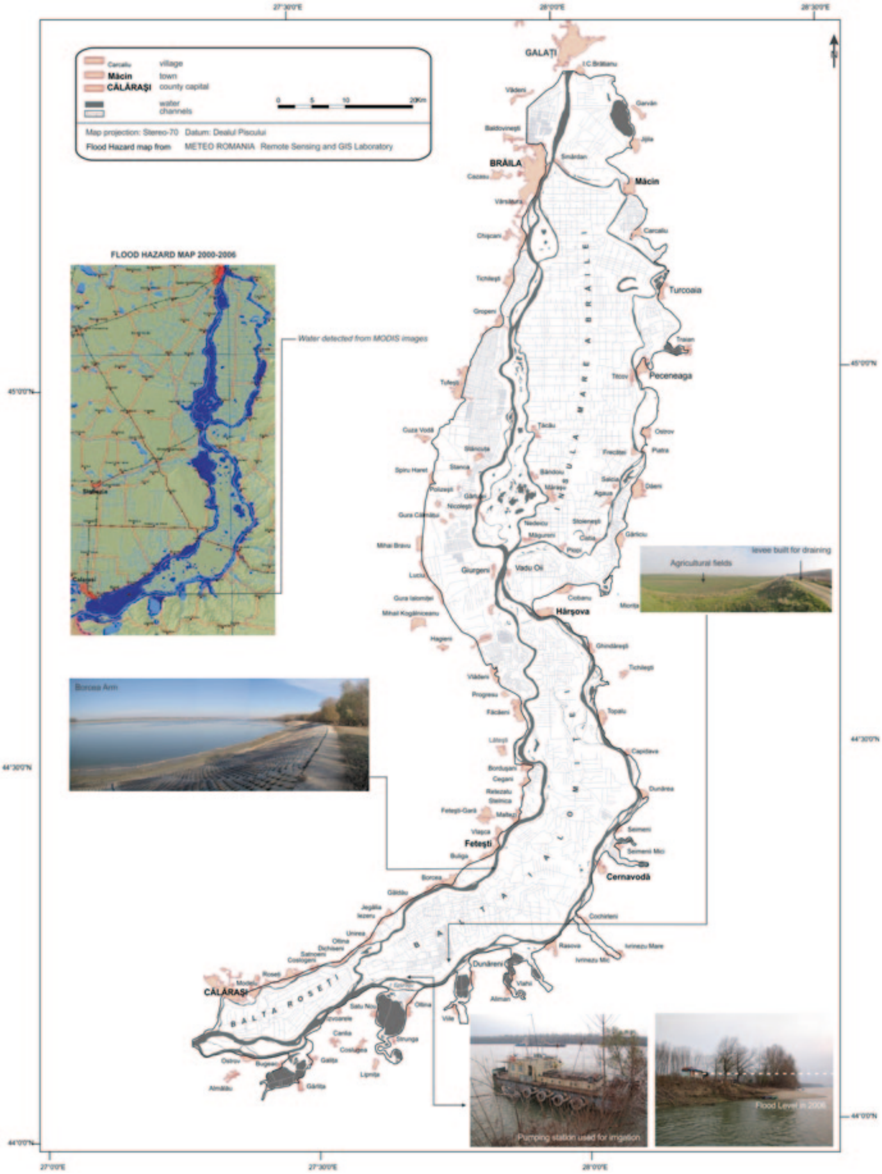


Fig. 6 Danube floodplain between Călăraşi and Brăila

(Fig. 5 P4). In these two central sections (Oltenia and Burnaz), the average floodplain width ranges from 5 to 6 km.

Farther downstream, the Danube branches repeatedly between Călăraşi and Brăila, and consists of two distinct sections: Balta Ialomiţei and Brăilei (Fig. 6). The valley in these sections is asymmetric with the left bank developed along the low altitude Romanian Plain and the right bank along the Dobrogea Plateau with an elevation of more than 100 m. Balta Ialomiței extends over 130 km along the course between Călărași and Giurgeni-Vadu Oii, with a maximum width of 18 km. The crescent-like sector, concave toward the Romanian Plain, changes in elevation from 10 to 11 to 8 m from the south to its northern extremity (Fig. 5 P5). The presence of lakes or fluvial limans at tributary junctions on the Dobrogea Plateau side is a unique characteristic of this section. Downstream, Balta Brăilei is only 70 km long but widens to extend over ~30 km (Fig. 5 P6). The sequential branching of the river, specific to the Călăraşi-Brăila sector, is indicative of a decrease in slope and sediment transport capacity (Fig. 6). The Small Islet of Brăila, with a surface of 17,529 ha located in the western part of Balta Brăilei, is the only floodplain area along the lower Danube valley subject to the natural flood regime (Toader 2005). In 2001 this section was declared a RAMSAR Wetland Site, and designated as a nature preserve in 2003.

Downstream of Brăila, the Danube valley becomes more symmetrical with its banks at low elevations. This 90 km long reach along the lower sector is also known as Balta Isaccei. Here, the river flows through a single channel until the first bifurcation at Ceatal Izmail, the apex of the Danube delta.

6 From Natural to an Engineered Floodplain

At the beginning of the twentieth century, two different conceptual models emerged for the use of the Danube floodplain. The first model championed by engineer Anghel Saligny and agronomist Gheorghe Ionescu-Sisești (1933), proposed a plan to drain the floodplain for agricultural development. Alternatively, a second model proposed by the polymath biologist Grigore Antipa (1910, 1913, 1928) and engineer Ion Vidrașcu (1915, 1921) was in favour of preserving the natural flood regime and floodplain features to develop fish farms and animal husbandry. After 1960, the agricultural model was implemented through extensive embankments and drainage works along lower Danube (Bondar 2008). As a result, over the next two decades the natural hydrologic and geomorphic regime was largely eliminated to make way for intensive agriculture. Despite their economic benefits, embankments along the river resulted in a narrowing of the channel bed with a direct impact on the hydrologic regime. After 1990, most of the floodplain returned to private ownership, renewing the debate of how to develop the floodplain. The conservative model promoted the continuation of agricultural activities, while an ecological model advocated a return to the natural hydrogeomorphic regime through the removal of engineering structures.

7 Natural Evolution: Flooding and Geomorphic Processes Before 1950

Under natural conditions when the Danube overtopped its banks, the width of the river increased ~4 to 12 times (Antipa 1910). The surface covered by lakes was approximately 14% of the floodplain (Antipa 1910), and the floodplain basins accommodated the surplus of fluvial waters during floods. In contrast to the modern engineering position which negatively views floods from the perspective of risk, floods were considered differently in the past. Until the early twentieth century floods were appreciated as natural gifts, which today would be analogous to viewing floods as ecosystem services. Years of major floods, when the Danube inundated the floodplain, were acknowledged as the most productive for fisheries. Before the construction of the embankments seasonal high discharge events mainly did not overtop the natural levees, with the discharge wave requiring 5–6 days to travel between Turnu Severin and Galaţi as in e.g., 1895, 1890 (Vidraşcu 1921). During high discharge years the flood wave was delayed up to 30 days because of flood water storage across the floodplain (e.g., 1889, 1897). Between 1921 and 1960, the maximum discharge generally occurred in April and May, in the Baziaş-Giurgiu sector. Downstream of Giurgiu the maximum discharge occurred in June and July, because of the slow propagation and strong attenuation of the flood wave by the floodplain geomorphology (Mihăilescu 1969). The important point of these examples is that the floodplain played an important role in attenuating the effects of floods. In 1897, for example, water storage in Balta Brăilei alone reached up to 5.5 billion m^3 of the total of 24 billion m^3 of water stored along the entire floodplain (Antipa 1921).

According to Vidrascu (1915), rather than infrequent extreme floods, a moderate hydrologic regime over long periods of time is the dominant force in the evolution of large river valley geomorphology. Floodplain characterization, therefore, should consider the geomorphic evolution of a river system over long time scales to understand the behaviour of fluvial system. To that effect, the Romanian engineer Ion Vidraşcu used hypsometry and hydrological characteristics to introduce a novel unit, the hydrodegree, which was locally defined by the maximum flood height. The hydrodegrees enable the following floodplain elements to be differentiated:

1. Natural levees with the highest elevations, overtopped only during exceptional floods. The elevation of the levee corresponds to an average value of discharge in the spring months of 7 hydrodegrees. For instance, at Dunăreni (Fig. 6) the 7 hydrodegrees corresponds to 5.10 m local stage and the elevation of the levee is between 4.6 and 5.2 m.
2. Lakes are the geomorphic units with the lowest elevations thus 0 hydro degrees. Our GIS reconstruction shows that in the natural regime, lakes represented 19.2 % of the entire surface between Călăraşi and Brăila compared to 2.9 % in 2005.
3. Floodplain marsh with Typha and reeds is the third geounit, having intermediate elevations between 0 and 7 hydrodegrees.

In natural conditions floodplain and lakes exchanged water with the river via a secondary natural stream network. While during the early twentieth century the density of this network between Călăraşi and Brăila amounted to 0.92 km/km^2, the current channel density has increased to 1.66 km/km^2 because of artificial channelling for drainage and irrigation. Many of these artificial channels are currently in an advanced state of infilling and have lost their efficiency. Natural stream channels reactivate only during large floods, such as those in 2005 and 2006, in areas where the protective embankments failed (Fig. 2). During normal spring floods, the river used to overflow into lakes, often covering the entire floodplain with water. When the Danube level decreased, the system reversed with water movement from lakes to the river. Discharge into the marshes reached 5–6 m^3/s. The discharge rate for the Filipoiu marsh, located in Balta Brăilei, was reported to be 450 m^3/s towards the Măcin branch in 1906 (Vidrascu 1915). The return flow was active by definition until 3 hydrodegrees, which corresponds to between +2 and +2.5 m in the Brăila-Hârșova sector. In 1897, a year of major floods, the floodplain between Giurgiu and Brăila had a storage capacity of 5–6% of the entire Danube discharge. The sector between Brăila and Hârșova, although covering a region three times smaller than Danube Delta, had a storage capacity of 80% of the entire delta (Vidrașcu 1915). The importance of the Balta Ialomiţei area in flood mitigation is clearly shown in the analyses of the discharge rate at Vadu Oii, where the average discharge was 231 m^3/s lower than upstream at Silistra (Tufescu 1974).

These data emphasize the importance of the floodplain in relation to the hydrologic regime, and further reveals the existence of feedback processes between lakes, marshes and river subsystems. The rotating polder system of Antipa, as opposed to the agricultural model, proposed a modern—integrated—development vision, with minor changes to fluvial ecosystems. During dry years, which were more damaging than floods to agriculture, the floodplain could be utilized as pasture for a source of revenue. During wet years fisheries revenue increased, compensating for the lost revenue from pasture. The relationship between the extent of the flood prone areas and fish production was well-known at the beginning of the twentieth century. The Communist regime brought new technology and a vision which strongly strayed from the natural rhythm, imposing human control to "conquer nature".

8 Anthropogenic Evolution: Flooding and Geomorphic Processes After 1950

The first engineering works were initiated at the end of the nineteenth Century, but by far the most extensive changes occurred after 1960. Between 1904 and 1906, floodplain was reclaimed at Chirnogi (1058 ha), Simoiu-Mânăstirea (334 ha) and Luciu Giurgeni (3150 ha). The floodplain was embanked during successive droughts occurring between 1904 and 1916. Large sections of embankments were built at Spanţov (1780 ha) between 1906 and 1908. This is also the location for the first agricultural research station on embanked floodplains (Ioaniţoaia 2007). The total surface of these embankments amounted to 23,370 ha 1928, but the agricultural production was below expectations because of the lack of irrigation and flood protection. The approach, based on the natural flood pulse and oriented toward developing fisheries, was the preferred alternative to be implemented by the Administration of Danube Fisheries and Floodable Land Improvement (Administraţia Pescăriilor şi Ameliorării regiunii Inundabile a Dunării—PARID). Subsequently, various land use authorities took charge of the works in the Danube floodplain (Ioaniţoaia 2007).

By 1962 101,000 ha of floodplain embankments were constructed, including 18 complete enclosures. The most intense period of floodplain development occurred between 1963 and 1971 (Fig. 2) when 289,000 ha of embankments were constructed with 24 new enclosures. Between 1971 and 1990, 14 new enclosures were constructed with a total surface of 41,800 ha. At present, 56 embanked enclosures subdivide the lower Danube floodplain in Romania. These enclosures cover 431,763 ha, with 55 % located on the left bank, 12 % on the right bank and 33 % on islets. Protective embankments with a total length of 1158 km are located on the floodplain with 619 km on the left bank, 175 km on the right bank and 31 km on islets (Ioaniţoaia 2007). As of 2007 the floodplain had the following land use distribution: arable lands 70.8 %, forests 10.3 %, fishery 3.5 %, reed processing 0.32 %, residential 1.49 %, transportation 6.7 % and unused 5.37 %.

The embankment works are described rather ambiguously in the literature, frequently using redundant information. The eulogistic tone, specific to the Communist era, is used when presenting the engineering works as a conquest of nature, vital for the economic development of Romania. This rhetoric served as a justification for actions over 50 years, each time invoking the need for increased agricultural production. The scientific literature, however, acknowledges that embankments caused a significant increase in the river stage during extensive discharge events in 1965, 1970, 1985, 2005 and 2006 when the floodplain was preferentially flooded upstream of Bechet (Vişinescu and Bularda 2008). Seven enclosures, for example, were flooded in 2006 covering 72,700 ha. In addition, two enclosures covering 15,165 ha were deliberately flooded to lower the stage of the floodwave (i.e., Borcea-Răul and Făcăeni-Vlădeni) (Fig. 2 in bold).

Embankment and drainage activities have completely altered floodplain geomorphic processes. The narrowing of the river bed and artificial levee (dike) construction resulted in an increase in streamflow, causing increased lateral erosion and river bed incision. As a result, the discharge increased by up to ~2500 m^3/s and the high water stage along the Danube was raised by 0.5 to 1.20 m (Mihăilescu 1969). These changes led to an acceleration of geomorphic processes that is best illustrated by the dynamics of fluvial islets (see section below). The embankments were built to withstand a 100-year flood upstream of Călăraşi, but with 5–10 % protection downstream (Ioaniţoaia 2007). The water volume stored behind these embankments amounts to ~7 billion m^3 along the Iron Gates II-Călăraşi sector and approximately 11 m^3 between Călăraşi and Isaccea. The embankment height varies between 3.5 and 4 m. The distance to the river valley varies from 150 to 200 m to 300–400 m.

In addition to floodplain development, agricultural lands in southern Romaniarely upon Danube River water for irrigation. Prior to 1989 irrigated lands amounted to 2.3 Mha, requiring not only impressive amounts of water but also high energy consumption to drive irrigation pumps. Sixty-nine percent of the total lands were on terraces, at 60–70 m elevation. If a minimum of 2500 m^3/s of Danube discharge is conserved to maintain navigation, only 45 % of Danube's water was available for irrigation and other uses (Stanciu et al. 2008). These data indicate the extreme pressure put on Danube River, which resulted not only in major imbalances in the overall fluvial ecosystem, but also proved to be economically unsuccessful.

> The 1158 km of embankments, the irrigation system for 418,000 ha, and the irrigation systems serving 224,000 ha of land are an investment of approximately 2,200 million euros, i.e. 5,250 euros per hectare. Adding the agricultural land preparation works, deforestation, reed removal, preliminary dewatering, modeling, movable and immovable assets of the 400 agricultural farms, buildings in private ownership and other infrastructure works and assets, the total lands and works under protection are estimated to value approximately 8.8 billion euros. (Maria 2008)

9 Floodplain Embankment Effects

Because of the scale (size) of the lower Danube such an intensive system of embankments had a significant impact to the fluvial ecosystems. These impacts included a reduction of fish spawning habitat and isolation of fish populations, decreased nutrient retention capacity, floodplain drought, increased soil salinity, reduction in water exchange with the river and within the floodplain, major changes in the structure and composition of vegetation, and the destruction of the last remaining natural floodplain forests in Europe (Antipa 1921; Vădineanu 2001; Iordache 2005).

In addition to the aforementioned internally imposed anthropogenic impacts, indirect external forcing is also important to understanding the modern hydrogeomorphic regime of the lower Danube. Climate change over the last century coupled with engineering works in the upper and central Danube basin resulted in a major change in discharge regime to the lower basin. In the Baziaş sector, for example, the average increase in water discharge increased by ~1,200 m^3/s, resulting in 40–50 cm increase in river stage along the lower Danube. In addition, the base level of the Black Sea increased at Sulina by approximately 35 cm, resulting in an increase in river stage upstream to Brăila (Mihailovici et al. 2006). These changes likely contributed to the 2006 flood being the largest in over a hundred and 50 years, since the extreme flood of 1840. At Baziaş the highest discharge reached 15,082 m^3/s, while at Isaccea the estimated discharge reached 17,700 m^3/s (Şerban 2006). These exceptionally high discharges led to stages up to 60 cm higher than previously reported. Uncontrolled embankment breaks occurred at Rast, Bechet, Spanţov, Oltina and Ostrov and forced authorities to undertake controlled breaches at Borcea-Răul and Făcăeni-Vlădeni (Moraru 2007). These breaches resulted in a cumulative decrease in stage by 28 cm, although not enough to prevent downstream flooding of low-lying settlements (Şerban 2006; Ioaniţoaia 2007).

Compared to the natural floodplain, embankments resulted in radical changes in floodplain land use. The arable land surface dramatically increased from 88,000 to 315,713 ha, an increase of 359 %. As a result, the most significant decline is observed in the area covered by forest, which decreased by 93 % from 95,000 to 6269 ha. In addition, other land cover and land use types also underwent considerable reductions, including lake area (−80.1 %), as well as pastures and grasslands (−85.5 %). The impact was not homogenous, with higher values in the Călăraşi-

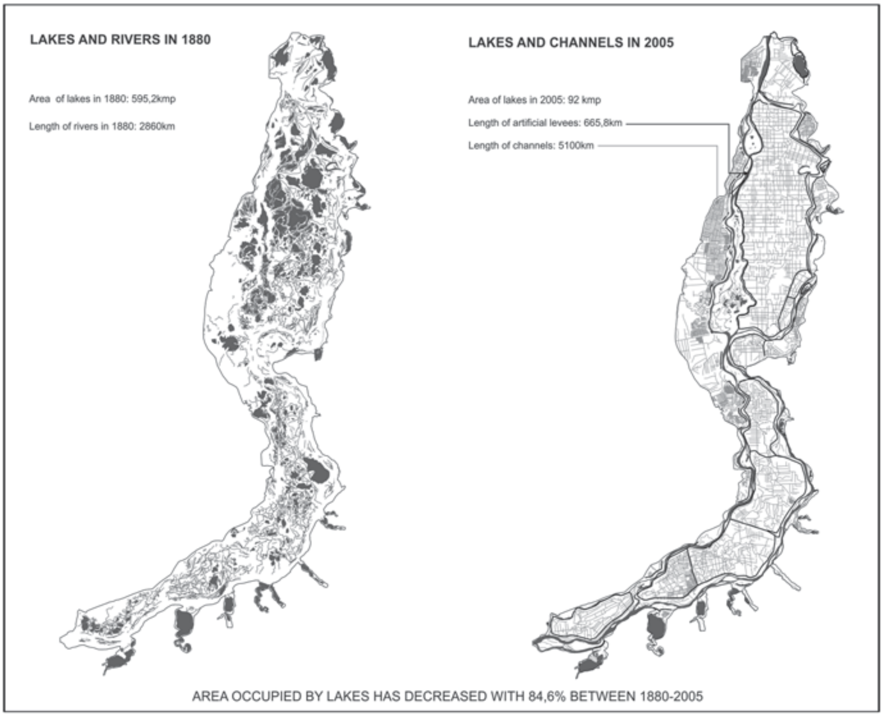


Fig. 7 Anthropogenic impact in the Călăraşi-Brăila sector

Brăila sector, where the lake area decreased by 84.6 % (Fig. 7). Engineering works also led to an increase in other activities which were previously under-represented. The surface area of rice crops, for example, increased to 42,126 ha, while vineyards and orchards covered 2919 ha (Maria 2008). Finally, the general degradation resulting from drainage works and embankments also led to a simplification and a loss of connection to the toponymy of the floodplain (Conea and Badea 2006).

10 Impact of Human Intervention on Fluvial Islets

The occurrence of fluvial islets and their morphometry varies considerably along the 993.5 km length of the Danube, as the river crosses various larger-scale physiographic and geomorphic units. In the upper sector, the river passes through a mountainous region and then a plateau-piedmont region (Mehedinţi Plateau and Getic Piedmont). The asymmetric plain and the Pre-Balcanic Plateau provide different fluvial morphodynamic conditions in the downstream sectors. These conditions are the cause of variations in the riverbed and fluvial islets morphology.

