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Flood management along the Lower Mississippi and Rhine Rivers (The Netherlands) and the continuum of geomorphic adjustment

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ABSTRACT

Flood management alters fundamental fluvial processes that have geomorphic consequences for rivers and floodplains. The Lower Mississippi and Rhine Rivers (The Netherlands) are two important examples of intensively regulated large rivers. Understanding the magnitude and direction of change caused by flood management requires a long-term perspective. This is particularly true of large lowland fluvial systems because of substantial lag-times required for adjustment to be manifest in the floodplain geomorphology. This study is a historical analysis and synthesis of the impacts of flood management on the Lower Mississippi and Rhine Rivers (The Netherlands), and investigates the interrelations of flood management with floodplain geomorphology.

Although flood management varies between the Rhine and Mississippi on many accounts, the actual techniques of flood (and river) management are somewhat similar, and primarily include dikes, groynes, cutoffs, and bank protection. The implementation and history of these specific types of activities, however, varies considerably. Historical flood management along the Lower Mississippi can be characterized as abrupt, with the major options imposed within about five decades, while historical flood management along the Rhine River in The Netherlands is characterized as incremental and adaptive, with the major options imposed over about eight centuries. Conversely, modern flood management plans are implemented much more promptly along the Dutch Rhine than the Lower Mississippi.

Changes to the Lower Mississippi include channel adjustment (width and incision) caused by meander bend cutoffs. The majority of the knickpoint incision in response to cutoffs occurred by 1963. Channel adjustment in some reaches is likely constrained by the presence of resistant alluvium and lithology. Floodplain geomorphic changes include the creation of new oxbow lakes within an embanked floodplain. Embanked floodplain sedimentation of oxbow lakes created from the 1928 Mississippi River & Tributaries Act have rapidly infilled, with 67% of the lake area converted to wetlands. In comparison, older oxbow lakes located outside of the embanked floodplain have undergone much lower amounts of infilling, averaging 37% of oxbow lake area converted to wetlands. The floodplain geomorphology is further modified by numerous large floodplain borrow pits and the selective removal of fine-grained deposits, primarily created for dike (levee) construction and maintenance.

The Dutch Rhine has been managed for flooding for over eight centuries and exhibits specific types of humanized embanked floodplain geomorphology that require a greater period of adjustment. Dike breaches create ponds (wielen) and sandy splay-like deposits, which represent distinctive anthro-geomorphic environments along the margins of embanked floodplains. Channel stabilization by groynes and dikes has resulted in the formation of new floodplains along Rhine distributaries. The trapping of flood sediments within the embanked floodplain has resulted in aggradation that has reduced the inundation capacity of the embanked floodplain. This geomorphic alteration reduced the effectiveness of the existing flood management infrastructure and has stimulated a change towards a new flood management approach designed to "work with the river".

The major conclusions are placed within a conceptual model, and illustrate that; 1. in many instances specific flood management options were constrained by the type of floodplain deposit; 2. geomorphic adjustment to flood management occurs along a time–space continuum; 3. flood management initiates positive feedbacks with unintended geomorphic consequences that require further management options to minimize flood risk.

1. Introduction

Fluvial systems consist of discreet spatial features ranging from the scale of the drainage basin to individual bedforms (Schumm, 1977). Each component of the fluvial system adjusts over different time-scales, and in general smaller features adjust more quickly than larger

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features (Schumm, 1991; Knighton, 1998). Humans alter fundamental hydrologic and sedimentary processes that control fluvial systems, commonly through the framework of river and flood management. Such actions intentionally modify specific components of the fluvial system, which can trigger unintended geomorphic response (Gregory, 2006). Gaining a comprehensive understanding of the magnitude, direction, and time-scales of change for human imposed geomorphic adjustments can only be attained through a historical perspective. This is particularly true of large lowland fluvial systems because of the long lag-times required for adjustment to be manifest in the floodplain geomorphology (Schumm and Winkley, 1994).