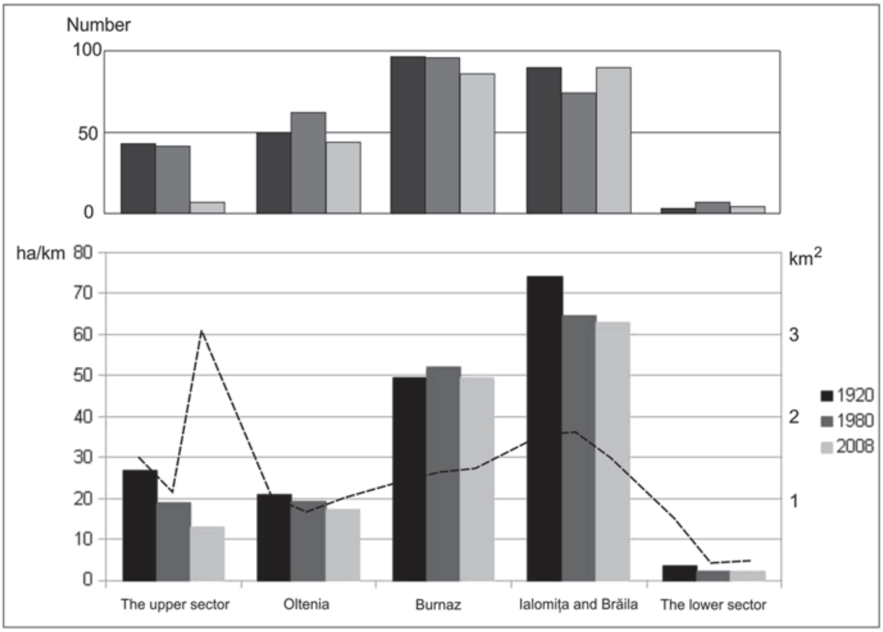


Fig. 8 Evolution of the fluvial islet number, density (ha/km) and average surface area (*dashed line*, in km^2)

The number of fluvial islets from Baziaş to Isaccea remained largely constant over the last century, varying from 270 in 1920 to 263 in 1980. However, over the last three decades their number dropped by almost 15 % (224 in 2008). The total surface area of the fluvial islets decreased constantly, from 379 km^2 (1920), to 341 km^2 (1980), to 315 km^2 (2008). In order to analyse the spatial distribution of these islets, a density index was calculated in hectares/kilometer (ha/km) of river length. The only sector showing relative stability is the Burnaz Corridor, but in all the other sectors the density decreased over time (Fig. 8). While the formation of the Iron Gates reservoirs explains the reduction in the upper sector, the decrease in sediment quantity may explain the evolution of the other sectors. The highest values of the density index in natural conditions occurred along the Balta Ialomitei and Balta Braila (74.1 ha/km in 1920), while the lowest values were typical for the Lower Sector toward the delta (3.5 ha/km in 1920). River bifurcation along the widest sector of the valley explains these values between Călăraşi and Brăila.

Over the course of about a century (1920–2008) only 6 km^2 of fluvial islets disappeared completely. Importantly, with embankment and enclosure the fluvial islets became assimilated into the floodplain, although there was spatial variability along the Danube. The largest average surface area for islets (in km^2) occurs in the Bălţi sector (1.7 in 1920; 1.81 in 1980; 1.5 in 2008), followed by the upper sector (1.5; 1.18; 3.08). The change from fluvial to lake regime led to the disappearance of several islets and the coalescence of other islets in the context of a sharp decrease in number, from 38 to 34 to 9. This explains the high average value of surface area: 3.08 (in 2008) in the upper course. An average value for the entire Danube sector reflects a reduction of the average surface area, from 1.27 km^2 (1920) to 1.08 (1980), followed by a subsequent increase to 1.46 (2008). This overall decrease, which occurred as a result of intensive improvement works in the floodplain, will likely be reversed as the system attains a new balance.

11 Evolution of River Banks

River bank erosion results in channel bed widening. A negative sedimentary balance occurred over the entire lower Danube. This drove an erosional phase in the fluvial regime, resulting in an average loss of 29.2 ha/km. Only in the Upper Sector the remaining lakes store sufficient water during floods. Downstream of Ostrovul Mare, however, embankments maintain a constant discharge cross-section and increased flood velocities result in channel bank and floodplain erosion (Fig. 9). The only sector where sediment accumulation exceeds erosion is the Balti sector, which explains why navigation on the Old Danube course has become increasingly challenging along this reach. Further, the presence of an underwater rock escarpment in the Izvoarele (Pârjoaia) area led to a discharge deviation from the Old Danube toward Rău Branch, and further to Borcea Branch (Fig. 6). It is estimated that 80 % of this discharge is lost as a result of this obstruction (Ministerul Transporturilor 2005). Given that the Old Danube is the main branch for navigation, several problems occur: the river depth is usually below 2 m and dredging activities are needed every year. Dredging increased from 300,000 to 700,000 m^3/year with no corresponding improvement in efficiency. Several attempts to remove the Pârjoaia rock proved ineffective. A new plan to improve navigation conditions is now underway (Ministry of Transportation, Construction and Tourism in Romania 2005). Navigation toward the Danube–Black Sea Canal is thus affected because the alternative

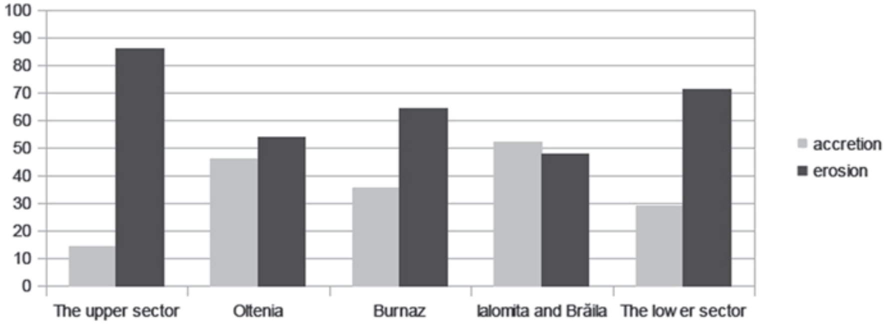


Fig. 9 Intensity of accretion and erosion along the Danube by sector (ha/km) between 1920 and 2008

route will be 105 km long. To maintain an optimal depth for the Old Danube branch new engineering works have begun at the entrance of the Bala Branch to decrease the discharge and strengthen the upstream banks. Similar works will close the secondary channels between fluvial islets and Dobrogea to redirect the water to the navigable course. Over time, some islets will become part of the river banks, as a result of sedimentation on the closed branches at critical points—Epurașu, Seica Islet (Dunăreni-Mârleanu), Fermecatu Islet, Cochirleni etc.

12 Current State of the Floodplain

Political changes after 1989 led to a new social and economic context for the Danube floodplain. A large part of the state-owned enclosures returned to their former owners. Many irrigation canals were not maintained at production standards because high maintenance costs led to a chaotic exploitation in an attempt to obtain easy agricultural profit without investments. The return to an old alternative pits the new owners, who are in favour of maintaining the agricultural terrains for profit, against environmental groups who favour returning the floodplain to natural conditions. Large-scale restoration was rejected as economically inefficient by all Romanian governments after 1990. Restoration can easily be achieved, however, starting with small embanked areas that were abandoned by farmers because of their economic inefficiency caused by salinization and waterlogging.

The European Union Strategy for Danube Region (EUSDR) represents a unitary response to all challenges that affect the entire river basin. This macro-regional strategy, adopted in 2010, was developed by the European Commission in order to coordinate the existing policies and plans across the Danube. At the European level, the EUSDR is the second macro-regional strategy after the same action regarding Baltic Sea Region (European Union Strategy for the Danube Region). An action plan of the EUSDR put the accent on the environmentally sustainable way and takes into account the impacts of climate change at a basin scale. The Danube River Protection Convention (DRPC) represents a political framework for cooperation and transboundary water management for the entire river basins. Danube River Basin District Management Plan (DRBM plan), adopted in 2009, constitutes an ample analysis of the main pressures, especially human induced, in order to improve water quality at the basin level (ICPDR 2013). Disconnection of floodplains from the river is one of the main problems underlined by the DRBM plan. The important role of the wetlands ecosystems within a more complex biodiversity background is recognized, as is the floodplain retention function at the flood events. Reconnection and restorations of different areas have been identified to ensure biodiversity and some implementation steps were discussed at the basin scale.

The latest documentary information on hazard and flood risk is the *Danube Atlas—Hazard and Risk Maps*, a result of the cross-border Danube Flood-risk project (www.danube-floodrisk.eu). The atlas is the result of international cooperation between 8 nations with territories in the Danube River basin, including Austria, Italy, Slovakia, Hungary, Croatia, Serbia, Bulgaria and Romania. Flood hazard maps were produced for three scenarios: Floods with 30 % probability of exceedance (high probability), floods with 100 % probability of exceedance (medium probability) and floods with 0.01 % probability of exceedance (low probability). Regarding the possibility of increasing floods as consequence of climate change the project delivered an important basis for future concepts: The risk areas identified and mapped in the atlas show the problem area if climate change will increase the floods. Thus, the project is fundamental for developing long term strategies regarding the impact of climate change along the lower Danube.

The "Romanian Waters" National Administration is the public authority that manages the hydrologic infrastructure system through the work of the 11 water management units found in its administration. On the basis of hazard and risk maps, "Romanian Waters" National Administration will establish flood risk management plans coordinated at the level of the water management units, until December 2015, according to Directive 2007/60/EC also known as "Flood Directive".

Romania recently completed a LIDAR-based Digital Elevation Model (DEM) for the entire Danube floodplain, including the delta. The high resolution DEM enables hydraulic scenarios to be envisioned for different flood levels. According to existing data, from the entire floodplain of 445,000 ha, three categories have been proposed as targets for the future: 43.3 % for agricultural fields; 40.8 % areas used as mixed (agricultural/polders and water storage); 15.9 % areas for natural restoration (Nichersu 2009; Fig. 2). The conclusion is that 84.1 % of the lower Danube floodplain will remain agricultural. The mixed category of 40.8 % is quite ambiguous since it retains an agricultural function and stores water only during floods events. After the floods in 2006, despite new studies and warnings from the academic community and civil society (e.g., Vădineanu 2001; Iordache 2005; Stanciu et al. 2008), the management plan stipulates that embanked enclosures will be largely maintained. Restoration with an extensive rewilding program, however, will be the only economic solution. This is because, while embankments are useful for agriculture over a short period, a permanent loss of biodiversity is unacceptable to future generations.

13 Instead of Conclusions: Antipa—Environmentalist *Avant-la-lettre*

After more than a century, the strategy envisioned by Grigore Antipa (1895, 1907, 1910) still remains the only forward-looking solution for the economic exploitation of the Danube floodplain. The principle of rotating polders with alternation of agricultural crops and floodable areas, not only offers the best economic benefits, but simultaneously also allows for a better preservation of the fluvial ecosystem. Antipa warned that solutions for the management of Danube floodplain should not be imported from other regions of the world with different climatic conditions, hydrology or geomorphology. To copy these solutions and implement them on the lower course of the Danube would be “a great misfortune, which would make us lose the little we have”. The floodplain improvement system should be based on the local geomorphology of the floodplain, and the conservation of large and permanent lakes (Antipa 1910) is a feature that should be respected. Antipa’s caution is desirable in any environmental engineering or restoration approach and contrasts markedly with the dominant attitude of the communist regime and its will to control nature at any price. The radical transformation of the Danube floodplain affected not only the region, but also the mindset of the local population. The key to returning the floodplain to its natural state is in restoring the collective environmental memory of its people.

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Historical Development and Integrated Management of the Rhône River Floodplain, from the Alps to the Camargue Delta, France

Jean-Paul Bravard and Pauline Gaydou

Abstract The Rhône is a large river of Western industrialized Europe and flows southerly from the Furka Glacier of the Swiss Alps to the Mediterranean Sea. The valley and the alluvial plain represent a complex history of fluvial change that started during the last deglaciation. Climate and land-use changes modified the balance of discharge and sediment, creating a diversity of fluvial patterns and floodplain landforms. The human perspective on Rhône River floodplains includes one of the communities threatened by floods during periods of low frequency high magnitude events, and channel and floodplain adjustment. Floodplain settlements coped with a constant risk from high-velocity floods, which were competent to cause destruction to property and agricultural lands. The complex history of floodplain construction and flood defence accounts for a maximum diversity of local to regional floodplain settings.

The modern development of the river has been undertaken to improve navigation, but has also impacted the Rhône River. The river metamorphosed from a braided to a sinuous single channel pattern, with consequent changes in the environment. The "improved" type of embanked floodplain promoted heavy overbank sedimentation. A second generation of human disturbance resulted from the construction of reservoirs, canals and power plants with a lasting legacy of specific fluvial impacts. Recent restoration and management actions include the reactivation of channel side arms and the removal of lateral embankments to widen the channel where it is bypassed a canal. Inherited local conditions are shown to be of major importance to modern restoration practices.

Keywords Rhône river · Embankments · Hydroelectric development schemes · Human-induced changes · River restoration

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1 Introduction

Like most large European rivers, the Rhône River has an extensive legacy of human impacts, motivated by the need for flood protection, improved conditions for navigation and hydropower production. Dams have dramatically increased energy production but have altered the longitudinal continuity of sediment transfer, notably through gravel storage and the downstream riverbed incision. Many gravel-bed rivers have been harvested or their water depleted for irrigation or other uses (Busch et al. 1989; Roux et al. 1989; Vischer 1989; Girel et al. 1997; Hohensinner 2004; Loczy 2007; Tockner et al. 2009). Also, rivers and floodplains have responded to changing fluxes of suspended sediment at the watershed scale (Walling and He 1999). Their landscape and functioning are heavily impacted by low embankments which promoted channelization and induced sediment deposition along river margins (Lammersen et al. 2002; Hohensinner 2004). In this context, and since about 30 years, impacts are analysed and attempts are made to mitigate some of these fluvial impacts. The rivers of Europe are being rehabilitated, if not restored (Dister et al. 1990; Müller 1995; Heiler et al. 1995; Tockner et al. 1998; Schiemer et al. 1999; Schoor et al. 1999; Buisje et al. 2005; Habersack and Piégay 2007). The Rhône River has been a laboratory for hydroecological studies since the 1980s, notably concerning riparian wetlands (Amoros et al. 1987a, b; Amoros and Roux 1988; Henry et al. 1995; Bravard et al. 1992). Active policies have been developed by state, river basin authorities and by the National Rhône Company (NRC) since the early 1990s (Fruget and Michelot 2001). In this chapter, we demonstrate how the complexity of historic natural and human-induced changes influence present policies and restoration measures.

2 The Rhône River, France: Present Conditions of Flow and Sediment Transfer

The Rhône River is a ninth order stream with a total length of 812 km (512 km in France). It drains a catchment area of 98,500 km^2, with the great majority of drainage being in France, downstream of Lake Geneva. About 50 % of the catchment is above 500 m a.s.l. (Fig. 1) and 15 % above 1500 m (the Alps, the Jura Mountains).

Having high-elevation source areas, the discharge regime of the Rhône upper course is affected by snowmelt, and both winter and spring floods. Floods play a major role in the shaping of some of the remaining free-flowing rivers and of floodplains. The northern part of the catchment (Saone River—Ternay station, Table 1) is influenced by the maritime climate with winter floods and low discharges reduced by evapotranspiration, before the major contribution of the Isere River as seen at the Valence station (see Table 1). The southern part of the watershed is under the influence of the Mediterranean climate, with floods occurring during the spring and the autumn (Beaucaire station). The melting of glaciers since the maximum of their extension in the 1860s induced an increase of summer flow, before a decrease

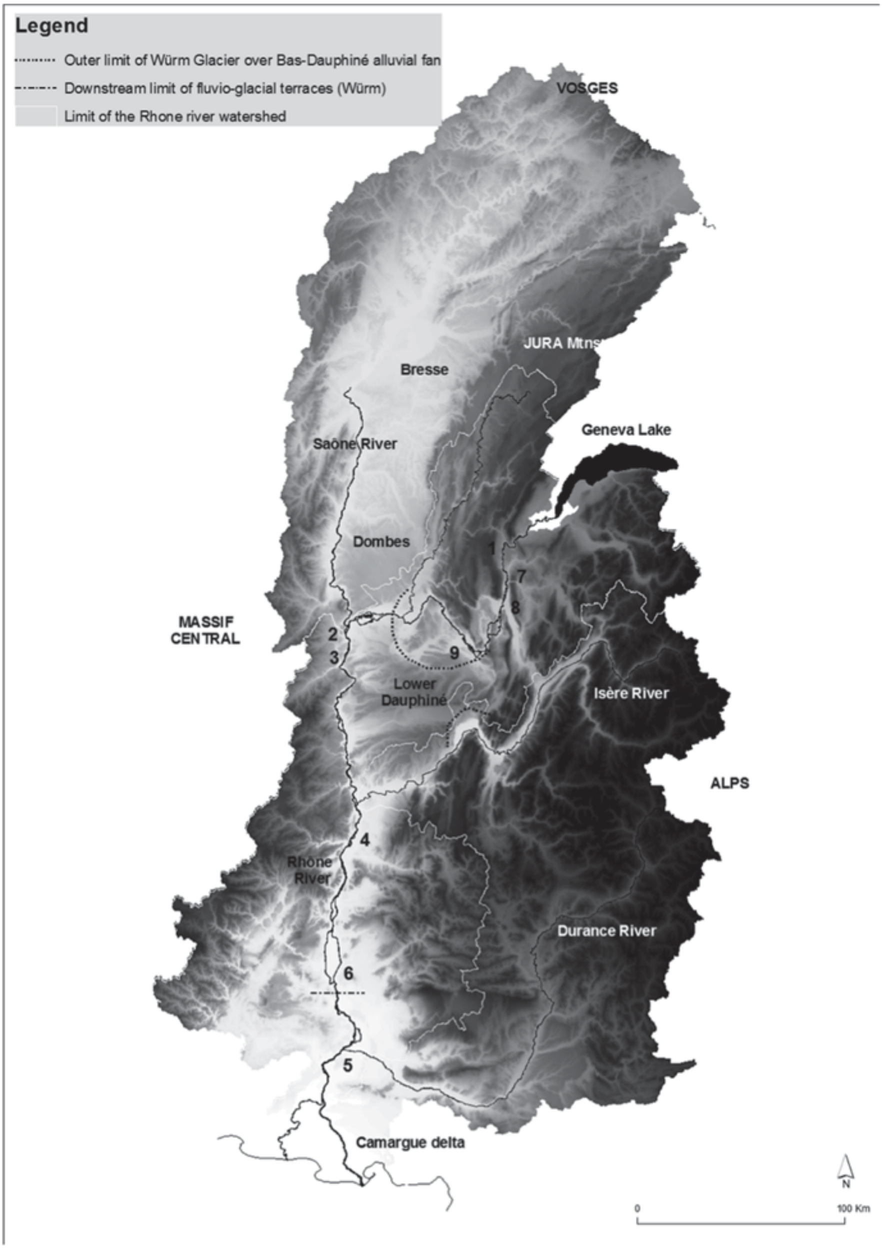


Fig. 1 Topography and main features of the Rhône River basin

related to the progressive reduction of ice volumes. This recent decrease has been exacerbated by the artificial retention of summer flow in high altitude reservoirs since the 1950s, notably in the upper Rhône watershed, Switzerland, and in the Isere watershed. If the seasonality of the flow regime has changed to the benefit of

Table 1 Flow regime of the Rhône River (after CNR; Olivier et al. 2009)

Gauging stations (Rhône R.)	Period	A	MQ	SpQ	Q2	Q10	Q100	Q100/MQ
Bognes	1925–2010	10,320	360	32.6	1,100	1,450	2,375	6.6
Lyon-Perrache	1920–2010	20,300	600	29.5	2,100	3,100	5,300	8.8
Ternay	1920–2010	50,560	1,030	20.4	3,100	4,500	7,300	7.1
Valence	1920–2010	66,450	1,410	21.2	3,000	6,000	9,350	6.6
Beaucaire	1920–2010	96,500	1,700	17.6	5,900	8,300	14,100	8.3

A catchment area upstream of gauging station, *MQ* arithmetic mean annual discharge, *SpQ* specific discharge. (m^3 /s/km^2), *Q2* magnitude of a 2-year flood, *Q10* magnitude of a 10-year flood, *Q100* magnitude of a 100-year flood

Table 2 Sediment discharge at different stations along the Rhône, from the late nineteenth to early twentieth to recent years

Station	Period	Suspended load (M m^3)	Bed load (Mm^3)
Seyssel	Late 19th–early 20th centuries Early 21st centuries	? 0.5	0.1–0.15 0
Lyon	Late 19th–early 20th centuries Early 21st centuries	0.15–0.30 ?	0.04 0
Beaucaire & Arles	Late 19th–early 20th centuries Early 21st century	11–16.8 4–7.5	2.7 0.2–2

Values for past suspended and bed load transport are rough estimations because of different sampling techniques. More recent values of suspended load were derived from discharge and concentration and later from ADCP measurements at Arles (Pardé 1925; Bravard 1994; Pont 1997; Pont et al. 2002; Antonelli et al. 2006; Maillet et al. 2007)

winter flow, the magnitude of floods is considered as stable since the late nineteenth century (Sauquet and Haond 2003).

Flood peaks of the Rhône upstream of Lyon and in Lyon (Bognes, Lyon-Perrache) are enhanced by steep tributary gradients (Ain River) but reduced by the storage capacity of large floodplains and lakes. For instance, Geneva and Bourget lakes store flood waters, as do large floodplains of the former glaciated valleys (Upper Rhône, France) and wide low gradient floodplains influenced by neotectonics (Saone River). The floods of the Rhône originate mainly from downstream tributaries, such as the Isere, Ardeche, Durance and Gard Rivers. This explains why the ratio Q100/MQ is remarkably constant along the river continuum (Table 1). The total area covered by large floods along the Rhône River corridor approximates 2470 km^2, including 1644 km^2 in the Camargue delta.

Sediment discharge has been drastically reduced since the late nineteenth century (Table 2), if compared to the conditions prevailing during the Little Ice Age (LIA). The LIA was a cooler period characterized by heavy summer rainfall, and was able to erode slopes weakened by the intensive use of land for pastures and agriculture. This reduction has been explained by a set of converging factors, such as the reforestation of the watershed since the 1860s (both natural and triggered by

Public Services), the trapping of sediment in artificial reservoirs since the 1920s, and the harvesting of sand and gravel, mostly since the 1950s (Bravard 1986; Arnaud-Fassetta and Provansal 1999). Sediment budgets at the basin scale do not exist because of the poor quality of sediment data both at the tributary and main stem scales. However, some estimates have been proposed for the lower stretch (Arles station), which integrates the whole watershed (Table 2; Antonelli et al. 2006; Sabatier et al. 2006).

3 The Geographical and Historical Complexity of Valley Bottoms in the Rhône Valley

The Rhône River has experienced a long and complex geological history. The course of the Rhône in France may be considered as a “partly-confined transfer zone” (Brierley et al., after Schumm 1977) between Lake Geneva and Pierrelatte, and as a typical “alluvial accumulation zone” between Pierrelatte and the Mediterranean Sea (Fig. 2). However, net accumulation affected upper reaches during periods of the Holocene, where glaciers have incised valley bottoms to the detriment of soft Tertiary sandstones located inside synclines. Valley bottoms may include Quaternary terraces and Holocene floodplains, which occupy the entire valley bottom, or are inset terraced valley bottoms. Quaternary terraces are located downstream of the domain affected by the branches of the piedmont Würm glacier. In the Rhône valley, they are notably located between the Ain River confluence and the upper limit of the downstream area affected by the sediment deposition induced by the stabilization of sea level ca 6000 years BP (see Donzere-Mondragon case study, 4.2).

3.1 Long-Term Natural Genesis of the Main River Floodplains in the Rhône Watershed

The larger Rhône and Saone valleys are trough-like corridors. The level of the Rhône River was also deeply affected by the level of the Mediterranean Sea.

The Rhône valley displays the following five reaches from Lake Geneva to the Mediterranean Sea, as a consequence of its glacial history and tectonic uplift (Fig. 2): (1) A gorge incised into Tertiary sandstone and folded Cretaceous limestone from Geneva to Seyssel, without space for floodplain construction. (2) Large incised valley bottoms from Seyssel to the Southern Jura, opened into large synclines, and contrasting with short narrow gorges. Lakes and floodplains display a major extension, but the reach upstream of the Ain confluence is incised into a low terrace, with the narrow lateral floodplain. (3) From the Ain confluence (the western limit of the Würm glacier) to Lyon, the Rhône has a wide valley and floodplain eroded into soft rocks. The valley widening was a long-term process, considering that the Rhône settled there since the Late Riss glacial period. (4) From Lyon to Pierre-

Fig. 2 Main structural and geomorphic features of the Rhône valley, France

latte, the main relevant geological event is the Eocene-Oligocene north-south rifting (Fig. 2). The foreland of the Alps has been submitted to significant vertical uplift due to compression induced by plate tectonics. Vertical incision (up to 400 m) was realized approximately in the present position since the late Miocene, partly into the metamorphic rim of the Massif Central, partly into the soft Alpine alluvial fan. The lateral extent of the valley bottom depends on the nature of rocks on the valley sides with a combination of epigenetic gorges and shaping of stepped Quaternary terraces (Mandier 1988). (5) Downtream of Pierrelatte, the postglacial deposition is fully developed. A wide and recent downstream alluvial plain built up by regressive sediment deposition because of sea level rise completed ca 6000 years BP (Fig. 3).

3.2 Late Glacial and Holocene Geomorphic Changes

In general, the late Glacial period has been one of sediment shortage due to the warming of climate and the encroachment of vegetation in the watershed. In unglaciated areas, rivers incised during the Bölling (14.6–14.1 ka years cal BP) as proven in the Saone and Rhône valleys. Due to decreasing hillslope sediment production and reducing discharge, the Saone deposited a layer of organic and fine-grained mineral sediment during the Alleröd. The last major event has been a major aggradation during the colder Younger Dryas and the Early Holocene (Preboreal), which may be related to increased inputs of coarse sediment. The main features of the floodplains were then built-up in the Early Holocene.

With the onset of the Holocene, floodplains became more stable. The changing balance between water and sediment fluxes displays two contrasting periods, with a climate-driven phase until the Early Subboreal, and a mixed human- and climate-controlled period during the Subboreal and the Subatlantic. River and associated floodplain dynamics are geographically distinct according to the four herein reviewed extrinsic and intrinsic controls:

1. Sediment fill of Bourget lake document evidences of contrasted hydrological phases, with high inputs of suspended sediments during several erosive crises (Chapron et al. 2005). Further downstream the once existing Basses Terres lake was reached by the prograding coarse sediment wave ca 5000 BP. Channel scars are well preserved in the Basses Terres basin and sedimentary fills record discharge changes since 5000 years (Salvador et al. 2004). When dams were built up along the Rhône in the late twentieth century, coarse-grained bed material had not yet prograded downstream of the Basses Terres basin, as evidenced by the characteristics of longitudinal channel profiles (very low gradient, and still unfilled deep pools in the lower reach of the basin). This major discontinuity in bed load transport induced continuous incision of the Rhône River channel into soft Tertiary sandstone until the Ain River confluence, since the melting of the ice sheet during the Late Glacial. The level of the thalweg is controlled by exhumed boulders (former glacial till), and as a result, the river displays a narrow string of floodplain patches along this 30 km long reach.

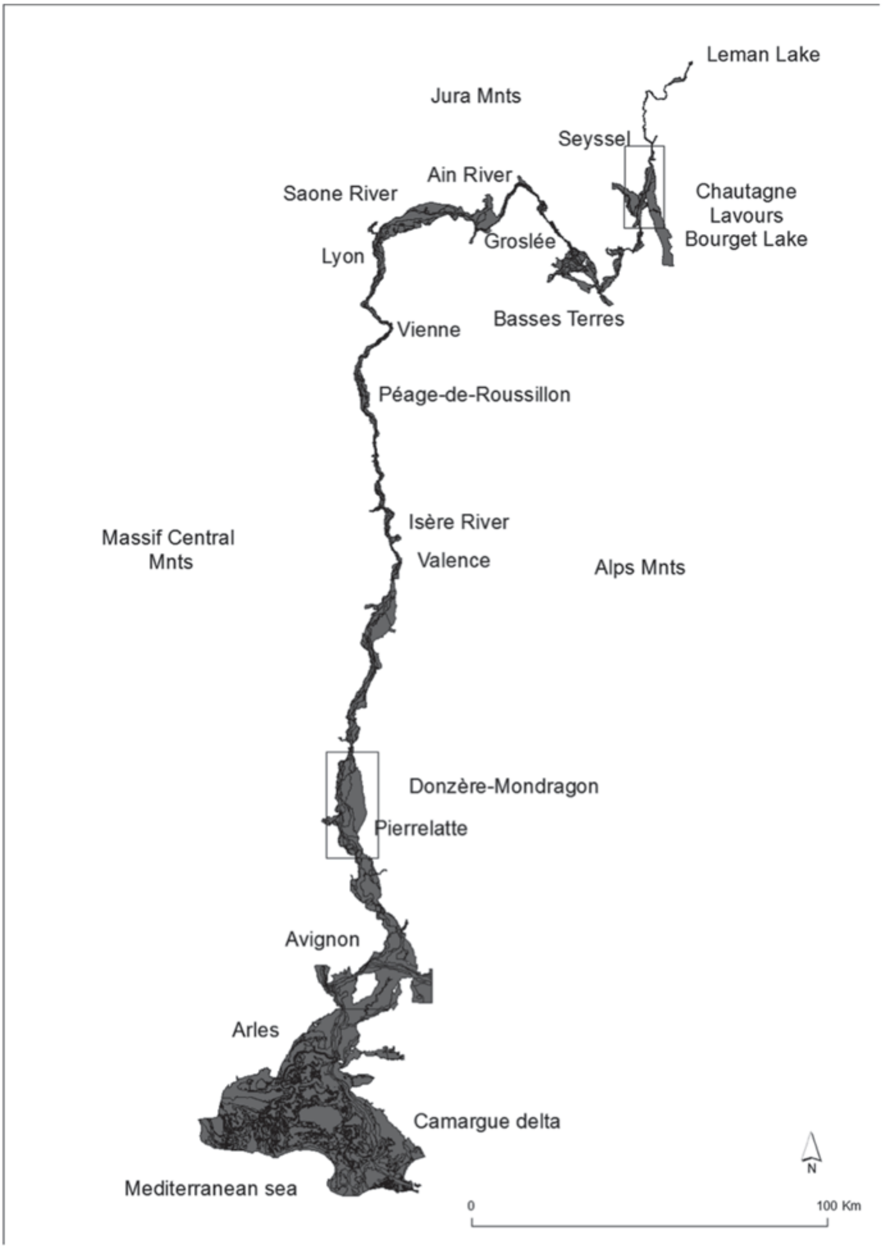


Fig. 3 Map of the Holocene floodplain of the Rhône

2. Downstream of the Ain confluence, the Rhône River has been subjected to upstream floods from the Ain River, which drains the Jura Mountains. The Ain also contributed considerable input of coarse sediment into the Rhône, which in turn affected river sediment discharge. Steep slope, sharp hydrographs of peak floods and the narrow upstream gorges explain the strong sensitivity of this proximal reach.

In 2008, an atlas composed of maps at 1/25,000 scale has been established for the reach between Seyssel and the Camargue delta for the Regional Direction of Environment in Lyon, the objective being to better understand the elevation of floods over the alluvial plain and the location of flood ways. This work was mapped on present IGN 1/25,000 maps, and benefited from information from the Bridges and Roads atlas dated 1857–1866, and from original works based on published and unpublished palaeo-environmental and geoarchaeological studies (Bravard et al. 2008b).

Here we present reach upstream of Lyon (Fig. 4). The modern braided reach, coloured in blue (Unit 041, and recently abandoned units 042–043), is narrow downstream of the Ain confluence, then widens south of Miribel (2500 m), before narrowing again across the city of Lyon (300 m). The relative elevation of the 1856 100-year flood was able to be mapped because of the Bridges and Roads atlas dated 1857–1866. The data was based on the width of the active tract and spanned from 2.5 to 6 m above low flow.

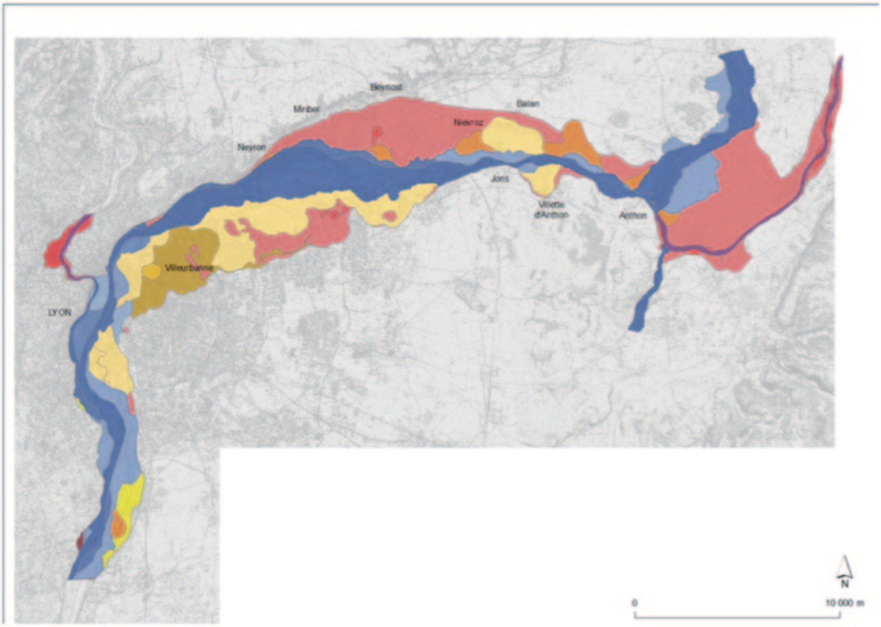


Fig. 4 Map of the Holocene floodplain: Lyon reach. The colours refer to the legend, which makes a distinction between floodplain units shaped. The modern braided reach is coloured in blue

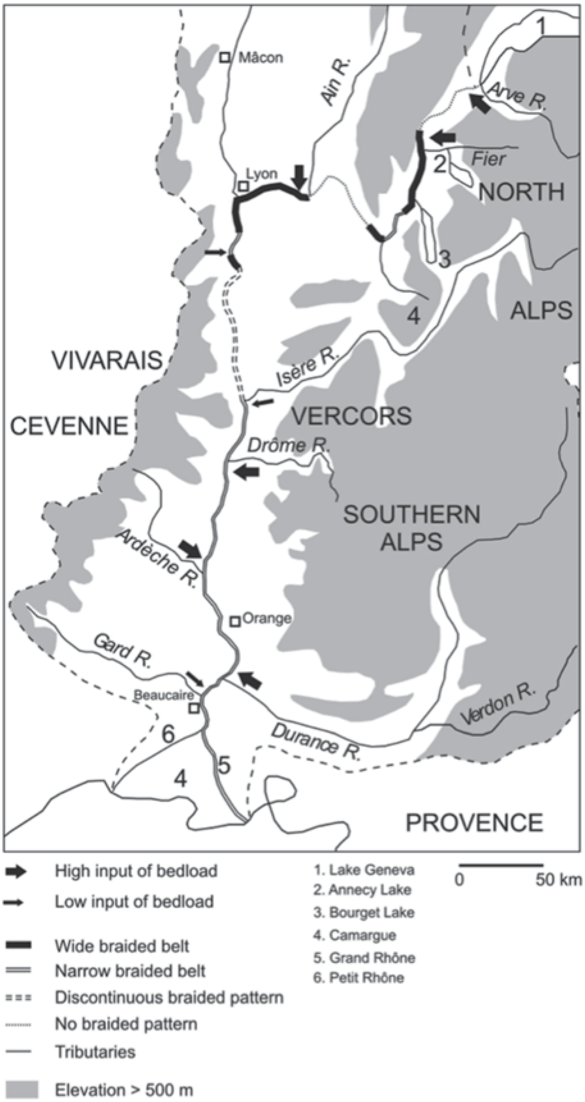


Fig. 5 Fluvial patterns of the Rhône River in 1860

The most important feature is the time succession of distinct fluvial patterns (Fig. 5). Fluvial metamorphoses are mostly related to climate change (increased energy and transport of bed load), but human impacts at the watershed scale have also increased the efficiency of slope processes. The braided pattern is documented from the eighth century BC to the fifth century BC, a meandering pattern between the fourth century BC and the fourteenth century AD, and braiding again from the fifteenth AD to the late nineteenth century AD. In 1856, the entire floodplain area was flooded at a depth of 1 or 2 m.

Table 3 Area and percentage of Holocene floodplain occupied in 1860 by different types of land units

Land units	Area (km^2)	% of Holocene floodplain
Main channel(s) of the Rhône River	32.7	1$^-$
Active and abandoned LIA braided belt	520	18
Back swamps induced by waterlogging	501	17
Lake in over-deepened area	41	1$^+$
Area beyond the braided belt flooded by low to strong floods	1,622	55
Area flooded by exceptional floods (Holocene terraces)	1,864	63
Holocene alluvial plain	2,960	100

A brief period of increased activity, however, occurred during the meandering phase noted above. The Roman cities of *Vienna* (Vienne) and *Lugdunum* (Lyon), whose setting is broadly dated second to first century BC, developed over patches of floodplain which were low terraces at that the end of the dry Iron Age period because of prior river incision. Urban settlements coped with increased levels of floods from the first century BC to the second century AD across their exposed floodplain districts. Past and modern city planning has been adapted to those emerging natural constraints, as evidenced by landfill over hectares.

3. From Lyon to Avignon, the Rhône river and its corridor of floodplains display different ranges of width and longitudinal slope according to the geological heritage (see above), to the bedrock control on the thalweg profile, and to coarse sediment input from the tributaries. In some reaches, relicts of asynchronous meander scars are visible outside the LIA braid belt. In the lower Rhône valley, in particular the Camargue delta, Holocene deposits overlay Late Glacial gravel deposits. Inside the area delimitated by the channels called Grand and Petit Rhône, former distributaries, levees and flood basins are presently protected by high dykes built up after the 1856 flood (Arnaud-Fassetta and Provansal 1993; Arnaud-Fassetta 2003).
4. At the valley scale, the Holocene floodplain covers 2960 km^2. The area occupied by the main land units in 1860 is shown in Table 3. By that time the whole floodplain area was prone to flooding, primarily because of aggradation of the braid belt during the LIA.

3.3 *Braided Channels, the Reference Landscape in the 18–19th Century*

A braided channel pattern occurred during the early eighteenth century in the Alps and their foreland, with exception of some meander relicts, which are well documented by ancient maps. The low-sloping Saone River did not experience a metamorphosis, despite the increased input of sand and gravel from some tributaries. The downstream succession of braided patterns, from the Alps to the sea, is represented in Fig. 5. Braiding is well developed but is discontinuous along the river continuum depending on the inputs of coarse sediment, valley slope and on channel width (Bravard 2010). Braiding of the late LIA was ancient in the memories of floodplain residents, and so widely developed, that until recently this fluvial pattern was considered a landscape from the remote past. As such, it may be considered as a reference landscape, if one considers the “reference state” promoted by the EEC directive for river restoration. But this “reference” does not take elder changes into consideration, which is questionable.

The Holocene history of large rivers explains the diversity and complexity of modern floodplains. The previous results confirm that Rhône floodplains may display a mosaic of distinct units related to present and abandoned active tracts (braided and meandering). These units are characterized by differences in gravel sediments (grain size, depth, porosity), topography and variability in susceptibility to flooding. Moreover, the reaches varied in the deposition of fine sediments according to the different channel type and floodway. Indeed, these reaches may be considered as “multi-pattern functional sectors”.

4 Modern River Developments for Navigation and Energy Supply

4.1 Embanking Rivers for Improving the Conditions of Navigation

Downstream of Lyon, the 1858 law-prohibiting levees for floodplain protection was not respected, probably because the fluvial cities were too small to benefit. Between 1840 and 1856, the Bridges and Roads Service tried to consolidate the protection of floodplains and the improvement of navigation with high longitudinal stone dykes. After some successful attempts upstream of Lyon, it was decided to constrict the navigation channel for the average yearly discharge by using low parallel longitudinal dykes (1856–1876). The channel was further constricted with lower dykes, attached to the previous ones (1876–1990), to concentrate low flow at the channel bed. It is noticeable that embankments realized in the 1880s for adapting the channel to navigation were low levees, which could not reach the level of the alluvial plain and interfere with flooding. The adjacent floodplain thus remained influenced by natural flood processes.

Finally, the Girardon dykes (Fig. 6), named after their designer, were constructed between 1880 and 1940. This system of dykes utilized an understanding of the channel geomorphology and river hydraulics, and included several distinct measures, including (1) stabilization of the thalweg and pools and riffles, (2) modify the flow to incise into the channel bed, to promote a regular thalweg with a straight 1.60 m deep channel and (3) increase discharge in the main navigation channel after closing side arms through siltation.

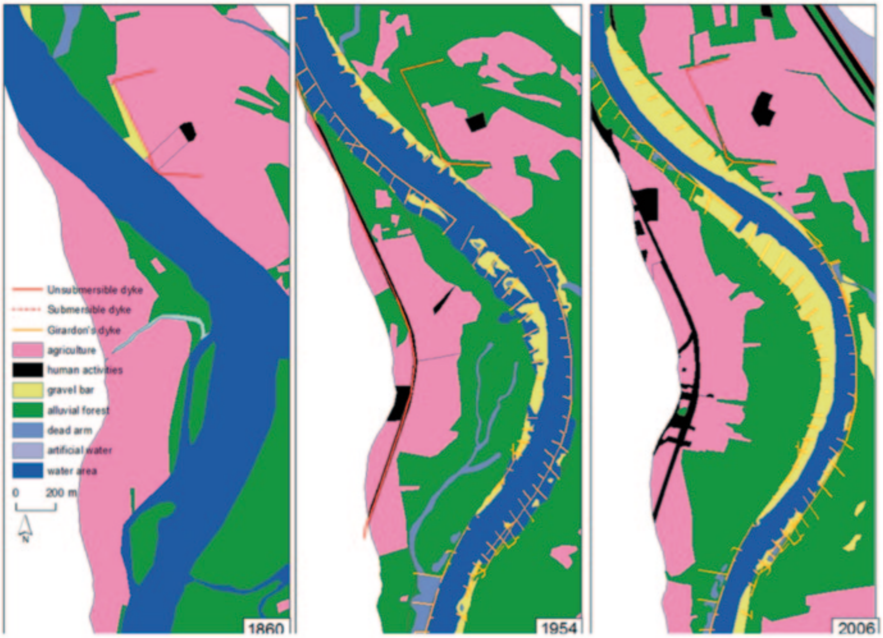


Fig. 6 The Girardon dykes, Peage-de-Roussillon reach

The complex network of superimposed navigation dykes had multiple consequences. Most of the geomorphologic changes occurred during the first decade after completion of embankments. These included: Flow concentrated in a single channel, with a reduced channel width (180 m on average). The wetted surface decreased between 200 and 70 %, depending on the reach, and the mean unit stream power increased (x 1.7 on average) as a consequence of the channel width decreasing. The values of unit stream power are comprised between 40 and 125 W/m^2. The high value of stream power enabled coarse channel sediments to be transported further downstream, or deposited on the lower banks between the groynes.