The Lower Mississippi (Fig. 1-A) and Rhine Rivers (Fig. 1-B) are two of the most intensively regulated and studied large rivers in the world. The development of the modern humanly altered geomorphic regime has involved considerable innovation and experimentation with different engineering procedures (Elliot, 1932; Ferguson, 1940; Van Veen, 1962;

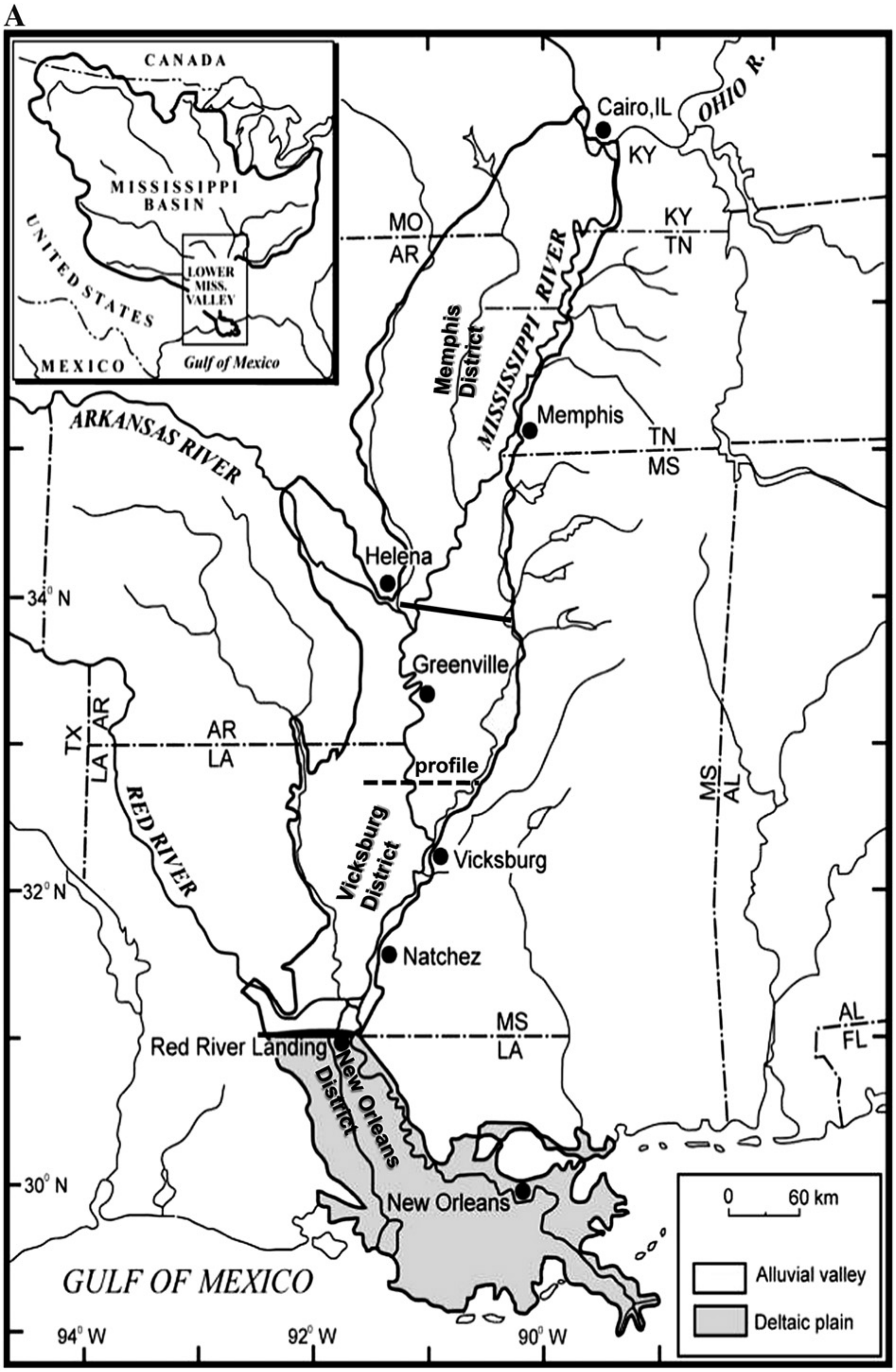


Fig. 1. A. The Lower Mississippi Valley and delta. The border between the alluvial valley and deltaic plain occurs at about Red River Landing. The dashed line indicates the location of a valley profile (cross-section) in Fig. 2. Urban locations are referenced in subsequent figures by the distance along the river as kilometers below Cairo, IL (KM/B/C), or kilometers above Head of Passes, Louisiana (KM/A/HOP) at the river mouth. The solid black lines demarcate management divisions of the US Army Corps of Engineers. B. The Rhine–Meuse Rivers in the Netherlands. The dashed line indicates the location of a valley profile (cross-section) in Fig. 5.