Further, reduced lateral mobility because of stabilizing the channel thalweg was related to the following two fluvial-environmental responses. First, fine sediments were trapped inside the frequently flooded compartments delimited by embankments (mean thickness of sediment is 3.5 m; maximum thickness is 5 m). Bottom sediments were comprised of gravels dating back to the pre-embankment functioning; floods deposit sand and silt, forming a fining upward sequence. The amount of sediment stored in the compartments depends on the sediment supply, the conservation of the dykes and the orientation of water fluxes. Sediment deposition increased at the channel margins behind the compartments because of the damming of secondary channels and consequent reduction of flow velocity. Secondly, the soft wood forest occurring on the former low bars of the braided belt aged, and progressively transformed into a hardwood forest. Channel banks became stabilized as the alluvial forest colonized channel bars. Vegetated surfaces increased up to 260 % in the most stabilized reaches. Because of the increased roughness, sediment deposits may be 5 m in thickness. With successive floods the deposits resulted in a higher channel bank, further reducing flood frequency.

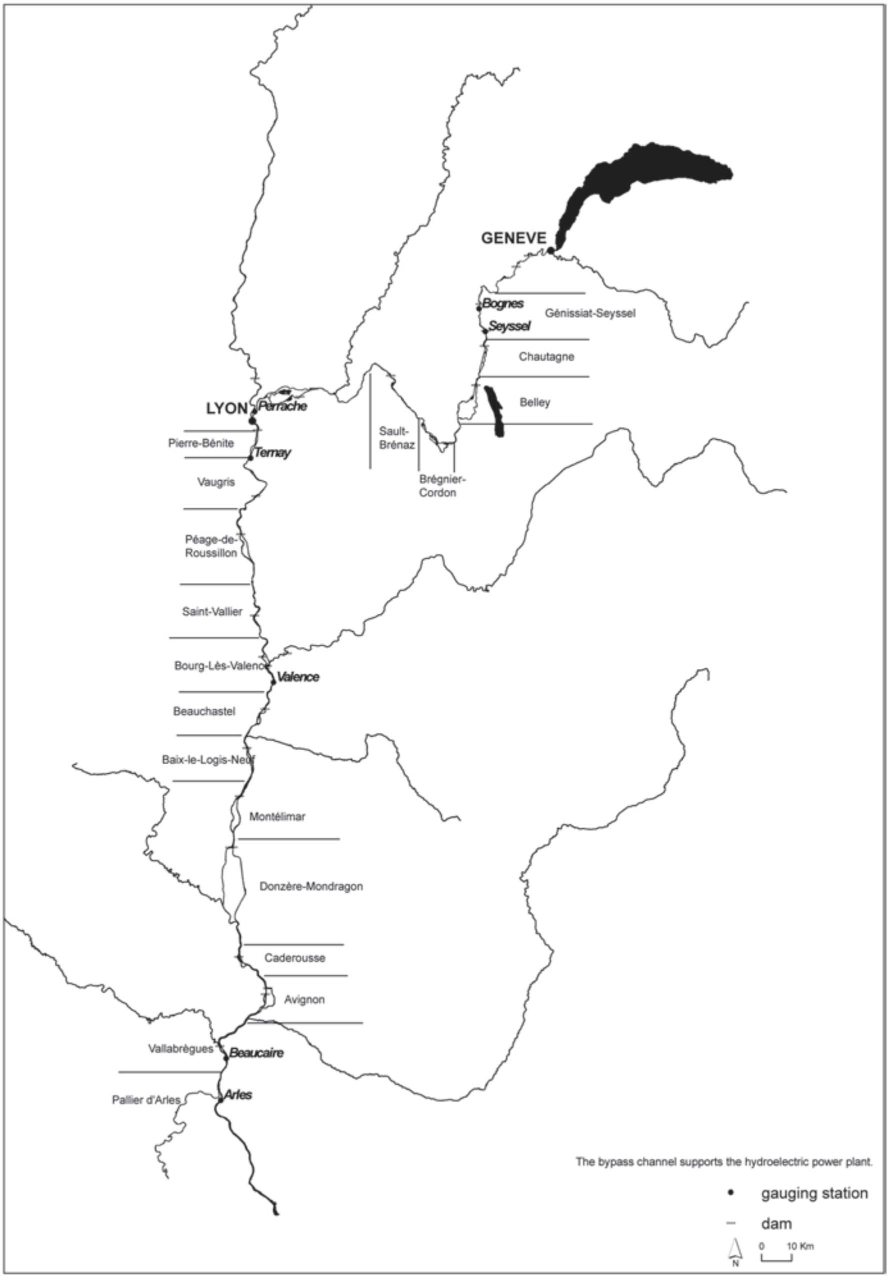
4.2 *Taming the Rhône for Energy Supply*

The second improvement phase was realized by the National Rhône C°. Launched by the French State in 1934 as a unique operator, as requested by the so-called 1921 Law of the Rhône, the CNR obtained the concession of this "public" river to build a chain of 18 dams with the triple objective to produce energy, enhance navigation and develop irrigation in the lower valley (Fig. 7). Two dams were raised in the upstream gorges (Genissiat in 1948 and Seyssel in 1952); downstream dams were put into operation between 1952 and 1986. They are similar to the Jonage-Cusset dam (1899) constructed to meet the growing energy demands of Lyon. The CNR run-of-the-river development schemes were conceived to take into account the presence of cities, railways and roads while limiting the consumption of fertile agricultural land. The technical units of development included the following three schemes. First, a shallow reservoir was constructed. The feature was controlled by a retention dam, narrowed by dykes, and perched over the floodplain. Both sides of the reservoir were drained by counter canals to maintain alluvial groundwater levels. The reservoir drowns the former navigation dykes. Secondarily, the diversion canal was constructed of two gently sloping races separated by the power plant and the navigation locks. The head-race was designed to be higher than the floodplain, while the tail-race is built into the floodplain. Lastly, the old Rhône, by-passed by the canal, was controlled with a minimum discharge that averages 5 % of the natural discharge, and serves as the floodway. Flood discharge is approximate to the upstream discharge minus the discharge diverted into the diversion canal. Importantly, the old Rhône preserves the fluvial landscape dating back to the navigation period.

As a consequence, NRC development schemes impacted a large area of floodplains for a couple of reasons. First, reservoirs and canals encroached over the floodplain. Secondly, large floodplains areas were protected from flooding by embankments, even if engineering works were devoted to the artificial watering of low areas. It must be stressed that the floodplains adjacent to the by-passed reaches drained by the "old Rhône" have preserved flooding and are prone to sediment deposition beyond the dykes.

4.3 *River Development and Changing Floodplains*

The two successive corrections of the Rhône River have deeply modified its morphology and currently impede any possibility of river adaptation to changing conditions at the watershed scale. The first correction succeeded in erasing the braided channel pattern born during the Little Ice Age, which was so detrimental to navigation. The former active channels were dammed and silted up, the former bars and



The bypass channel supports the hydroelectric power plant.

Fig. 7 Development schemes of the National Rhône Company vegetated islands attached to the floodplain experienced vertical accretion because of deposition of fine-grained suspended sediment. These impacted reaches belonging to the former braided tract are presently referred to as “river margins”. Since accretion reduced the frequency of flooding, hardwood forest encroached over these areas while softwood trees could not sustain the change in groundwater hydrology. In many cases, this newly formed land has been reclaimed for agriculture and gravel mining. In 1860, 17 % of the braided active stretch (89 km^2) were impacted by dykes developed along a cumulated length of 706 km. Surface areas frequently inundated decreased, while agricultural land surfaces and other activities increased.

In the next section of this chapter, we present two cases of river and floodplain development. Importantly, the character and the impacts of these case studies illustrates the value in understanding geomorphic heritage. The present management, implicitly or explicitly based on the concepts of integrated management, is deeply influenced by these heritages.

5 Floodplains in Search of Integrated Management. Two Case Studies Along the Upper and Lower Rhône River

The concept of *integrated management* is not new. The study of the Rhône floodplain reveals that since the 1858 law (see below) it has been forbidden to embank the river and restrict flooding of the floodplain, except at cities. This law was not seriously applied downstream of Lyon but was strictly respected upstream of the city, to the benefit of what is presently referred to as sustainable development of the valley and ecology, as demonstrated by the Chautagne case study. Downstream of Lyon, integrated management was concerned with systematic development of the river for improving navigation, then with hydro-development in the respect of floodplains, in particular along the so-called by-passed “old Rhône”. The Donzere-Mondragon case study exemplifies long-term changes, recent impacts of development, then mitigation measures conceived in an integrated way to compensate for a poor preservation of the flood capacity of the alluvial plain.

5.1 The Chautagne Reach, Preserving Flooding Capacity and Compensating for Hydropower Impacts

Managing Commons and Private Land with the Help of the Floods Braided river belts were so unstable in space and time that in several regions of the basin, development was rendered impossible by natural conditions or could be impeded by restrictive regulations. “Let the river run wild” was the basic principle. It was the case when (i) braid belts were preserved as no man’s lands preventing conflicts between territories separated by the river (for instance along the Lower Durance delimiting the former Pope’s domain, and (ii) embankments were forbidden for the sake of local mountain communities which needed flooding and sediment deposition for preserving stable resources. As an example, fierce opposition from the upland community of Chautagne in Savoy prevented such kind of "improvement" during the nineteenth century before the official recognition of their role to control floods. Most of the bottomland, owned by landlords before the 1789 was given to communities during the Revolution. The reason for defending those "commons" was the deep understanding by those communities of the positive effect of flooding. Indeed, for those populations, water, suspended load and nutrients restored the fertility of the alkaline backswamps every year and provided the empirical prerequisites for good crops of hay (Bravard 1986). The large lateral marshes of the Upper Rhône were used for cattle in winter. Hay was valuable since it was used as green manure in the vineyards, which provided cash since wine was sold to cities (Chambery, Geneva). However, part of the land was privately owned. Increased human densities in the mountains triggered rural colonization of the bottoms, to the risk of destruction by floods. Every farmer used the mosaic of gravelbars and side channels for producing cereals and breeding cattle, as farmers presently do along tropical rivers with the bank gardens. Summer flooding was a persistent hazard, threatening cereal production in floodplain bottomlands (Fig. 8).

Based on the intensity of flood losses three types of areas can be classified. These include, (1) completely eroded land, (2) land partly eroded (soil stripping), (3) land covered with crude sand. The gradient of energy between the adjacent braided channel and the margin of the floodplain is clearly visible. Stone-made groynes to divert the flow and prevent erosion, and high longitudinal dykes to prevent flooding, were constructed in the 1780s to protect the floodplain, but the system was never completed. Large undeveloped stretches, however, were preserved (Fig. 9) by a system of longitudinal dykes.

Preserving Flooding in Rural Floodplains: An Official Policy to Benefit Large Cities The kind of socio-economic equilibrium between the river, its floodplain and the adjacent slopes maintained natural flooding as a local practice in the Savoy valleys, but elsewhere it was threatened by the development of modern agriculture. Concurrently, urban areas experienced spectacular growth during the early nineteenth century as the result of the Industrial Revolution, and factories were looking for flat land to the risk of being flooded. Large floods of the late LIA impacted the developing cities. Lyon was affected by the 1812, 1840 and 1856 floods. The latest destroyed the levee erected in 1835 to defend the newly built up area on the left bank of the Rhône, and was the cause of human and economic losses (Combe 2007). Because of the severe losses related to the 1856 flood, which affected all the large French rivers, a new law was passed in 1858 which recognized the importance of flood prone areas upstream of urban areas. The law forbid the construction of embankments in rural areas, while public funding helped to protect cities. Such regulation passed during the 2nd Empire testifies that France had entered the era of urbanization and that rural areas had to comply with this domination. It was relatively easy for people living in Chautagne to accept those public regulations since they were in the wake of their empirical practices. Without doubt this practice was

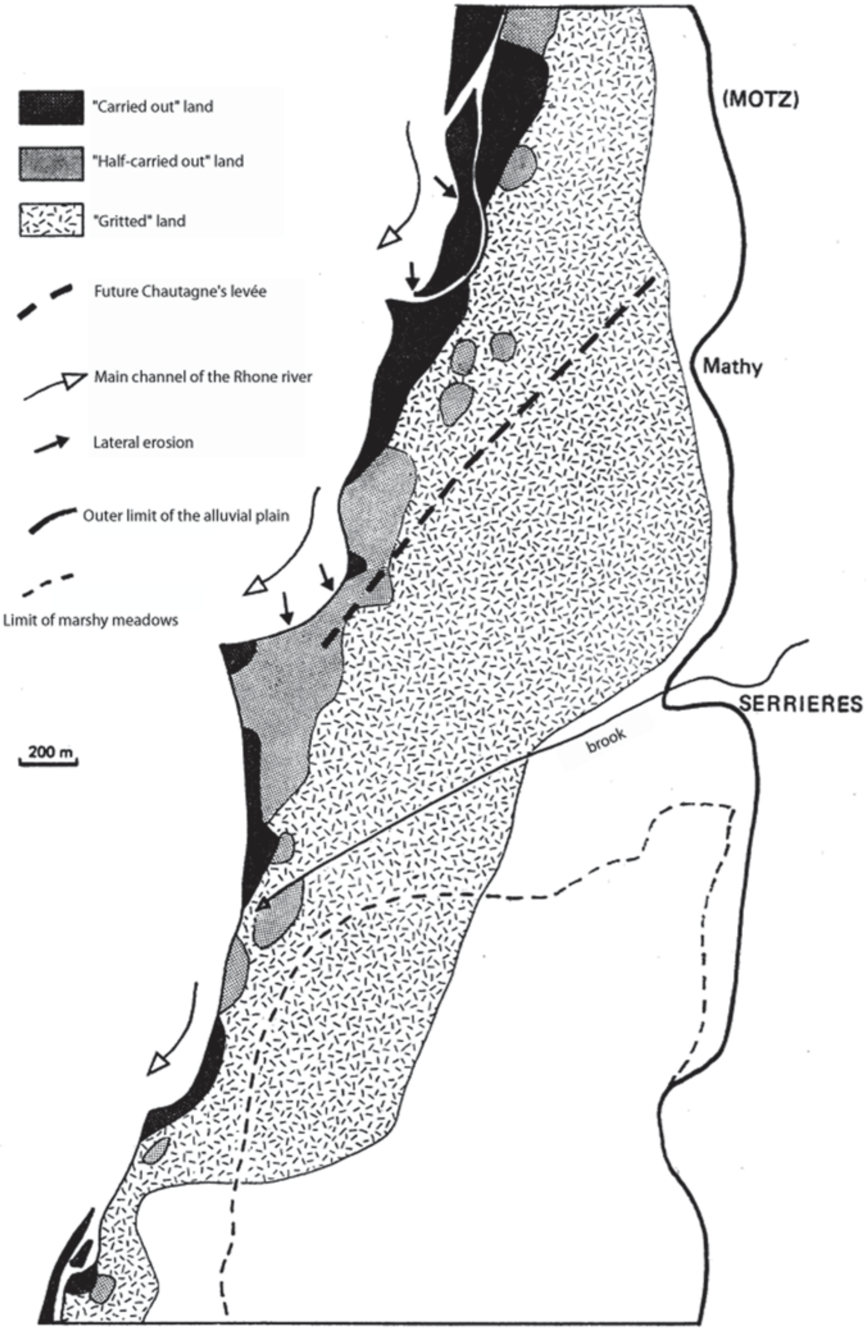


Fig. 8 Erosion of bottomlands by the 1732–1733 flood in Chautagne reach, Savoy

Fig. 9 Location of longitudinal dyke placement to protect land from erosion in Chautagne reach (1860)

more controversial to residents in the downstream fertile plains, but the significance of the law is that it represented a first type of integrated management at a national scale. The economic importance of Lyon justified a severe application of the law along the Upper Rhône. In the Chautagne plain, the crisis of vineyards and the human losses of the 1st World War were responsible for the dereliction of marshy bottomland, which was then bought by State and planted with poplars. No doubt that local development was constrained, but the flooding areas were preserved to the benefit of flood peakreduction, of land fertilization by floods, and for the benefit of the floodplain ecology.

The Impacts of Hydropower Development The type of equilibrium described in Chautagne, was considered to be strictly related to water management and ignored sediment fluxes, which were intended to be constant. After implementation of the Chautagne development scheme (1978–1981), with the upstream reservoir controlled by the Motz retention dam and an 8 km long hydroelectric canal (700 m^3/s^{-1}) within the power plant, the technical conceptions of the modern plan coincided almost perfectly with the 1858 flood law requirement (Fig. 10). Floods continue to transit through the Old Rhône (km 137–145 upstream of Lyon), since the power plant is closed when a large flood is expected to threaten Lyon, and the Chautagne plain is flooded as before, with an equivalent discharge. The brief impact study performed before the implementation of the development scheme considered that bed load would not be a question because of the large size of particles close to the confluence of the Fier River, a steep alpine tributary. The first registered impact was the lowering of the water level in the Old Rhône, the minimum discharge being reduced from 350 to 10–20 $m^3\ s^{-1}$. Concurrently, ground water levels lowered in the Chautagne plain and the 1000 ha wide peaty back swamp dried up and subsided, with consequences to the poplar forest whose trees were partly uprooted. In fact, after 10 years without any significant flood, the 1990 1:100-yr flood (peak of 2850 m^3/s^{-1}) submersed the marsh, as expected, but also scoured the railway, which since its completion in 1860 had never been subjected to such an extreme event.

A geomorphic survey confirmed that flood ways had been modified by adjustment of the longitudinal profile, as the channel incised downstream of Motz dam. Using detailed maps and cross sections surveyed by the NRC, Klingeman et al. (1994, 1998) estimated the volume of gravel transferred to downstream reaches. The authors proposed several technical solutions, such as the construction of transverse weirs across the incising reach and the upstream transfer of gravel below the retention dam. The Chautagne reach is a good example of the sensitivity of mountain floodplains to changes in river channel morphology. Since the early 1990s, other fragile by-passed reaches have been monitored after large morphogenetic floods.

Fig. 10 Photograph of the Chautagne reach seen from upstream. In the north-south Chautagne syncline, the land units are, from the right to the left: the former braided belt, the CNR canal with power plant, the lined gravel pits used to raise the levees of the canal head race, the by-passed Rhône River ("Old Rhône") with gravel bars and sinuous unique channel, the Chautagne flood plain with former braided belt upstream and marsh (back swamp) downstream. Upper left stands the Bourget Lake. (Courtesy: R. Montagnon/PARACOM/UMR 5600)

5.2 The Donzere-Mondragon Reach: Reactivating Fluvial Dynamics Along the Old Rhône to Compensate for the Loss of Flood Expansion Zones

Heterogeneity of the Floodplain and Search of New Land for Agriculture The geomorphic history of the floodplain is diverse and explains the conditions of land occupation in the braid belt from upstream to downstream (Fig. 11).

During modern times, the upstream Donzere alluvial plain (170–176 km downstream of Lyon) has been completely reworked by the lateral migration of the braided tract. On the 1860 map, most of the ancient channels are clearly visible and often watered. Many kilometer markers, erected after the 1840 flood on the left bank of the main channel, stand in the middle of the floodplain 20 years later. Place names refer to recent landforms, such as islands and former arms. The farmers of the Lower Rhône, both individuals and unions of landowners organized by the 1807 law, preferred sandy natural levees to protect land and newly built up houses. These levees have been dated 1790–1840 (Poinsart 1992). The objective was to reduce the velocity of flow from upstream, while accepting downstream flooding. The 1860 map testifies that the cultivated land was flooded everywhere, with water depth being 1 m. The areas reclaimed after 1840, now cultivated and built up, have a water depth of ca 1.5 m during floods.

The floodable Pierrelatte plain (176–184 km) is composed of a narrow former braided stretch and an eastern plain shaped by the lateral shifting and the vertical erosion of the Rhône River into the Würm terrace. The water level of the 1856 flood was between 1 and 2 m above the floodplain, likely because of the narrow floodplain corridor and upstream aggradation of the braided tract.

The downstream floodplain (184–190 km) has been shaped by the shifting of the modern braided tracts. Lateral mobility of the Rhône was enhanced by the floods of the Ardeche River (6000 $m^3 s^{-1}$), which occasionally caused the Rhône to shift eastward. On the eastern side of the floodplain, a marshy area, dammed by the braided stretch, was submerged by 3 m of water during the 1856 flood.

Navigation Dykes, Vertical Accretion of the River Margins and Floods Levels The large extent of the LIA braid belt and the associated low depths for navigation at low flow rendered river training necessary. Embankments for the improvement of navigation were erected between 1840 and 1940. The Donzere-Mondragon hydroscheme was completed in 1952, mainly for providing energy to a nuclear plant devoted to military uses. The head of the power plant is 22.5 m, and the by-passed Rhône is 31 km long.

Along the by-passed reach of Donzere, the length of the dykes erected along the two banks of the channel is surprisingly high (Table 4).

Over a 200-year period the intensity of embankment resulted in 8.85 km of dyke construction per km of river (Table 4), 4.4 km on each bank. Indeed, since the late eighteenth century, at least, farmers, syndicates of farmers and State services have been erecting levees against flooding and protecting banks from lateral erosion.

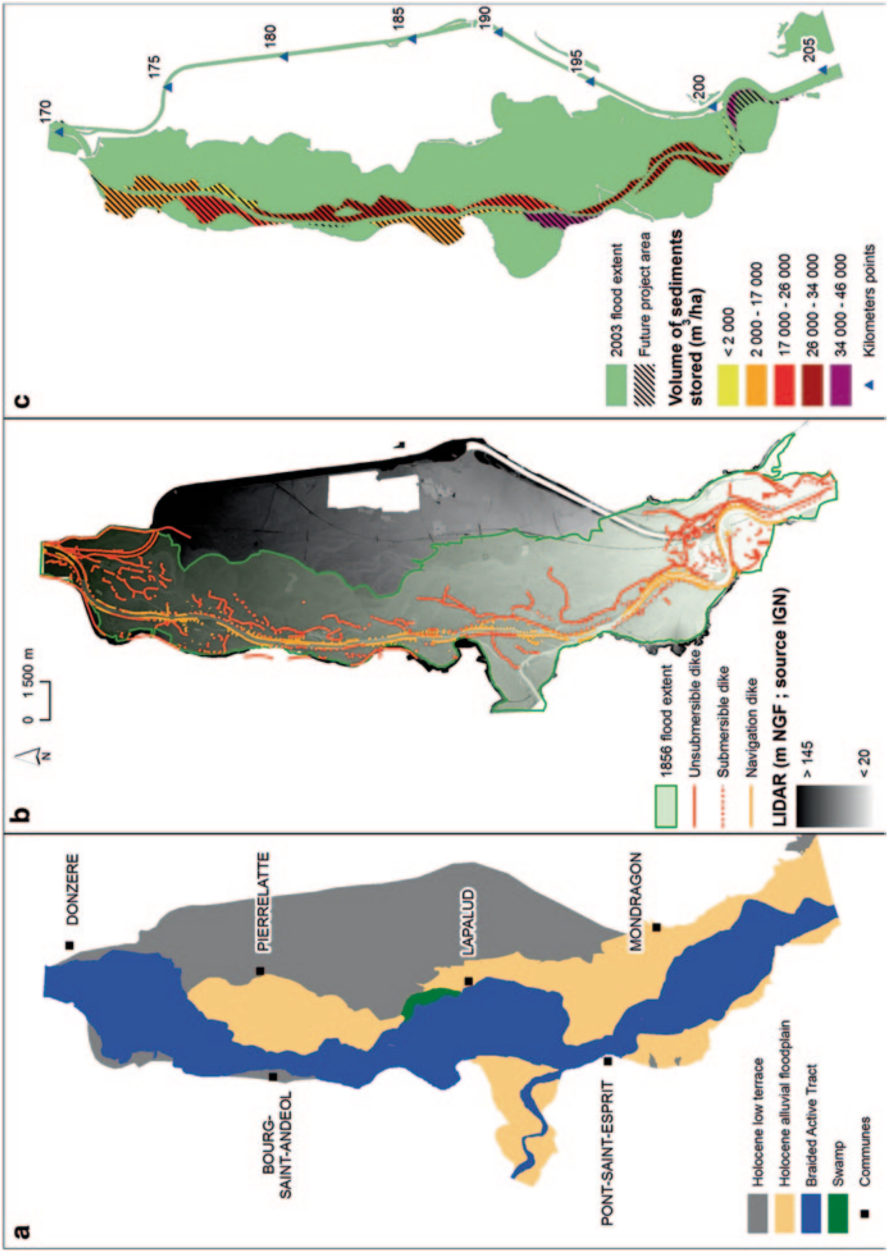


Fig. 11 The Donzere-Mondragon floodplain. **a** Simplified sketch of the Holocene geomorphic units, **b** Topographical map of the plain (from LiDAR) with the successive generations of embankments inside the LIA-braided belt, **c** Land units of the river margins prone to active sedimentation

Table 4 The different types of embankments built up in along the by-passed Donzere-Mondragon reach

Type of embankments located in the former braided tract	Cumulated length (km)
Ancient levees protecting the floodplain from high floods (18th c.?)	114
Low dykes and rip-rap structures protecting the floodplain from the lateral erosion of the channel (1814–1910)	62
Navigation dykes present in the channel in 1860	1.9
Navigation dykes built in the channel between 1860 and 1882	15.8
New navigation dykes post-1882, including final Girardon works	59.6
Non floodable CNR levees (1952)	17
Low floodable CNR levees (1952)	4
Total	*274.3*
Average length of embankment structures per km of river course	*8.85*

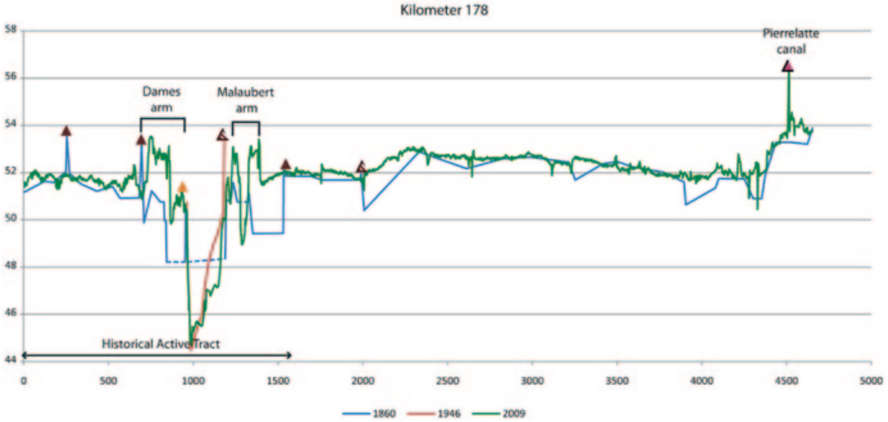


Fig. 12 Cross profiles dated 1860, 1946 and 2009 across the Donzere-Mondragon plain showing gross sedimentation over the floodplain and mainly on the river margin (A: 178 km; B: 195 km)

Between 1840 and 1876, the Rhône Special Service erected low dykes along the concave banks, with a low relative elevation (2–3.5 m above low flow) to concentrate low and medium discharges. The dykes were also erected to dam the side channels located on the convex bank. Most development is in the wide braided area upstream of the by-passed Rhône.

Between 1876 and 1884, a new type of low-water dykes, constructed below average annual stage, resulted in channel constriction and concentration of flow. After 1884, a new generation of dykes was superimposed atop the previous ones to enable navigational low flow. Most of these structures were built between 1890 and 1910 but improvement lasted until 1939. This new set of low dykes was placed in several hydromorphologic locations, including atop convex banks (plunging groynes), along the concave banks (to create "compartments"), on the channel bed (to constrict the channel at low flow), and across channel side arms. Floods transported gravelfrom the channel thalweg and redistributed it along low banks between groynes.

The volume of sediment stored on the margin has been computed using cross profiles surveyed in 1860, 1946 and 2009 (Fig. 12). The total volume of sediment stored by the floods in the alluvial margins of the Donzere-Mondragon reach during the last 150 years is estimated 3653×10^{-6} m^3. The specific sediment volume per sedimentation unit has been estimated 23,850 m^3/ha (or about 2.40 m in depth). The cumulated error of the two generations of maps may be up to 70 cm (ancient map: 70 cm; LIDAR: 20 cm). Considering a 2.5 m high deposit, the margin of error is 7 %.

The impacts of sediment deposition on the river margins are the following: (1) a general succession of softwood forest into hardwood forest due to the relative lowering of the water table, (2) a decrease in the number and depth of former braided channels, (3) a decrease in the number and accessibility of side channels considered suitable as refuge and reproduction for aquatic organisms and (4) a reduction in inundation of riparian areas during moderate floods because of changes in flood stage relative to floodplain levels.

A by-pass channel constructed in 1952 has effectively maintained flooding to historic levels. The maximum discharge in the by-passed channel for the December 2003 flood, for example, was 6040 $m^3\ s^{-1}$, however the extension of the flooded area was similar to the 1856 event (despite diversion of almost 2000 $m^3\ s^{-1}$ into the industrial canal). Maintenance works must be implemented when flood levels increase over the 1952 reference level, which takes the reduced discharge into account. These measures may consist of dredging, clear cutting and softening of surface sediment to enhance the mobility of particles. An independent survey conducted in 2004 confirms the stability and even a slight increase in channel discharge capacity through a deepening of the channel, but this positive evolution does not compensate for the negative impact of deposition along the margins. To prevent a further decrease of discharge capacity caused by sediment deposition on the channel banks, a new policy was launched by the CNR in 2003.

The Reactivation of River Margins: Widening the Channel and Increasing Discharge Capacity The Rhône Global Study (SOGREAH 2000) concluded that the large amount of sediment was stored along the river margins. Deposition of suspended sediment inside the margins was attributed to the rapid reduction of discharge at the retention dam during flood recession. The study stressed the responsibility of the CNR. The RGS proposed exploring removal of some sand to gain discharge capacity. In 2003, one of the authors of this paper proposed the NRC° to study the development of embankments, the evolution of land occupation, and the geomorphologic changes over 150 years. Without excluding the role of dam closure, the result was a clear assessment of the responsibility of the Girardon dykes in the trapping of sand and silt. Maps of the land units prone to the highest rates of deposition were designed and validated using hydraulic models of discharge and velocity. The method, including a sediment study (tests of resistance to penetration giving an evaluation of the cohesiveness of deposits, grain size, content in heavy metals) and hydraulic feasibility, allowed successful pilot tests in the two by-passed reaches of Bourg-les-Valence and Montelimar (Collilieux et al. 2007, 2010; Bravard et al. 2008a). This method complements the policy launched by the NRC in the early 1980s, which became official in 1995 as the "10 Years Hydraulic and Ecological Restoration Plan". Part of the Plan was the restoration of side arms with the double objective to improve flood capacity and improve the ecology of wetlands. Also, the increase of minimum discharge improved the watering of the restored side arms. In fact, considering the importance of the deposited volumes of sediment, rehabilitating the side arms cannot meet the challenge, and since 2006 the Rhône Master Plan officially promotes the reactivation of the river margins with more ambitious goals (Fig. 13).

The general principles concerning the reactivation of the fluvial dynamics of the Rhône consists primarily in the removal of some of Girardon dykes along the by-passed reaches of the river. This policy has much in common with the European concept of "more room for the river" (Piégay et al. 2005; Bravard 2011). However, the Rhône project is original in Europe, in part because it is based on the self-restoration of the river during floods. Some limited works will help the Rhône River

Fig. 13 Photographs of erosion of the left bank of the Rhône River upstream of Pont-Saint-Esprit bridge. *Left photo*: lateral erosion of a former gravel bar; *right photo*: lateral erosion of sandy top layer. In the back ground the mediaeval Pont-Saint-Esprit bridge. (Courtesy: NRC)

to mobilize fine sediments stored in the alluvial margins beyond the embankments. This reactivation project aims at:

- Restoring fluvial dynamics in the channel,
- Reconnecting the channel to side-arms closed since the 1880s. Restoring vertical exchanges between the channel and groundwater,
- Reshaping aquatic habitats of the former braided tract,
- Managing better flooding over the alluvial plain,
- Improving self-purification capacities of water bodies,
- Improving the landscape once plant species have colonized the landforms shaped by lateral erosion.

In the Donzere old Rhône, after the 2002 and 2003 floods that affected the communes of the left bank, a study was conducted which arrived at several sustainable options. The best scenario consisted in (1) maintaining flooding over the floodplain with the lowest possible energy because of downstream–upstream flooding behind the levees, and reducing erosion of dykes, (2) diverting part of the flow into rehabilitated ancient arms, (3) improving the flood levels under the mediaeval Pont-Saint-Esprit bridge.

Preparatory works for the reactivation of fluvial dynamics, performed in December 2009, consisted in dismantling 17 Girardon groynes, in removing a longitudinal back-dyke, and opening two furrows into the gravel bars of the main channel to initiate erosion of the bank sediment. The topographic survey undertaken by the CNR proved that the restoration procedure was effective, even for limited floods, because (1) the base of the left bank has deepened and the new channel has been rapidly colonized by aquatic vegetations and (2) downstream of the de-commissioned reach, the retreat of the bank is up to 3 m along a 160 m length. Erosion covers 0.94 ha and the eroded surface is 3200 m^2 corresponding to a volume of 5300 m^3. The result may be considered modest in proportion to the total volume of storage, but it is important to note that the relatively low magnitude annual flood has been able to reinitiate river dynamics. The results adequately supported the selected policy and approach. Additionally, floodplain residents along the river are satisfied of the initial results, which is crucial for further public support of large-scale management and restoration initiatives.

One of the major challenges is that the restoration and management projects must not be detrimental to residents along the river, or endanger the riverine and floodplain landscape. Such projects often suffer from various constraints, which are both natural and human-induced. From the standpoint of the Rhône case study, the following two issues are of concern to a successful implementation of integrated management and restoration. First, the proven efficiency of the method inherently includes a stochastic element, because it depends on the occurrence and nature of floods, which are unpredictable. Second, river pollution, started by the end of the nineteenth century, has resulted in considerable pollution of sediments that the project plans to remove. In spite of decreasing pollution by heavy metals in recent decades, polychlorinated biphenyl and polycyclic aromatics pose a serious problem to the implementation of the proposed approaches. In some areas, downstream of cities and factories, the pollution may exceed the authorized limit, beyond which law forbids the remobilization of sediments. It is a major constraint to the success of a policy of the margins as long as techniques allowing de-pollution of large bulks of sediment at a reasonable cost are not available.

A further limitation to implementation is the reluctance of experts within the Ministry of Environment to authorize a larger-scale programme. Generally, the government contends that improving the discharge capacity of the Rhône River could reduce the efficiency of upstream floodplain (reducing the capacity of flooding) and further risk dyke breaches along the Lower Rhône because of higher flood levels. Nevertheless, a strategy of sediment removal (or "more room for the Rhône River") is currently in its testing phase; and importantly in this stage it re-establishes the public awareness of landscape flooding and of "flood risk". Similarly, recent improvements to the capacity of the Rhône channel in the Donzere-Mondragon stretch to prevent flooding by events of less than 1-in-10-year frequency are publically accepted. Alternatively, the programme not only decreases the frequency of flooding, but also reduces peak discharges of floods exceeding the 10-year frequency because of upstream floodwater retention. Finally, although the project would reduce the area of alluvial forests in its initial stages of implementation, it will rehabilitate landforms, habitats, and promote ecological succession, which fits in well with the objectives of the Rhône Master Plan.

6 Conclusions

The Rhône River valley is a complex assemblage of floodplain patches, which (1) are largely Holocene, (2) pertain to an alternation of braiding and meandering patterns which in turn condition the shape of ancient channels, (3) are perched over the present river level because of the modern river being incised, and locally because of neotectonics. The conditions of flooding were influenced by its geomorphologic history until the 1860s, i.e. when the floodplain was still widely floodable.

The complexity of hydrogeomorphic landforms and associated ecology, which prevailed until the mid-nineteenth century, has been progressively offset by the indirect impact of embankments constructed for the improvement of navigation. Since protection against floods has never been a priority (and was even forbidden as early as 1858), except in the Camargue delta, the embankments were designed to modify the channel and the river margins without affecting the alluvial plain. Indeed, the dominant pattern of the Rhône was one of the braidings during the Industrial Revolution, with the direct consequence that the training works were primarily implemented in braided reaches and that the river lost its previous capacity to adjust to changes in sediment and discharge.

From this policy, the construction of river margins by overbank sedimentation-increased flood levels, to the detriment of adjacent land and villages, despite diversion of floodwaters into the CNR industrial canal. The wet period from 1993 to 2003, which was associated with an increase in flood frequency, demonstrated that the river/floodplain system had experienced a shift toward worsening conditions. This had likely been masked by an absence of floods from 1957 to 1993. During this last period, floodplain residents were convinced that the flood risk was over because of the CNR schemes.

An additional consequence of river training which impacts floodplains, is their reduced capacity to store flood waters. Downstream of Valence, for example, it has been shown that such changes are primarily the result of vertical accretion along river margins, which further reduces the capacity to store floodwaters.

Overall, floodplain environments along the Rhône valley are degrading, as they have been developed (communities claim for protection), have lost capacity to store flood waters, and are experiencing worsening floods. Facing the difficulty to impose efficient flood expansion zones and considering the limited efficiency of the hydraulic rehabilitation of silted side channels, the State services decided in 2006 to include the margins policy into the Rhône River Master Plan. We have seen constraints against implementation, but there is no doubt that they will be overcome in the foreseeable future, particularly if a large flood occurs. The question of climate change has been very recently considered by the Water Agency as a challenge along the Rhône valley. It may be because of the fact that models had predicted no more than a modest increase of winter floods, but the social acceptance to present flooding conditions is so limited downstream of Lyon that the perspective to cope with higher floods discourages State services. Their main concern is to introduce the concept that the 1-in-200-year flood is considered the reference flood by the EEC, and that states of Europe should transcribe the 2002 EEC Flood Directive into their own legislation. Obviously the Rhône valley is not ready to implement such a drastic policy. The present policy is conceived at the watershed scale and incorporates the flood expansion zones of the tributaries into an integrated strategy, while preserving floodplains of the Upper Rhône. The objective is limiting further degradation of the present situation, which is essential because of the local population being reluctant to re-open developed flood expansion zones of the Rhône valley to flooding.

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The Role of Floodplain Geomorphology in Policy and Management Decisions along the Lower Mississippi River in Louisiana

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Abstract Control of policy and management decisions on the Mississippi River floodplain in Louisiana are shared among the U.S. Army Corps of Engineers, state agencies, parish levee boards, and individual landowners. Several examples illustrate how geomorphic expertise can help resolve conflicting issues between different stakeholders while having input into project design and management. These issues include (1) navigable waterways and the ordinary high water mark, (2) the formation of river bars and islands in regards to ownership, (3) the formation of floodplain lakes in regards to determining ownership, and (4) river diversions constructed to control downstream flooding and distribute sediment into adjacent marshlands. The science of fluvial geomorphology concerns the processes controlling river and floodplain development and should be consulted for decisions involving stakeholder disputes and environmental management.

Keywords Channel islands · Diversions · Floodplain lakes · Floodplain ownership · High water · Louisiana · Mississippi River floodplains · Navigable water

1 Introduction

River floodplains represent one of the most dynamic and variable landforms in fluvial geomorphology. They are subject to changes occurring at annual to millenial time-scales (Knighton 1998). Annual change results from the seasonal hydrologic regime and may be manifested by erosion triggered by overbank flooding, while over decadal to century time-scales rates of river bank erosion and overbank sedimentation influences the overall river channel patterns and floodplain topography. The floodplain surface has considerable variability in physical characteristics, in-

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cluding topography, vegetation, sediment accumulation, and water bodies. Fluvial geomorphology is the science that concerns the processes of river and floodplain formation and can provide valuable input for management decisions which involve different floodplain stakeholders, such as private and governmental interests. Many environmental management issues along floodplains, for example, first require that the ownership and boundaries of riverine and floodplain lands be determined. The issue is complex, however, because of rivers and floodplains being inherently dynamic entities over time and space.

By their very nature floodplains are constantly adjusting, being subject to various physical processes, such as, flooding, channel migration, formations of bars and islands, and the creation of floodplain lakes. Floodplains have historically been among the first areas to be settled because of their flat topography, fertile soil, riverine transportation, as well as providing water for drinking, agriculture, and industry (Costa 1998). For all of their attributes, however, flooding continues to pose a serious risk to most types of floodplain development. To minimize these risks, the USA has drafted regulations and implemented policies to control the use, development, and in some cases, ownership within floodplains. These regulations and resulting policies; however, are written by the legal profession without expertise in the science of fluvial geomorphology.

In addition to federal regulations and policies, state and local governments also have regulations pertaining to floodplains, and such is the case of Louisiana. Louisiana's Civil Code regulates the ownership of navigable waters within the state boundaries, which range from small creeks and slow-moving bayous, to the enormous Mississippi River.

This study focuses on the tension between legal interpretations and scientific understanding of fluvial processes related to several important federal and state policies applicable to the embanked floodplain of the Lower Mississippi within Louisiana. The policy issues examined hereby include: (1) navigable waterways and the ordinary high water mark, (2) state ownership of bars and islands that form in the channel bed, (3) the ownership of lakes formed from a navigable waterway, and (4) river diversions for flood management and sediment redistribution.