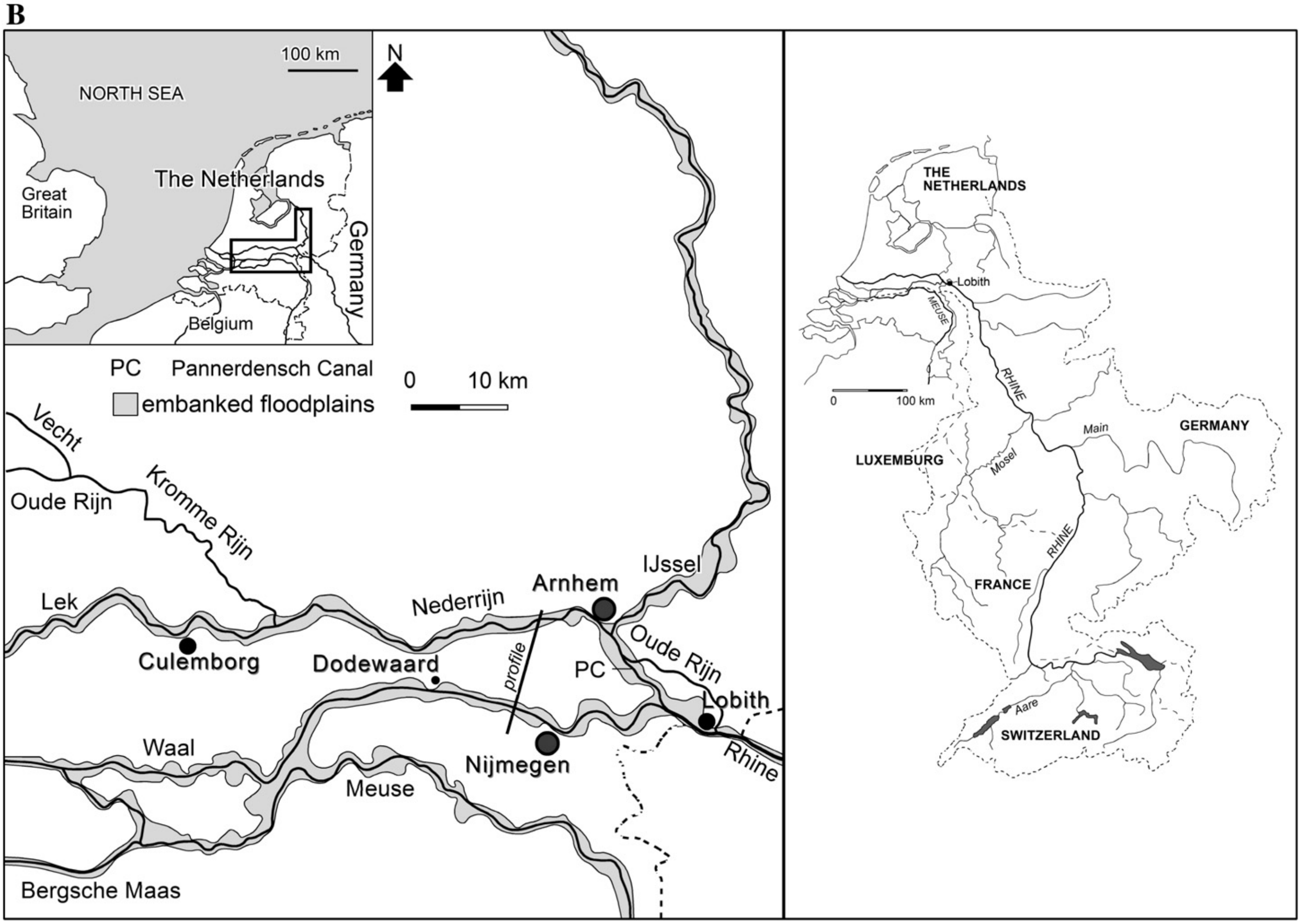


Fig. 1 (*continued*).

Winkley, 1977; Van de Ven, 1993; Winkley, 1994; Smith and Winkley, 1996; Te Brake, 2002; De Bruin, 2006), with each river serving as a model for the diffusion of flood management concepts to other fluvial systems. Differences in management history and geomorphology between these two systems represent excellent opportunities to examine the sequence of geomorphic change that occurs in response to flood management over varying time-scales.

This study examines the interrelations between floodplain geomorphology and flood management for the Lower Mississippi and Rhine Rivers (The Netherlands). Research concerning the effectiveness and impact of flood management are dominated by studies that primarily consider hydrologic and hydraulic processes over short time-scales. Such approaches often do not consider longer term environmental change that is occurring naturally within the system (e.g., Törnqvist et al., 2008), or the longer term consequences of flood management to the floodplain geomorphology (Middelkoop, 1997; Hesselink, 2002). This issue is increasingly seen as vital, and in having broader societal importance, because of the greater concern over climate change and flooding (IPCC, 2007; Kundzewicz et al., 2007). Additionally, the 2005 flooding of the US Gulf Coast and New Orleans associated with Hurricane Katrina and Rita storm surge has resulted in a greater public awareness of fundamental linkages between flood management and geomorphology (New York Times, May 7, 2007). Fluvial geomorphology has a substantial legacy of scientific enquiry regarding floodplain processes over time-scales relevant to understanding such issues, and as such, is well poised to make important contributions to this topic that are relevant to broader societal interests.