2 Background

The Mississippi River drains 3.2×10^6 km^2 of North America and follows a 3700 km course from its source at Lake Itasca, Minnesota to the Gulf of Mexico. The 1600 km portion from Cairo, Illinois to the Gulf of Mexico is among the world's most intensely regulated rivers. This lower portion of the river can be subdivided into two geomorphologic sections (Fig. 1): The alluvial valley and delta. The upper section is the alluvial valley, which represents two-thirds of the Lower Mississippi River and extends from Cairo to Red River Landing, Louisiana. Here, the river flows through a floodplain which ranges from 40 to 200 km wide and is primarily comprised of alluvial sand, silt, and clay. Prior to intensive modification in the early 1900s, the

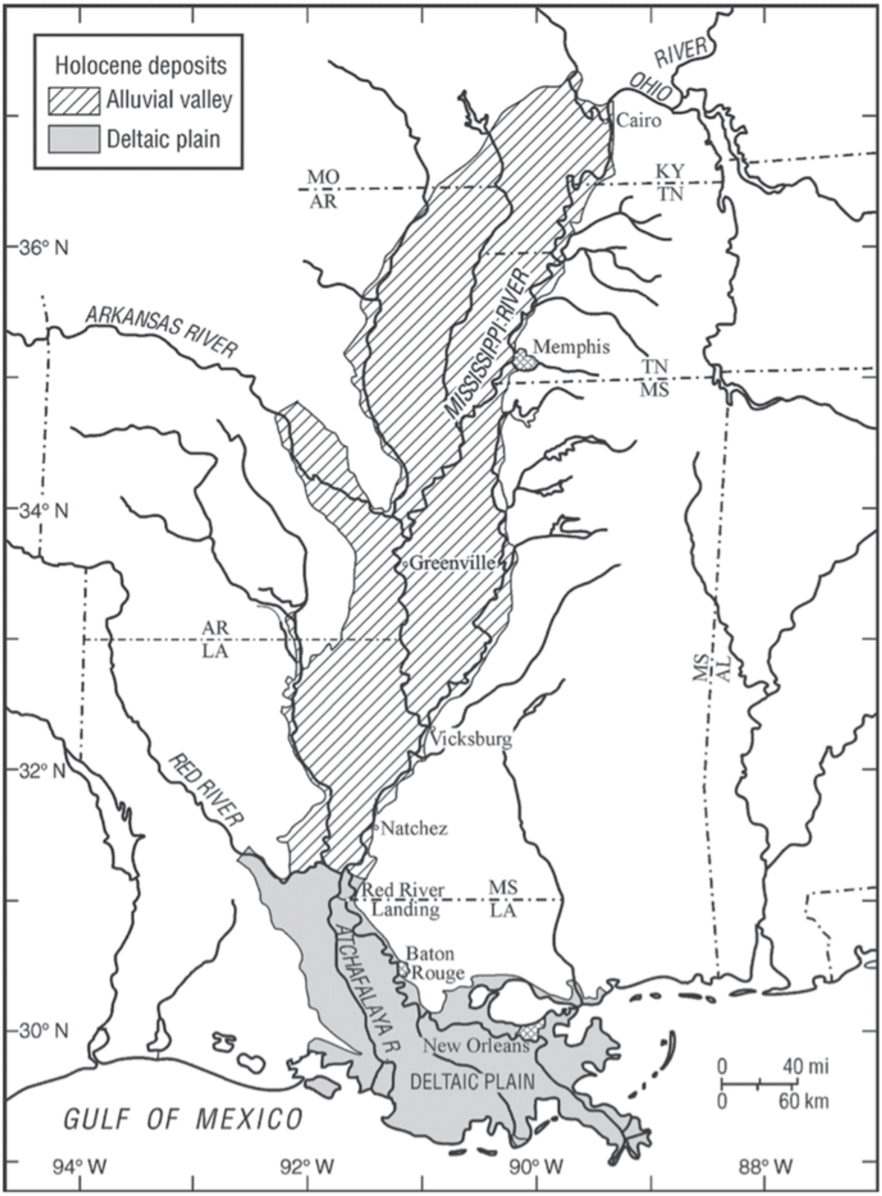

Fig. 1 Lower Mississippi River Valley showing geomorphologic divisions

river within the alluvial valley was able to meander freely and had an average lateral migration rate of 25 m/year. (Kesel et al. 1992; Hudson and Kesel 2000). Geomorphically, the Mississippi Delta begins downstream of Red River Landing. The river channel within the delta is composed largely of cohesive clayey sediments, with some sections of the channel incised into resistant Pleistocene deposits. The cohe-

Table 1 Policy issues and relevant geomorphic impacts

Policy issue	Geomorphic entity
1. Jurisdiction below the high water mark	Batture, bank, shore
2. Ownership of attached islands and sand bars	Side or mid channel bars or islands
3. Ownership of lakes formed from in navigable water	Floodplain lakes
4. Diversions	Crevasse, wetlands

sive and resistant deposits have restricted lateral migration and overbank sedimentation. The average lateral migration rate in the delta is 3 m/year (Kesel et al. 1992). The considerable geomorphic differences between the embanked floodplains of the alluvial valley and delta have an important role in floodwater policies.

3 Policy Issues

A host of federal, state, and local regulations control activities within the Mississippi floodplain. At the federal level, the US Clean Water Act and Title 33: Navigation and Navigable Waters of the U.S. Code gives the US Army Corps of Engineers the authority to regulate ownership and uses of the floodplain. State laws, such as the revised Louisiana Statute 9:1101, govern the ownership of portions of floodplains. The term "navigable water" is key, and refers to all water bodies within the United States, whether navigable or not. The term does not apply to artificial ponds, such as stock ponds. Local governmental agencies, however, also regulate these water bodies via parish (i.e., county) level and levee boards which are also concerned with flood control.

In this section, we examine four federal and state regulatory policies (Table 1). While these policies may be legally sound and have been implemented for decades, they are problematic from the perspective of their scientific justification.

3.1 Policy Issue 1: Jurisdiction Below the High Water Mark

Both state and federal regulations govern the land located on navigable waters below the mean (formerly ordinary) high water mark (33 CFR § 329.11 and Article 456 Louisiana Civil Code). In Louisiana, the area of the floodplain covered by floodwaters often coincides with artificial levees built upon the natural levee. The area of floodwater extending from the low-water stage to the mean high-water elevation is termed the batture, which is equivalent to the embanked floodplain. Battures vary in width and generally become narrower downstream. The width of the batture within the alluvial valley is wide, as here the artificial levees are set back several kilometers from the river (Fig. 2a). In the lower part of the river, towards New Orleans, the batture is very narrow (Fig. 2b) because the levees are adjacent

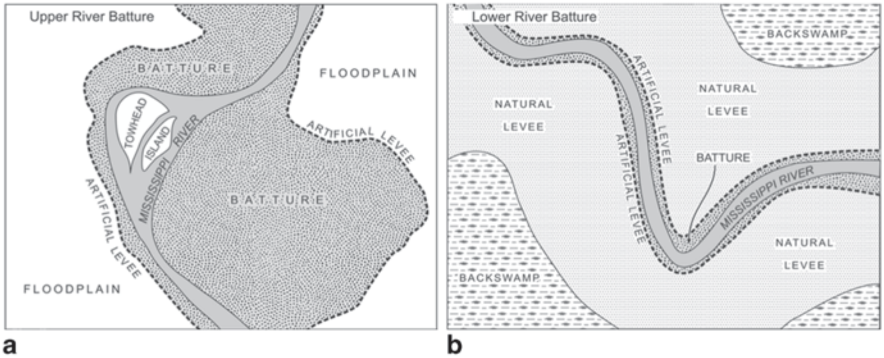

Fig. 2 Differences in area of batture lands. **a** Upper river batture above Baton Rouge, LA and **b** Lower river batture below Baton Rouge. In North America the term batture is associated with floodplain between the river and levee (*dike*) of the lower Mississippi River, and is equivalent to the embanked floodplain

to the river banks. Regulations allow governmental agencies to use the batture for sediment quarrying to build or repair artificial levees. Landowners may own or lease the batture, and generally use the land for livestock, campsites, and agriculture. Most of these activities occur on the wide battures north of Baton Rouge and within the alluvial valley, but not on the narrow battures further downstream, within the delta. An advantage of the wide batture in the upper section of the river is that it allows the river to inundate a large area of the floodplain, providing water storage while still providing flood protection. Ownership of the land, however, creates a constant friction between government and private parties with competing interests.

Additionally, the term "ordinary high water mark" is problematic to fluvial scientists. Legally, imprecise physical evidence, such as indentions and shelves on riverbanks, debris lines, and change in soil, are used to identify the "ordinary high water mark". These features can be subject to much interpretation, as well as considerable annual variation. Considering the potential impact to private ownership, a more precise method to determine the "high water mark" should be utilized. Long-term gauge readings, perhaps a 30–40 year average, to produce a mean high-water elevation would be an improved technique that would bring science into the policy.

3.2 Policy Issue 2: Ownership of Unattached Islands and Bars

According to Article 505 of the Louisiana Civil Code, mid- and side-channel bars, which are formed and rise to the surface by sediment deposition in the beds of navigable rivers or streams and which are not attached to the bank, belong to the state of Louisiana. Such bars are not related to bed load dunes that migrate as waves along the channel bottom and may be exposed during exceptionally low-discharge levels. The policy, however, is not based on an understanding of flow dynamics in major meandering rivers. Deposition of channel bars on the riverbed is limited to shallow water channels, as in braided river systems. Deposition of sand and silt within the channel bed, rather than along the banks, in large single channel rivers such as the Mississippi is unlikely to occur because of the velocity and shear stress associated with water depth. Thus, this policy, as written, is not supported by scientific knowledge of fluvial processes, and as such should not be implemented unless preceded by a study which considers the hydraulics of sedimentation.

During the 1930s, an extensive study by Elliott (1932, p. 57) concluded that islands in the Mississippi River were the result of chute cut-offs. Chute cut-offs are formed by the scour of arcuate swale depressions within point bars during flood events, which severs the end of the meander bend (e.g., Knighton 1998) thereby creating an island within the river. The channel at the point of cut-off is termed a chute, and the cut-off portion of the point bar is termed a towhead. The towhead island can undergo a complex history of development (Shull 1922). The channels bounding the island may initially be of equal size before one infills with sediment, resulting in a single dominant channel. Towhead bars often undergo numerous changes, including shifting position in the channel, re-attaching to the bank as the chute channel infills with fine-grained deposits, and can also be detached again from the bank. A representative example which displays the evolution of an attached bar over about five decades, from the 1880s to the 1930, is displayed in Fig. 3. Here, we can see that bars are formed initially attached to channel banks and are then eroded by chute cut-off, with subsequent migration within the channel and possible reattachment at a downstream location.

3.3 *Policy Issue 3: Ownership of Lakes Formed from Navigable Waters*

Lakes that existed in 1812 became a possession of Louisiana upon its admission to the United States. Lakes that have formed from a navigable river or stream after 1812 also belong to the state of Louisiana (Pollard's Lessee v. Hagan (3 How 212)). The large oxbow lakes in the Mississippi floodplain are former river channels and formed according to the well-known general model of an oxbow lake (e.g., Knighton 1998).

Oxbow lakes exhibit characteristics, which include: (1) an arcuate shape, often with a planform geometry (e.g., radius of curvature and width) similar to the main channel, (2) natural levees, (3) a depth similar to the main channel, (4) a bottom elevation approximate to the main channels, (5) persists for decades or centuries, and (6) forms in a short time, usually within a year or two (Table 2). Well known examples of oxbow lakes in Louisiana include, Lake Providence, Lake Bruin, Lake St. John, and False River.

Not all floodplain lakes, however, are oxbow lakes. Other lakes on the floodplain may have arcuate shapes, but are generally quite small and ephemeral in comparison to oxbow lakes, with many persisting for months to several years. These lakes occupy swale depressions found along the path of migrating meander bends, which

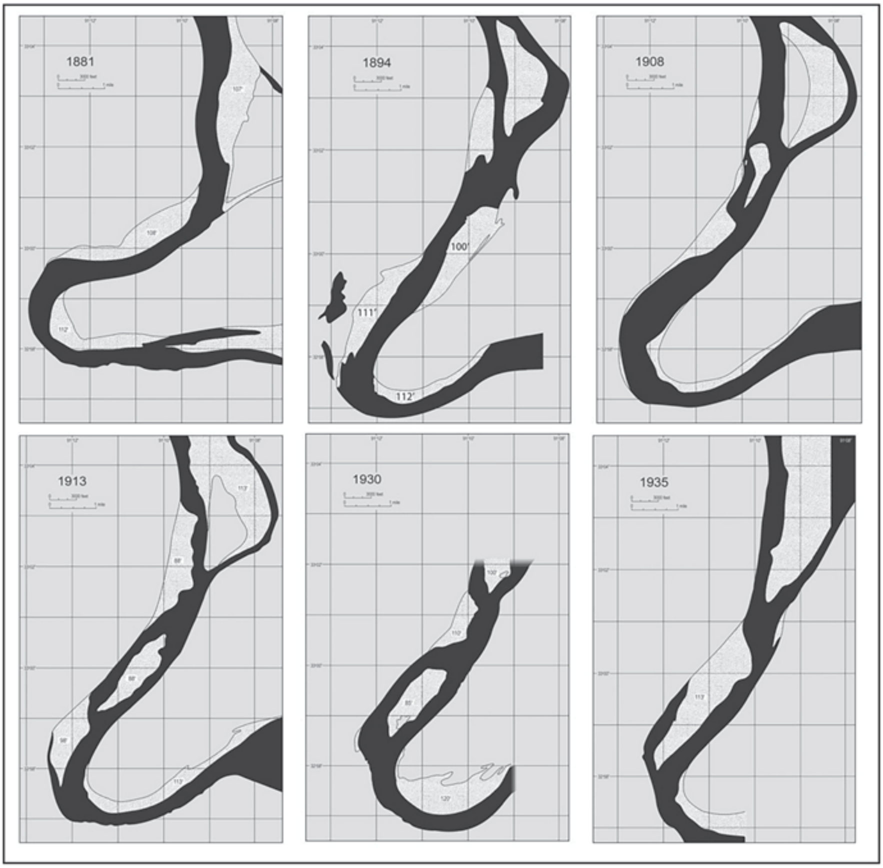

Fig. 3 Formation of island originating as chute cutoff

may be seasonally inundated by alluvial groundwater and floodwaters. The lake morphology is then influenced by the pattern of lateral migration of large meander bends. Several types of lakes have been incorrectly identified as being formed from a navigable river or stream, thus belonging to the state of Louisiana. Gassoway Lake is a good example of this mistaken identification.

Table 2 Comparison of physical characteristics of Oxbow Lakes and Gassoway Lake

	Oxbow Lake	Gassoway Lake
Arcate shape	Yes	No
Narrow neck	Yes	No
Natural levee	Yes	No
Deep[a]	Yes	No
Bed elevation[a]	Yes	No

[a] Compared to main river channel

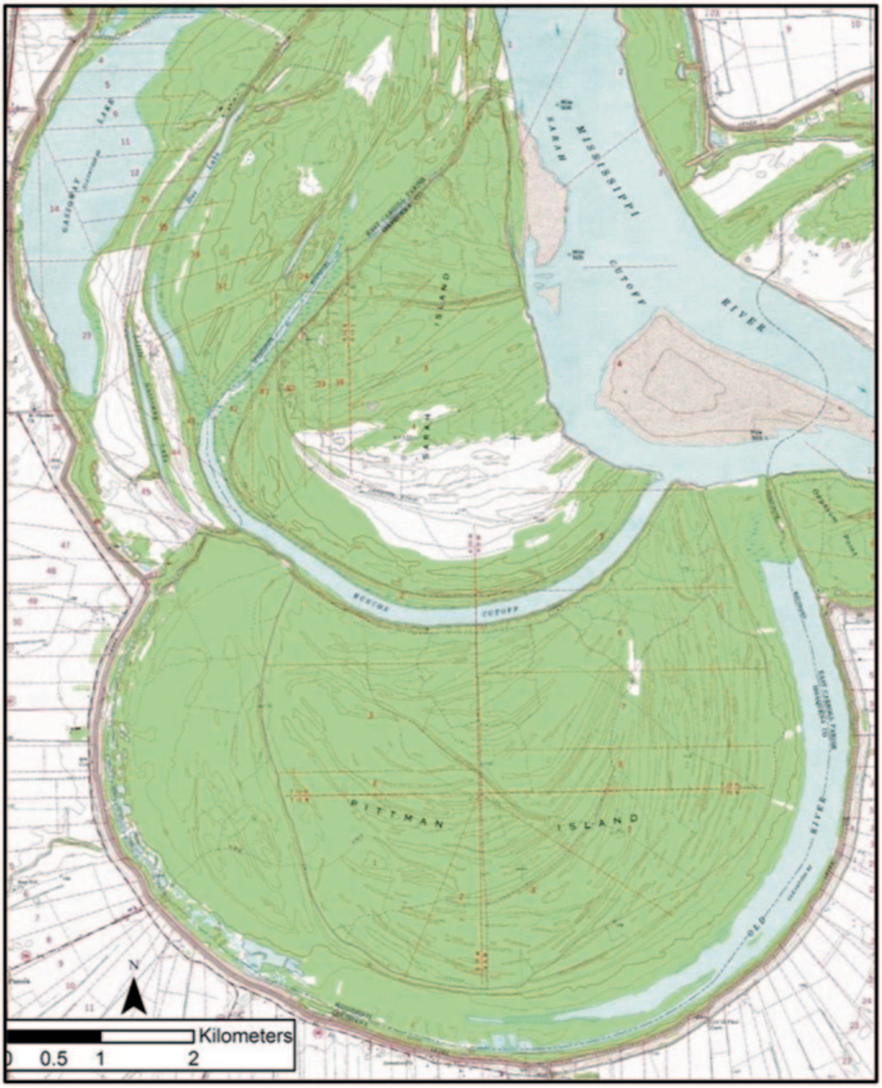

Fig. 4 Mid-channel bar considered by Louisiana to be an island formed by channel deposition. Note location of Gassoway Lake in northwest corner of map (Adapted from Milliken topographic map, 1:62,500)

Gassoway Lake is located south of the northern boundary of Louisiana (Fig. 4). Because the state had classified it as an oxbow lake, the state took possession of the lake property. The lake does not exhibit characteristics of an oxbow lake formed from the Mississippi River (e.g., Table 2). While Gassoway has a moderate crescent shape, it is not a true arcuate shape, nor does it have a narrow neck or natural levee. The depth of Gassoway Lake is extremely shallow (about 2 m) com-

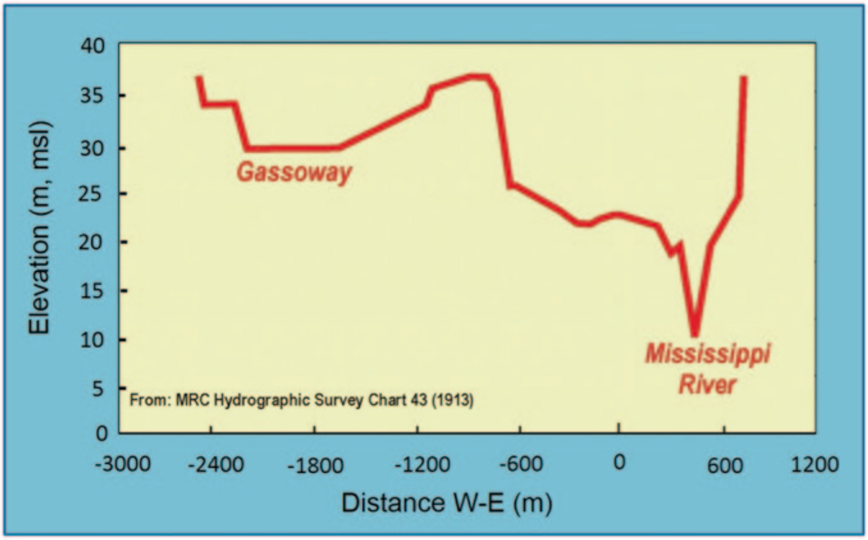

Fig. 5 Cross-section profile from Gassoway Lake to the Mississippi River (not to scale)

pared to the nearby (5.5 km east) Mississippi River channel (approximate depth of 17 m) and the elevation of the lake bed is also much higher than the river channel bed (Fig. 5).

During the 1860s and 1870s, the Mississippi River was migrating in a westward direction towards Gassoway Lake. Around 1880, however, the Mississippi River started to slowly migrate to the southeast, preserving Gassoway Lake as a shallow elongated slough (Fig. 6). During this southeast movement, overbank sedimentation along the natural levee created a topographic barrier that block drainage of the lake, forming the present day shape of Gassoway Lake (Fig. 6).

The issues which relate to Gassoway Lake provide a basis for re-examining and enlarging our knowledge regarding the formation floodplain lakes. Such information is crucial to understanding the evolution and historic development of floodplain lakes, which is vital to the legal interpretation of floodplains for the development of effective management approaches.

3.4 Policy Issue 4: Diversions

Because of enormous wetland losses, the State of Louisiana and US Army Corps of Engineers have constructed a number of structures along the Mississippi River to divert freshwater and sediment into adjacent wetlands (Fig. 7). Additionally, flood spillways are used to funnel excess water from the Mississippi River during periods of extreme high water, as the case of Bonnet Carré Spillway (Figs. 8a, b) located

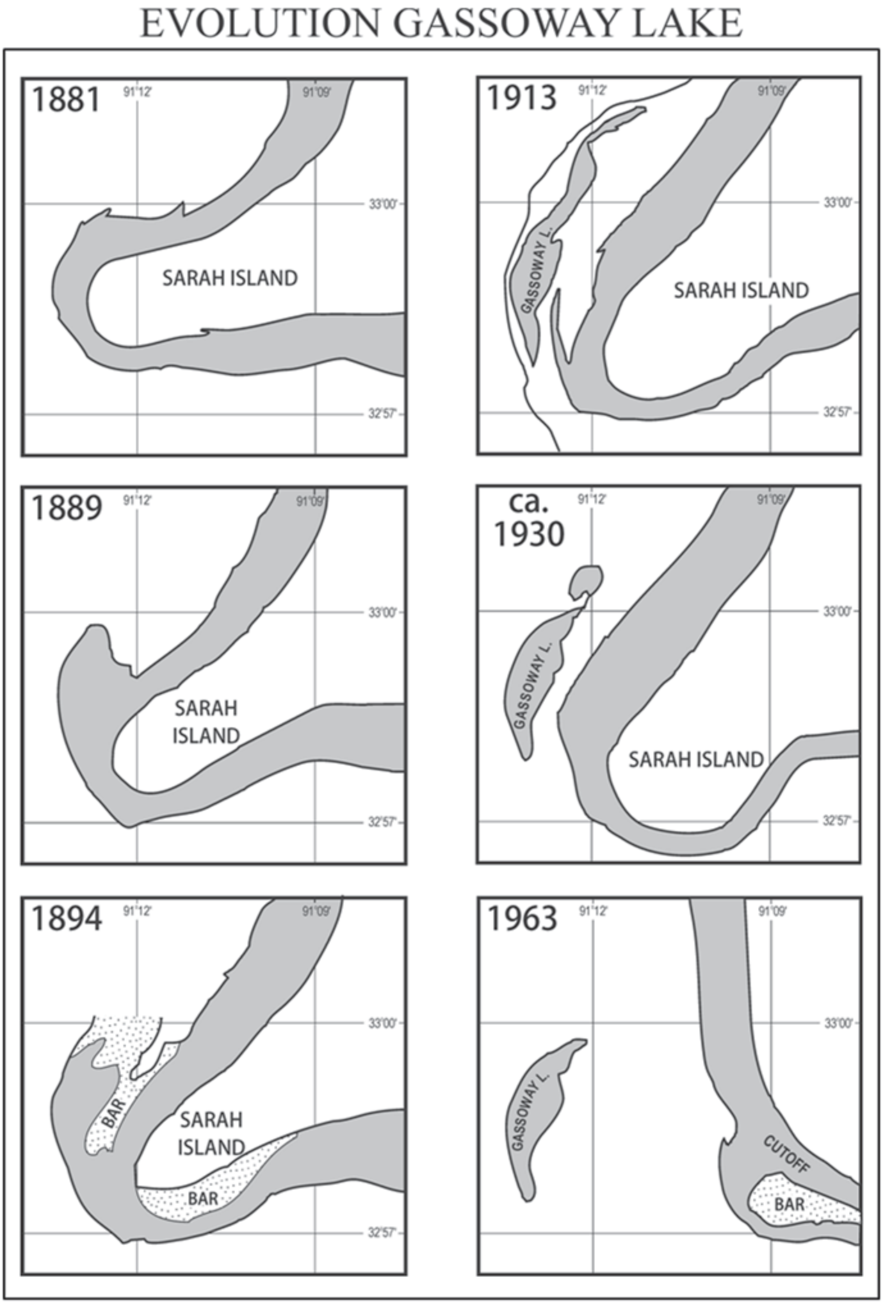

Fig. 6 Formation of Gassoway Lake as Mississippi River migrated to the southeast (Data from various MRC hydrographic surveys)

Fig. 7 The location of diversion structures along the lower Mississippi River

Fig. 8 Bonnet Carré Spillway Weir. **a** Weir bays open during a flood of 1983, **b** Showing open spillway during flood of 2011

upriver from New Orleans. Freshwater from these diversions may also have negative effects on the brackish and saline coastal marshes.

To understand the deficiencies of the existing diversion structures one must understand the basic hydraulics and sediment transport processes of the Lower Mississippi River. The discharge and sediment load of the river is strongly seasonal. The sediment load typically increases with the increased discharge in the late winter and or the early spring, and declines with decreased discharge in late summer and fall (Mossa and Roberts 1990; Demas et al. 1987). Below Red River Landing (Fig. 1),

Table 3 Mississippi River suspended sediment load at high- and low-water discharge at Belle Chase, LA (Data from Moody and Meade, 1991, 1993)

	Silt & clay	Sand	Total
	<63 um	>63 um	
High stage	317,500	123,500	441,000
Low stage	70,000	550	70,550

Moody and Meade (1991, 1993)

only clay, silt, and sand-sized sediment is transported by the river. Silt and clay-size particles are dominant during high and low water (98–100 % high stage vs. 67–81 % during low stage), with the sand fraction increasing with discharge. During the high stage, the sand fraction ranges from 19 to 35 % compared to low stage where the percentage is only 0–2 % (Moody and Meade 1991, 1993) (Table 3). Understanding the fundamental concepts of suspended sediment load is essential to designing and operating a diversion.

The size and concentration of sediment entrained in the water column vary with depth. Coarser sand particles are usually transported as bedload with large migrating dunes along the channel bed, while silt is carried near the middle of the water column and the finer clays occupy the top of the column. During the rising limb of the high-water stage, the sand in the dunes becomes entrained, thus increasing the sand fraction of the suspended sediment load (Nittrouer et al. 2011).

With the purpose of rebuilding Louisiana wetlands, diversions should be designed to capture water that contains the maximum concentration and the coarse sediment available within the water column. Most of the existing diversions divert flood waters only from the top of the water column that, in theory, have low-sediment concentration and suspend the finest-sized particles, both of which are of little help in building new wetlands. For wetland vegetation to take root, future diversions should be designed to take water from the base of the water column, near the channel bed, where a higher amount of coarse sand is available. This, however, would be a complex and expensive engineering design.

The siting of a diversion is also an important parameter to consider to maximize sediment and freshwater flow into adjacent wetlands. Ideally, the best location for a diversion is where crevasses have repeatedly occurred. Thick sand deposits underlie these sites and provide a solid shelf for the sheet flow of sediment-laden water into adjacent wetlands.

The Bonnet Carré Crevasse and the Bonnet Carré Spillway, located approximately 45 km upriver from New Orleans, provide a unique opportunity to compare the dynamics among river stage, sediment load, and channel location related to a natural occurring crevasse and an artificial spillway (Fig. 9). The Bonnet Carré crevasse was active from 1848 to 1874 where the river makes an almost 90^{o} meander bend. The spillway was not constructed at the actual location of the historic crevasse

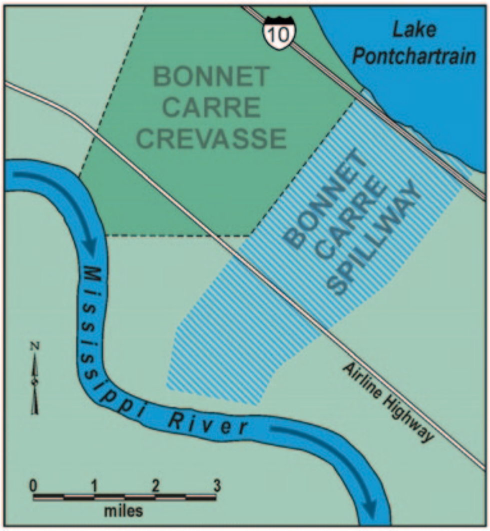

Fig. 9 Location of the Bonnet Carré Crevasse in relation to the Bonnet Carré Spillway. For scale, the width of the spillway at Airline Highway is 5.3 km

because of concerns that the Mississippi River would erode through the spillway and permanently divert its course into Lake Pontchartrain (U.S. Corps of Engineers 2012). Instead, it was built just downstream from the crevasse.

The Bonnet Carré Spillway is a 9-km long straight floodway that diverts water from the Mississippi River into Lake Pontchartrain. The diversion is controlled by a 2-km long weir equipped with 350 bays, each containing 20 timbers or needles which can be removed by a crane to control the discharge through the structure. The spillway was constructed in the 1930s to protect the City of New Orleans from extreme high-water events and has only been opened ten times since construction, most recently in 2011 (U.S. Corps of Engineers 2012). Sediment studies indicate that sand-size sediment has been deposited in the spillway during operational periods, most being deposited within 2 km of the weir. The sediment size and spatial extent (within several km of the river) of sand deposits are similar to what is found at the upriver crevasse site (Kesel personal communication). This is an interesting case, since most of the water diverted into the spillway is from the top 10 % of the water column compared to the crevasse which drew water from much deeper in the Mississippi River (Fig. 10). In addition, the spillway is not located on a cut bank along the apex of the bend, such is the natural crevasse.

Suspended load in the river is the source of overbank sediment. Observations at the Bonnet Carré spillway indicate the complex dynamics of turbidity cells that cause suspension of sediment in the water column. To optimally manage the use of the spillways requires an understanding of the turbidity cells to effectively estimate sediment concentration at a given depth in the river during a discharge event.

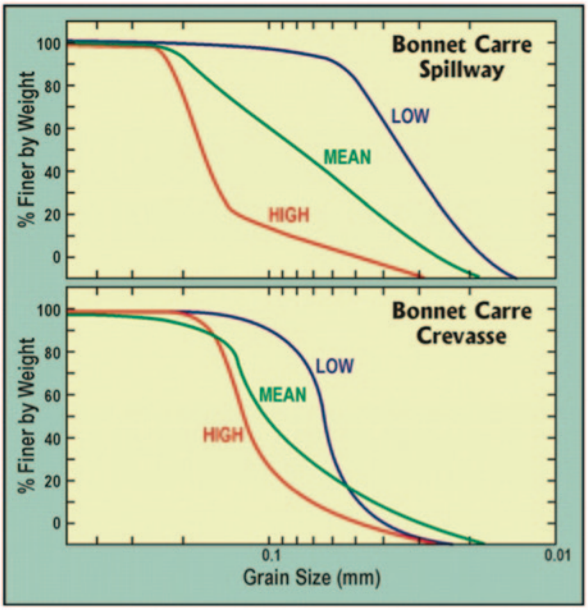

Fig. 10 A comparison of the sediment sizes from the Bonnet Carré Spillway and Bonnet Carré Crevasse

4 Summary and Conclusions

Fluvial geomorphology has only recently become integrated into floodplain management and development planning, although from the standpoint of the Mississippi River there is much more to accomplish. Several issues have been outlined in this study where rules and regulations formulated by the state for the Louisiana Mississippi River floodplain were designed without a firm understanding of the scientific principles of fluvial geomorphology. Among the issues discussed include the “mean high water,” growth of mid- and side-channel bars by sedimentation processes, development of floodplain lakes, and sediment diversion and operation of spillways to manage flood waters and restoration. These issues provide some background as to the role fluvial geomorphology can play in future research on floodplain management for large embanked floodplains.

Vague terminology, such as the “ordinary high water mark,” found in Policy Issue 1: “Navigable Waterways and the Ordinary High Water Mark” leave considerable room for legal interruption while being relatively meaningless to scientists. To determine property ownership, we contend that a better method is to use the average of high water elevation based on decades (~30 to 40 years) of measurements, which are readily available for the Lower Mississippi.

Similarly, regulations governing the formation of river islands and floodplain lakes were drafted without regard to scientific principles. An understanding of fluvial geomorphology and lake evolution in the Mississippi River flood plain is necessary to apply Policy Issue 2: “State Ownership of Bars and Islands Formed in the Channel Bed” and Policy Issue 3: “The Determination of Ownership of Floodplain

Lakes between Public and Private Entities." The hydraulics of sedimentation for large single channel meandering rivers does not support the position that islands and bars are formed in the middle of the channel of the Mississippi River. Additionally, there are other processes which form lakes on floodplains than the oxbow lake model. Therefore, we contend that not all channel bars and lakes along the Mississippi River and floodplain should belong to the State of Louisiana. An important conclusion of this study is that, an improper understanding of fluvial geomorphology could result in the unlawful government seizure of floodplain and riverine lands.

Finally, the recent construction of river diversions and spillways (Policy Issue 4) often exhibits a lack of scientific input. A growing body of evidence has increased our understanding of geomorphic processes including overbank sediment. Suspended load in the river is the source of overbank material, and observations at the Bonnet Carré spillway indicate the complex dynamics of turbidity cells that cause suspension of sediment in the water column. The effective operation of spillways for management purposes, therefore, requires an understanding of the hydraulics of sediment transport.

The science of fluvial geomorphology concerns the processes controlling river and floodplain development and should therefore be consulted for decisions involving stakeholder disputes and environmental management.

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The Palimpsest of River-Floodplain Management and the Role of Geomorphology

Paul F. Hudson and Hans Middelkoop

Abstract Embanked floodplains are the status-quo where humans are a major component of the environment, especially across Europe and North America. Effective management of embanked rivers requires a comprehensive knowledge of past and present-day geomorphic processes, including sediment transport and channel and floodplain dynamics. Many approaches to management include activities and modifications which take into account past natural and human impacts and management decisions, resulting in a palimpsest of river and floodplain management. A synthesis of 12 diverse case studies provides evidence of the palimpsest in river-floodplain management, and illustrates four key roles for geomorphology in the design of effective management strategies, including (1) regional and longerterm context, (2) system evolution and past human impacts, (3) engineering design and management options, and (4), environmental and geomorphic restoration as an end-product. A review and comparison of heavily managed embanked rivers spanning a range of climatic and geomorphic provinces across North America and Europe illustrate the role of geomorphology in this palimpsest and its value to integrated management.

Keywords Fluvial geomorphology · River dynamics · Palimpsest · Embanked floodplains · Integrated floodplain management

1 The Management Palimpsest

River and floodplain management of the active system is superimposed upon the impacts and structures of natural channel and floodplain development, and older forms of engineering and management, either in conceptual design or actual physical space. In many cases, the present-day state of the river has not reached an equi-

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librium to past natural or human changes. Modern management is thus directly interacting with, and in some cases responding to, older management decisions imposed upon the system at either the local (e.g., channel reach) or basin scale. This sequential “layering” of steps of natural evolution and management in which each new layer interacts with the impacts of the previous is hereby conceptualized as a “palimpsest” of river-floodplain management (Fig. 1a). The concept of palimpsest in geomorphology has gained attention during the past decade in view of renewed attention to interpretation of landscape evolution within the anthropocene context (Goudie and Viles 2010; Cotterhill and De Witt 2011; Knight 2012; Von Elverfeldt 2012). Here, we present the palimpsest as a stack of forcings, with the lower representing tectonics/subsidence, and then subsequently followed by climate, land cover change (natural and human-induced), past engineering, and the top layer representing the restoration actions (Fig. 1). Each of these layers may be represented as a conveyor belt of infinite length, and one belt is resting upon (and thus moved laterally) by the underlying belt. Each belt drags the fluvial system laterally, along a dimension that represents its state, varying from wide braided, meandering to narrow and deep channelized rivers. A shifting belt may represent an ongoing forcing such as tectonic subsidence or a long-term response (Fig. 1a), e.g., long-term river adjustment to climate change or river damming (Fig. 1b). The intensity of the forcing or the river response is represented by the velocity at which the belt runs. Different forcings may push the river towards different states, represented by alternating movements of the belts. Over time, the direction of movement may even change, for example, under varying climate forcing. As belts may shift in opposite directions, the final lateral movement of the system state, being positioned on the top layer, depends thus on a combined and dynamic evolution of the system (Fig. 1c). Thus, this perspective is more dynamic and complex than a simple “inheritance” view, which suggests a static “base” status as the initial condition for the subsequent stage in river evolution. In addition, it is more dynamic and less “tidy” than the symmetrical goal often pursued by government agencies (Fig. 1d). Such a static approach neglects that multiple forcings act over different time scales while delayed responses of the fluvial system results in a “stacked inheritance” of *changes*, and not solely *states*.

This interpretation of a floodplain geomorphic palimpsest acknowledges therefore that management and human activities are continuously being overlaid upon an adjusting fluvial system to various past forcings. Although the human-associated forcings (land use change, past engineering) had their intrinsic aims (e.g., agriculture, collecting water for irrigation), many—or even most—impacts on the fluvial system were unintended. For example, the Bronze Age people who cleared forest in the upper Rhine basin for agriculture certainly did not intend to cause accelerated sediment deposition in the Rhine delta (cf. Middelkoop et al. 2010), neither did the reservoir builders aim at drowning a downstream delta. It is only the top belt, representing restoration management that aims at dragging the river towards a desired state, and often less than a pristine state. The concept of the management palimpsest can be imagined by means of floodplains, for example, along a river in a subsiding basin that has changed to a meandering style after the last glacial, and where its ongoing overbank deposition is interrupted due to embankment. Renewed channel–overbank interactions will occur after dike removal, but future deposition amounts still depend on the river's sediment load and accommodation space associated with climate and tectonics, respectively. Thus, any approach to river management is engaged with a physical system that has already undergone prior attempts at management.

The impacts of historic human activities and management approaches on the fluvial system vary according to scale and magnitude. But each discrete form of management that influences actual geomorphic processes requires certain timescales to unfold, which is spatially dependent (see chapter "Impact Scales of Fluvial Response to Management Along the Sacramento River, California, USA: Transience Versus Persistence"). In addition, while each management action may have a specific life-span, such as in the case of a meander bend cutoff or groyne construction, its legacy remains physically part of the river and floodplain environment in which subsequent management must engage. Excellent examples are provided by the extensive documented management chronologies of the Mississippi and Rhine Rivers (Hudson et al. 2008), which include specific impacts which are common to many managed river systems across North America and Europe.

2 The Role of Geomorphology

The 12 diverse case studies provided in the preceding chapters provide evidence of the above described palimpsest in river management and demonstrate four key stages in which geomorphology plays a vital role in the design of effective river management strategies to account for this palimpsest. These include, (1) regional and longer-term context, (2) system evolution and impacts of past human actions, (3) design of engineering structures and management options, and (4) environmental restoration as an end-product.

2.1 Regional and Longer-Term Past Context

The regional context provides background information on the past evolution of the system represented by the bottom belts (tectonics, climate, land use) in Fig. 1, which cannot be obtained from direct instrumentation, and which may require long timescales to detect. A prime example includes subsidence and neotectonic controls, which slowly induce shallow warping of floodplain surfaces. Such influences result in small amounts of incremental change over short (e.g., annual) time-scales, but result in significant changes to the floodplain topography and drainage (e.g., Guccione et al. 2002) over long time-scales. The importance of this is appreciated along the Red River of Manitoba (see chapter "Flooding, Structural Flood Control Measures, and Recent Geomorphic Research Along the Red River, Manitoba, Canada"), where subsidence of Pleistocene deposits influences the modern river valley gradient associated

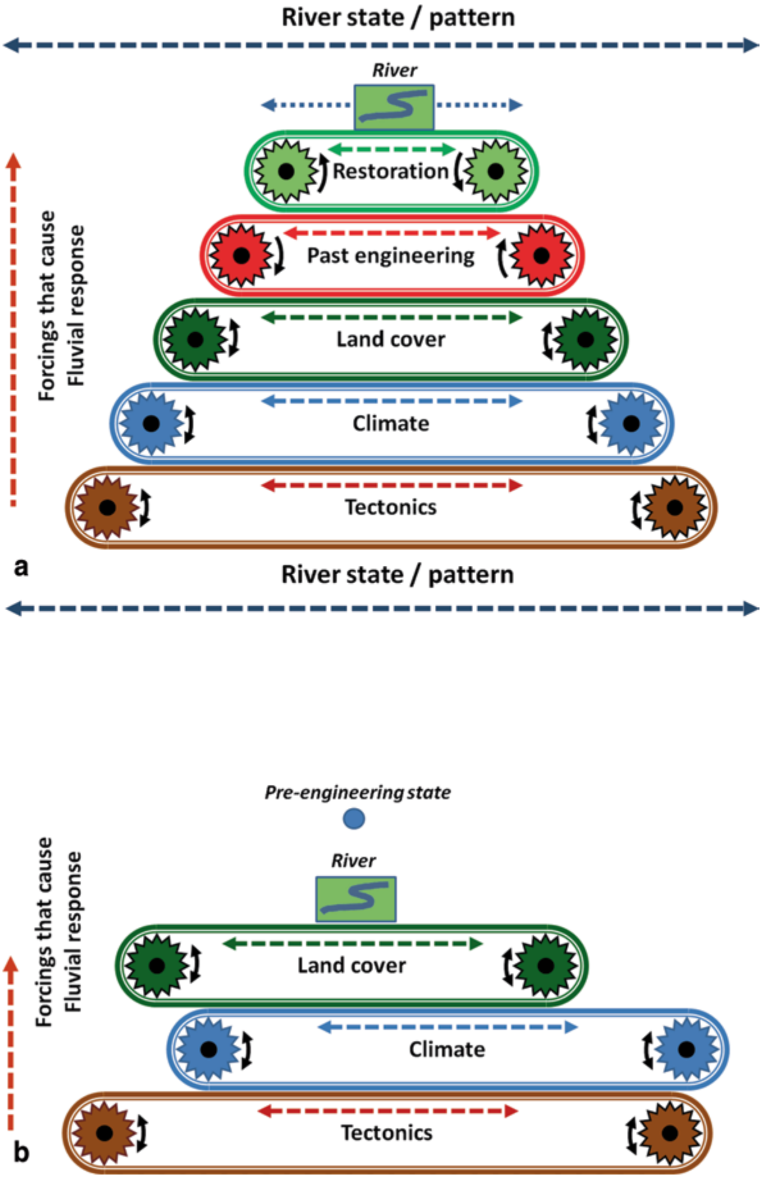

Fig. 1 **a** The palimpsest of river-floodplain management, represented as a stack of conveyor belts, each representing a different type of forcing and fluvial response, driving the river across different states, **b** Underlying belts represent natural (*often slowly proceeding*) forces and responses, **c** Past engineering may have caused a significant—still progressive-state disturbance, **d** River restoration is the top belt to move the river towards a desired state—while the underlying belts remain to turn