Flood management for large lowland rivers requires a number of distinct engineering activities and infrastructure that results in substantial channel and floodplain modification, commonly resulting in a straighter channel within a narrower embanked (diked) floodplain. In addition to dike (levee) construction, other modifications to manage flooding include channel straightening, drainage ditches, and the creation of flood bypass corridors (Elliot, 1932; Ferguson, 1940; Van Veen, 1962; Van de Ven, 1993; Smith and Winkley, 1996). Successful application of these technologies to large river systems is highly dependent upon the floodplain geomorphology, because of the interaction between alluvial channels and floodplain deposits and the hydrological importance of the floodplain sedimentology (Fisk, 1947; Mansur et al., 1956; Krinitzsky and Wire, 1964; Winkley, 1977; US-ACE, 1998a,b,c; Dunbar et al., 1999; US-ACE, 2000; Li et al., 2003; ASCE, 2007). Moreover, the flood management infrastructure and channel modifications fundamentally alter hydrologic and sedimentary processes within the embanked floodplain (Middelkoop and Van Haselen, 1999; Silva et al., 2001). This potentially results in changes to future floodplain processes, thereby influencing flood management over longer time-scales (Middelkoop, 1997; Hesselink et al., 2003). Dams are also fundamental to flood management and have significant geomorphic impacts on fluvial systems (e.g., Keown et al., 1986; Meade et al., 1990; Graf, 2006), but are not located along the lower reaches of the Rhine or Mississippi and therefore are not considered in this study.

Large river floodplains serve as a framework for various human activities (e.g., agriculture and settlement) but are too often considered as stable landforms. Over the time-scale in which government agencies conceive, design, and eventually evaluate flood management (with actual events), however, this misconception can have serious consequences. The lower reaches of large river floodplains are complex and dynamic entities influenced by autogenic and allogenic controls (Stouthamer and Berendsen, 2007). Allogenic controls include climate, sea level, neotectonics, and ground subsidence. Autogenic controls occur as "natural" geomorphic change and represent fundamental processes by which floodplains evolve through river migration, erosion and sedimentation, and channel avulsion. Over time-scales spanning more than a few decades, and certainly within a century, such controls can potentially greatly influence the geomorphic setting and processes in which flood management is implemented, requiring substantial adaptation of infrastructure to a changing environment (groundwater, channel change, sedimentation…). Because human settlement quickly follows flood management infrastructure (White, 1945; Pinter, 2005), modifying such infrastructure typically involves very expensive and highly controversial solutions. Understanding autogenic and allogenic controls on fluvial systems can assist with future flood management planning, and by answering questions regarding the motivation and rationale for the implementation of specific historic (and prehistoric) types of flood management options, such as dike heightening and relocation, river bank stability, and drainage channels.

Decades of data collection by government agencies and researchers for geomorphic, hydrologic, and environmental study in the US and The Netherlands have produced numerous data sets appropriate for examining fundamental issues in flood management over different time periods. To this end, in recent years interest has increased in developing comparisons between the Rhine and Lower Mississippi Rivers. Considerable research has examined specific aspects of these two systems, such as human impacts to hydrology (Pinter et al., 2006a b), flood management (De Bruin, 2006; Törnqvist, 2007), and floodplain geomorphology (Gouw, 2007). The differences between the two systems must be acknowledged, however, and principally occurs as differences in size and in the history of human influence and its impact on the fluvial environment. The two systems also vary in terms of how management has evolved, and in the adaptation of flood management following large floods. The increased attention to flood management does not always distinguish between flooding driven by upper basin controls and coastal storm surge flooding, such as occurred along the Rhine delta in 1953 and in New Orleans from Hurricane Katrina–Rita in 2005. Regardless, comparisons between the Rhine and Mississippi have been made for about a hundred and fifty years (Hewson, 1860; New York Times, October 3, 1890), and since the New Orleans flood disaster, frequent exchange has occurred between The Netherlands and US (e.g., US Congress, 2005). Indeed, delegations of US engineers and policy makers frequently tour the "Delta Works" project in the Netherlands to examine the appropriateness of adapting such strategies to the Lower Mississippi River.

2. Physical setting

2.1. Lower Mississippi

The Mississippi basin drains 3.2×10^6 km^2 of North America, and is the fourth largest drainage system on Earth (Fig. 1-A). The Lower Mississippi River is supplied by a continental-scale catchment, and flows 1535 km (1963 post channel cutoff distance) from Cairo, IL to the Gulf of Mexico, where it discharges through a deltaic distributary network. The average daily discharge for the Lower Mississippi River, above the Atchafalaya River diversion, is 18,400 m^3/s (Mossa, 1996). Discharge, however, varies little in a downstream direction because few large streamflow inputs occur downstream of Cairo, IL at the confluence with the Ohio River. During the period prior to major human impacts, the average annual high water discharge downstream of Cairo, IL (at Columbus, KY gauging station), representing the total inflow at the head of the Lower Valley, was 35,700 m^3/s, while the average high water discharge at Vicksburg was 34,160 m^3/s. At Red River Landing, Mississippi streamflow is diverted into the Atchafalaya distributary, and the average high discharge decreases to 29,120 m^3/s. Discharge characteristics are markedly seasonal, with high flow and floodplain inundation potentially lasting a couple of months during the late winter and spring, and a low flow period during the summer and fall. Based on a 132 year record, from 1799 to 1931, before large reservoirs were constructed in the upper basin and an effective dike system had been constructed on the main-stem, the Lower Mississippi flooded on average every 2.8 years. The largest Mississippi flood of record occurred in 1927 and had a peak discharge of 49,812 m^3/s (Elliot, 1932; Ferguson 1940).