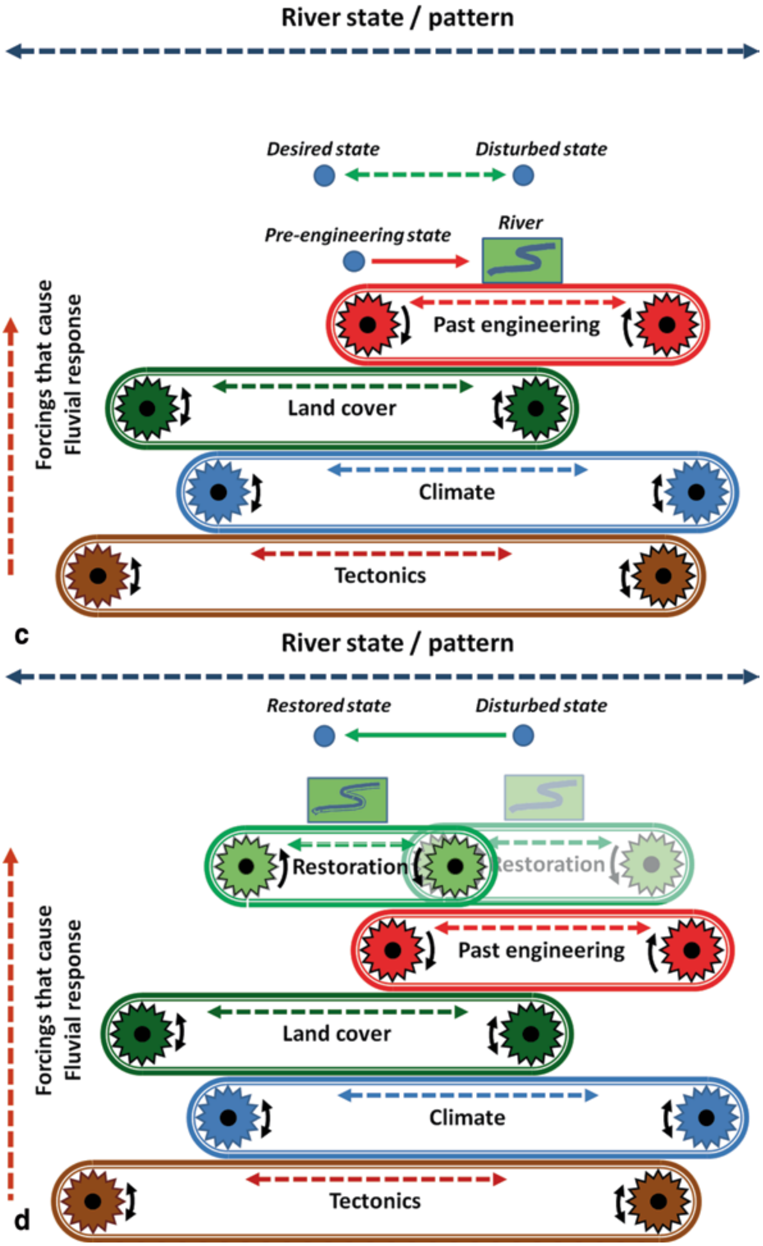

Fig. 1 (continued)

with the high flood frequency. Likewise, restoration plans for the Rhône River should consider the fact that the valley has been greatly influenced by climate and land cover change since the last deglaciation, affecting discharge and sediment load, and driving the river to create its fluvial landscape that later became occupied and modified by humans (see chapter "Historical Development and Integrated Management of the Rhône River Floodplain Between the Alps and the Camargue Delta, France").

2.2 System Responses to Prior Human Activities and Management

It is well established that many river basins in Europe and North America are heavily impacted by historic human activities. Although European basins have been significantly impacted by humans for a much longer period of time, there is also a longer record available to reconstruct the impacts of human disturbances and management. If restoration measures are to have an opportunity to be successful underlying natural dynamics and sensitivity of the various modes of the fluvial system must be understood (e.g., Schumm 1991). A key issue requires an assessment of the impacts of past human activities to the contemporary system (see chapter "Historical Development and Integrated Management of the Rhône River Floodplain Between the Alps and the Camargue Delta, France"). As much as possible, the goal should be to specifically address what was the impact of engineering and management to specific modes of the fluvial system, including sediment, discharge, channel dynamics, and floodplain adjustment (e.g., see chapter "Impact Scales of Fluvial Response to Management Along the Sacramento River, California, USA: Transience Versus Persistence").

2.2.1 Sediment

Changes in sediment load are a dominant control of river response, since the sediment forms the river's building material for morphologic adjustment (Church 2006; Gomez 2006; Knighton 1998; Meade and Moody 2010). Therefore, any plan at integrated river management must consider the sediment regime, and bed material load in particular (see chapter "Sand and Gravel on the Move: Human Impact on Bed-Material Load Transport in the Lower Rhine River"). Yet, sediment discharge in rivers adapting to changed boundary conditions or human impact may show considerable changes when compared to an equilibrium, unaffected situation. Accordingly, channel modifications have profound and long-term impacts on sediment transport and deposition.

Human impacts to sediment load and linkages with channel change are observed where main-stem dams have been imposed on the channel. Although the role of downstream sediment starvation has been widely recognized (e.g., Syvitski et al. 2005), the awareness of this upstream–downstream relation remains crucial for the development of a comprehensive understanding of the downstream impact of dams on alluvial rivers (Graf 2006). Reservoir trapping not only reduces sediment fluxes to drowning deltas, but also may result in a reduction in the size of channel bars and still progressive channel-bed incision, such as demonstrated for the Lower Volga (see chapter "Post-Damming Changes in Channel Morphology and Floodplain Inundation of the Lower Volga River") and the heavily dammed and engineered Ebro River in Spain (see chapter "Channel Responses to Global Change and Local Impacts: Perspectives and Tools for Floodplain Management (Ebro River and Tributaries, NE Spain)")).

The lower Rhine River provides an ideal case study because of the rich data set of sedimentary measurements, as well as the extensive documentation of the timing and dimensions of specific types of engineering impacts (Nienhuis 2008), common to many intensively modified rivers. Past engineering of the Rhine River (Kalweit 1993) has not only changed the volume of bed load transported by the river, but also the style of sediment transport changed, and the particle size has become coarser (see chapter "Sand and Gravel on the Move: Human Impact on Bed-Material Load Transport in the Lower Rhine River").

The linkage between changing sediment load and fluvial adjustment should not be overly simplified. In nearly all cases, river impoundments which result in changes in sediment load frequently concur with other human impacts being imposed on the system, such as land-use change, channel engineering, and flood control. Thus, while it may be straight forward to understand the direct impact of dams to sediment load and channel morphology immediately downstream of a dam ("locally"), it remains much more challenging to untangle cause and effect relationships between sediment load, altered discharge regime, and fluvial adjustment with increasing distance and fluvial complexity (see chapter "Impact Scales of Fluvial Response to Management Along the Sacramento River, California, USA: Transience Versus Persistence").

2.2.2 Channel Changes

Other than large main-stem dams, channel straightening and engineering for the sake of flood control and ship navigation is a direct human impact imposed on rivers (Gregory 2006). Such changes to channel morphology and hydraulics have the potential to influence channel incision, sediment transport, alluvial aquifers, floodplain processes, and to adversely impact a host of aquatic ecological processes. Direct channel engineering, often involving cut-offs and channel straightening, was a preferred method of flood control from the late-nineteenth to middle-twentieth centuries in North America. The Kissimmee River in subtropical Florida, for example, underwent extensive draining and straightening (see chapter "Geomorphic Perspectives of Managing, Modifying and Restoring a River with Prolonged Flooding: Kissimmee River, Florida, USA") since the 1880s, and artificial meander cut-offs in the 1930s. Further flow structures in the 1960s virtually canalized and radically changed the hydraulic geometry of this once unique meandering river floodplain system.

Examining channel changes over long-time periods reveals not only changes in channel pattern, but also their linkage to specific types of floodplain environments (e.g., see chapter "Historical Development and Integrated Management of the Rhône River Floodplain Between the Alps and the Camargue Delta, France"; see chapter "Fluvial Geomorphology: Its role in Policy and Management Decisions on the Mississippi River Floodplain"). This is increasingly important because the emphasis on river and floodplain restoration frequently assumes a natural base-line for establishing restoration and management goals (Walter and Merritts 2008). In this context the Rhône River represents an ideal example because of the well-documented legacy of human impacts and recorded changes in channel morphology. In contrast to prior ideas, Bravard and Guyout (see chapter "Historical Development and Integrated Management of the Rhône River Floodplain Between the Alps and the Camargue Delta, France") illustrates how the natural channel of the Rhône had a braided pattern over much of its length since about the mid-Holocene. While the channel pattern adjusted to alternating sediment and discharge regime, the meandering pattern that currently dominates the Rhône River should be seen as an artificial legacy of river engineering, as it primarily developed since about the mid-1800s following engineering works to reduce erosion and create a navigable channel.

2.2.3 Floodplains

The alterations of floodplains associated with embankment frequently results in an overall disconnection of natural channel-floodplain interactions, often causing degradation of physical aquatic habitats. In combination with upstream damming and channel modifications, impacts may become more severe. River incision, whether caused by upstream dams and sediment starvation or by meander cut-offs and channel straightening, fundamentally alters floodplain hydrology. Most commonly this is manifest as a reduction in the frequency and duration of floodplain inundation, which has important consequences to riparian ecosystems. For example, while the natural flood regime of the Kissimmee River was annually associated with several months of overbank inundation, the impacts of engineering abruptly reduced the flood pulse frequency and duration, which had subsequent profound consequences to aquatic ecosystems associated with the extensive floodplain wetlands (see chapter "Geomorphic Perspectives of Managing, Modifying and Restoring a River with Prolonged Flooding: Kissimmee River, Florida, USA"). The lower Danube provides an interesting perspective (see chapter "Embanking the Lower Danube: From Natural to Engineered Floodplains and Back"), as it has undergone a reduction in sediment supply and a reduction in floodplain inundation because of large mainstem dams, floodplain embankment and other structural flood-control measures. In addition to adverse impacts to the floodplain habitat, the reduction of the flood pulse has consequences to the floodplain biogeochemistry, as illustrated by the example of the Lower Mississippi River (see chapter "Managing the Mississippi River Floodplain: Achieving Ecological Benefits Requires More than Hydrological Connection to the River"), where reduced exchange between the channel and floodplain has strongly impacted floodplain fisheries.

2.3 Design and Calibration of Management Options

Prior engineering pushed rivers into a disturbed state (Fig. 1c) while river restoration aims at bringing the system back towards a desired—more natural—state. In terms of the conveyor belt model, this requires adding a top belt that turns the river towards that new state (Fig. 1d). The model of turning belts remains valid because the underlying belts may continue to move. Additionally, the top restoration belt means that the new restoration measures will not result in a static future condition. In this scenario the river will continue to adjust over time. Thus, restoration plans should be aware of the continued movement of the underlying belts as well as that their measures will have an effect as represented by a new belt. Geomorphologists and ecologists are well aware that intricate and comprehensive knowledge of active geomorphic processes is essential not only for the proper design and operation of engineering structures, but also for planning a range of management options. Channel engineering operations, such as dredging, groyne placement, and bank protection (revetment) measures require knowledge of the interrelations between channel hydraulics and sediment transport, especially bed material (Gomez 2006). Similarly, the opening of flow diversion structures to reduce flood risk or to manage floodplain wetlands requires an understanding of suspended sediment dynamics, in addition to complex flood basin hydraulics and floodplain sedimentology (e.g., Nittrauer et al. 2012). Moreover, when adopting more recently proposed approaches of "building with nature" as advocated in the Netherlands (e.g., De Vriend et al. 2014), a thorough knowledge of processes and requisite skills in predicting the impacts of measures that promote natural processes is indispensable to effective floodplain restoration.

Sediment management should be a key issue in considering the design and restoration of rivers for sustainability, from the perspective of economic activities and nature. For the purpose of reducing the downstream impact of dams, a measure gaining in use is the downstream flushing of sediment trapped within reservoirs. The procedure is complex to implement, depending largely upon the configuration and morphology of the river valley, sediment type, as well as the dam and reservoir operation and design (Asaeda et al. 2014). Experiences along the Rhône River, for example, have been somewhat effective at reducing the impact of hungry water. Experiences along the Colorado River (Arizona), were introduced in the mid-1990s, and while less effective at restoration, are seen as a necessary component of the management schema. From the standpoint of managing the lower Rhine bed material load, although dredging is necessary in some reaches, other reaches require that bed sediment be moved by ships and dumped into river reaches undergoing incision. This "surgical" system of sediment management is feasible in a river such as the Rhine, as well as a number of intensively utilized rivers in North America and Europe, but is impractical for rivers that do not serve such an important economic function.

Although considerable attention is currently being paid to "soft" engineering approaches, hard engineering structures continue to have an important role in the management of embanked river systems, especially as regards flood risk reduction, or to serve as "hard" boundary conditions for "soft" restoration measures. Flow diversion structures which route flood waters beyond the embanked floodplain, for example, remain an essential component of managing flood risk in North America. For the Red River of Manitoba (see chapter "Flooding, Structural Flood Control Measures, and Recent Geomorphic Research Along the Red River, Manitoba, Canada"), structures were engineered to establish a flow diversion system to bypass urban areas. Research by Singer (see chapter "Impact Scales of Fluvial Response to Management Along the Sacramento River, California, USA: Transience Versus Persistence") considers how the opening of such structures locally influences sediment transport and channel adjustment along the Sacramento River, as well as overbank sedimentation. Along the lower Mississippi River, a fundamental component of the flood management plan includes flow diversion structures activated at specific discharge (stage) magnitudes, and these structures are also being utilized for the restoration of adjacent wetlands (Nittrouer et al. 2012). The placement and operation of flow diversion structures, however, should take into account reach-scale variation in hydraulics and sediment transport processes, because ultimately this influences the quantity and grain size of overbank sedimentation. This is observed for the Bonnet Carre flow diversion structure along the Lower-most Mississippi, which results in sand deposits that approximates sedimentation of former natural crevasse processes (see chapter "Fluvial Geomorphology: Its role in Policy and Management Decisions on the Mississippi River Floodplain").

2.4 Ecosystem Restoration and Geomorphology as an End-Product

The above examples serve to reinforce the position that in addition to natural forcings humans have imposed a multitude of actions that have impacted—and degraded—fluvial systems, by their sediment load, discharge regime, channels, and floodplains. The result of these modifications—many of which are imposed by the old "hard engineering" approaches—are fluvial systems that are very different from natural systems, but yet represent the status quo for environmental managers. While every river is different, it is the case that a number of these modifications have resulted in rather *signature* impacts, such that they suggest certain measures for management and restoration. It is therefore informative to consider those measures which have been successful, and to consider their potential for having a larger role in integrated management and restoration.

The concept of integrated river management is often depicted as a world in which rivers are free to erode, migrate, and flood. As integrated river management becomes an increasingly entrenched paradigm, even in North America, what is the role of classical hard engineering measures? Clearly many fluvial systems are simply unable to return to a natural status, as the space is not available and the upstream boundary conditions have been drastically altered by land use change and impoundments. In such cases classical hard engineering approaches remain important, at least to create an opportunity to locally "re-activate" fluvial processes. In this case flow diversion structures can also serve an important function of reconnecting floodplains with sediment and nutrient rich flood waters, such as along the lower Sacramento River basin of California (see chapters “Promoting Atmospheric-River and Snowmelt Fueled Biogeomorphic Processes by Restoring River-Floodplain Connectivity in California’s Central Valley” and “Impact Scales of Fluvial Response to Management Along the Sacramento River, California, USA: Transience Versus Persistence”).

Although the engineered diversion structures provide some measure of connectivity with the original floodplain, their limited extent and hydraulic conditions make them less likely to restore floodplain wetlands. An alternative approach may be intentional levee breaks for lower magnitude events, such as are occurring along the lower Sacramento Riverbasin (see chapter “Promoting Atmospheric-River and Snowmelt Fueled Biogeomorphic Processes by Restoring River-Floodplain Connectivity in California’s Central Valley”). These structures closely mimic natural crevasse events in scale and function, and provide important topographic, sedimentologic, and hydrologic (i.e., as crevasse splays) variability along the floodplain, which is preferred for enhancing biodiversity. The Kissimmee River's extensive and expensive restoration project has become an important case study of US river restoration and integrated management (see chapter “Geomorphic Perspectives of Managing, Modifying and Restoring a River with Prolonged Flooding: Kissimmee River, Florida, USA”). A hallmark of the project is to reactivate the old meander bends which had been cutoff when the river was canalized, and to set the levees (dikes) back to encourage a broader zone of inundation. Early results are promising, as sedimentologic and hydrologic data suggest reconnected cutoffs are functioning as natural channels, and ecosystem services have been enhanced.

Management and restoration of large embanked floodplains is ultimately coordinated and implemented by government agencies. Among the most controversial actions associated with integrated floodplain management is the use and acquisition of floodplain lands and associated water bodies by government entities for the purpose of floodplain inundation and nature restoration. The process of land acquisition is expensive, and legally complex. Some management and restoration options require a specific knowledge of property ownership, whereby determination of ownership legally depends upon an understanding of the origin of a floodplain water body (see chapter “Fluvial Geomorphology: Its role in Policy and Management Decisions on the Mississippi River Floodplain”). The potential for floodplain management to actually be implemented then becomes dependent upon the appropriate legal interpretation of the formative processes of floodplain water-body construction. For this reason, a new form of management is being proposed for floodplain restoration in the Netherlands (floodplain stewardship council; Fliervoet et al. 2013), which would replace the presently responsible parties including water boards and government institutes at national, provincial and municipal levels. Conversely, when the river-floodplain system is allowed to be morphologically active and changing, legislation should accommodate regulation of ownership and maintenance obligations of newly formed features, such as channel bars, secondary channels, and floodplain lakes. This is not a new issue: Along the lower Rhine in the Netherlands there were established legislative criteria already in the seventeenth and eighteenth century to decide whether or not a newly formed channel bar would belong and become possession of the owner of the adjacent floodplain. The law stated that the adjacent floodplain land owner would gain legal possession only if the separating channel was too shallow to allow passage of a boat of specified dimensions (Hesselink 2001). Nevertheless, to allow creating and maintaining a more dynamic environment in the future, legislation should be coordinated with geomorphic processes and concepts (e.g., see chapter "Fluvial Geomorphology: Its role in Policy and Management Decisions on the Mississippi River Floodplain").

3 Contrasting Continental Visions to Managing Rivers for Climate Change?

The case studies provided by this volume represent a continental perspective to consider different approaches to river and floodplain management and restoration, and for being prepared to cope with various climate change scenarios. Management along large alluvial rivers in Europe and North America contrasts sharply in its management vision. In terms of the implementation of strategies that are prepared to cope with climate change, the U.S. is in its infancy. A reliance on hard engineering approaches and the political difficulty (especially along rivers in some states) to incorporate alternative approaches, such as increasing the area of the embanked floodplain, makes a "room for the river" plan exceedingly difficult to implement (U.S. Army Corps of Engineers 2012). In comparison to Europe, the North American approach to floodplain management is more fragmented (National Research Council 1995, 2005), and less flexible to adapt to varying climate change scenarios. This is not to state that environmental river management does not have its success stories in the U.S, as there are many discreet cases of effective management which enhances river environments. The example of the Kissimmee River in Florida (see chapter "Geomorphic Perspectives of Managing, Modifying and Restoring a River with Prolonged Flooding: Kissimmee River, Florida, USA"), should certainly be upheld. Additionally, the science of dam removal has accelerated greatly over the past decade, and is being led by government agencies. These sucesses are in part because of greater attention to the dependence and interconnectedness of ecological river habitat to the geomorphic dimensions of rivers, as championed by Graf (2005, 2006) in regards to the "physical integrity" of rivers. Many large river basins in the U.S., however, lack a basin-scale perspective for coping with projected regional climate change scenarios. The enormous lower Mississippi, for example, has yet to have a specific approach for coping with climate change, although major tributary basins, including the Ohio, Missouri, and upper Mississippi River have conducted studies and initiated pilot studies (see chapter "The Role of Floodplain Restoration in Mitigating Flood Risk, Lower Missouri River, USA").

In contrast to North America, Europe in the 1990s underwent a significant paradigm shift in its vision for river and flood management (e.g., Kondolf 2012), away from a primary reliance on traditional "hard" engineering for flood control, towards “integrated flood management” with “soft” landscaping measures for nature restoration. While these measures were not necessarily implemented to cope with specific climate change projections, they included two important tenets. First, they approached river management from a basin-scale perspective, and, secondly, they viewed management for nature as being complementary with preparation for climate change. The approach to flood and environmental river management in Europe was solidified in two major continental-scale legislative acts passed by the European Union, namely the Water Framework Directive (2000) and the Floods Directive (2007/60/EC). Although implementation of the directives has not been uniform across the EU, and in particular some Eastern European nations (e.g., the Polish situation), it can be stated that the EU shares (mainly) a common vision, and has a “general” goal in mind as regards river management. Within the Rhine basin in Germany and the Netherlands, for example, substantial modifications have been made to embanked floodplains and river channels which required soft and hard (e.g., structural) approaches for the purpose of accommodating larger flood magnitudes and nature enhancement, which also is seen as preparing the fluvial system to better cope with climate change. Still, such management actions are expensive and complex to implement, requiring a geomorphologic assessment to provide a context for interpreting changes in rates and magnitude of channel adjustment, such as river migration, and ultimately to apply the appropriate model of restoration.

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