The Lower Mississippi Valley has a complex surface that exhibits considerable lateral and down-valley topographic and sedimentologic variability. From Cairo, Illinois the alluvial valley and deltaic plain extend in a southerly direction more than 780 km to Head of Passes, Louisiana. The Quaternary valley is dominated by Holocene meander belts and backswamp deposits, which become increasingly prevalent towards the southern portions of the alluvial valley (Saucier, 1994; Autin and Aslan, 2001; Gouw, 2007). Valley train and braided channel belts, associated with a more variable Pleistocene glacial meltwater discharge and sediment regime, are prevalent in the northern portions of the study area (Saucier, 1994; Rittenour et al., 2007). Valley widths average 120 km, but range from 40 km near Natchez, MS to 200 km across the Arkansas Lowlands (Fisk, 1944). Valley cross-sections reveal considerable floodplain topography (e.g., Fig. 2) associated with the active meander belt, flood basins, and older Mississippi River channel belts and "yazoo" style tributaries (Gouw, 2007).

Conventionally the Lower Mississippi River is subdivided into a laterally migrating meandering channel within the alluvial valley extending from Cairo, IL to Red River Landing, and a non-meandering channel within the deltaic plain (Fisk, 1944; Schumm et al., 1994; Hudson and Kesel, 2000; Wasklewicz et al., 2004). Floodplain deposits in the alluvial valley are notably heterogeneous (Fig. 3), and the active channel is frequently in contact with coarse or cohesive sediments, most commonly associated with older channel belts or Pleistocene deposits, or infilled cutoffs (clay plugs) and backswamp deposits, and older Tertiary bedrock. The heterogeneity in floodplain deposits is an important consideration in management, such as dike (levee) construction and bank stabilization because it influences channel bank erosion and meander bend migration (Fisk, 1947; Dunbar et al., 1999; Hudson and Kesel, 2000) and groundwater seepage (Mansur et al., 1956; Krinitzsky and Wire, 1964; US-ACE, 1998a,b,c, 2005). Floodplain borings (Fig. 3), adjacent to the active cutbank, represent the bank material subject to the hydraulics of fluvial erosion, and the initial interface with groundwater recharge of the alluvial aquifer during flood pulses.

The Lower Mississippi is influenced by neotectonic controls and older bedrock, which influence channel geometry and warps floodplain and terrace surfaces (Fisk 1944; Saucier, 1994; Schumm et al., 1994; Guccione et al., 2000; Schumm et al., 2000). A longitudinal profile of the Lower Mississippi River meander belt (Hpm1), extending from Cairo to the Gulf of Mexico, reveals considerable topographic variability (Fig. 4). The profile of the meander belt was obtained by sampling the elevation of active point bar surfaces and represents the actual floodplain topography along the meander belt. Previous valley profiles of the Lower Mississippi River were developed from river stage data, which is influenced by downstream hydraulic geometry. Major topographic undulations occur at sedimentary wedges input from major tributaries and uplift zones associated with neotectonic controls, such as the New Madrid (Reel Foot), Monroe and Wiggins Uplifts. These locations are also associated with the location of Tertiary bedrock that likely represents an important control on channel processes (Humphreys and Abbot, 1861; Ferguson, 1940; Burnett and Schumm, 1983; Schumm and Winkley, 1994; Schumm et al., 2000). Subsidence is highly variable across the alluvial valley and

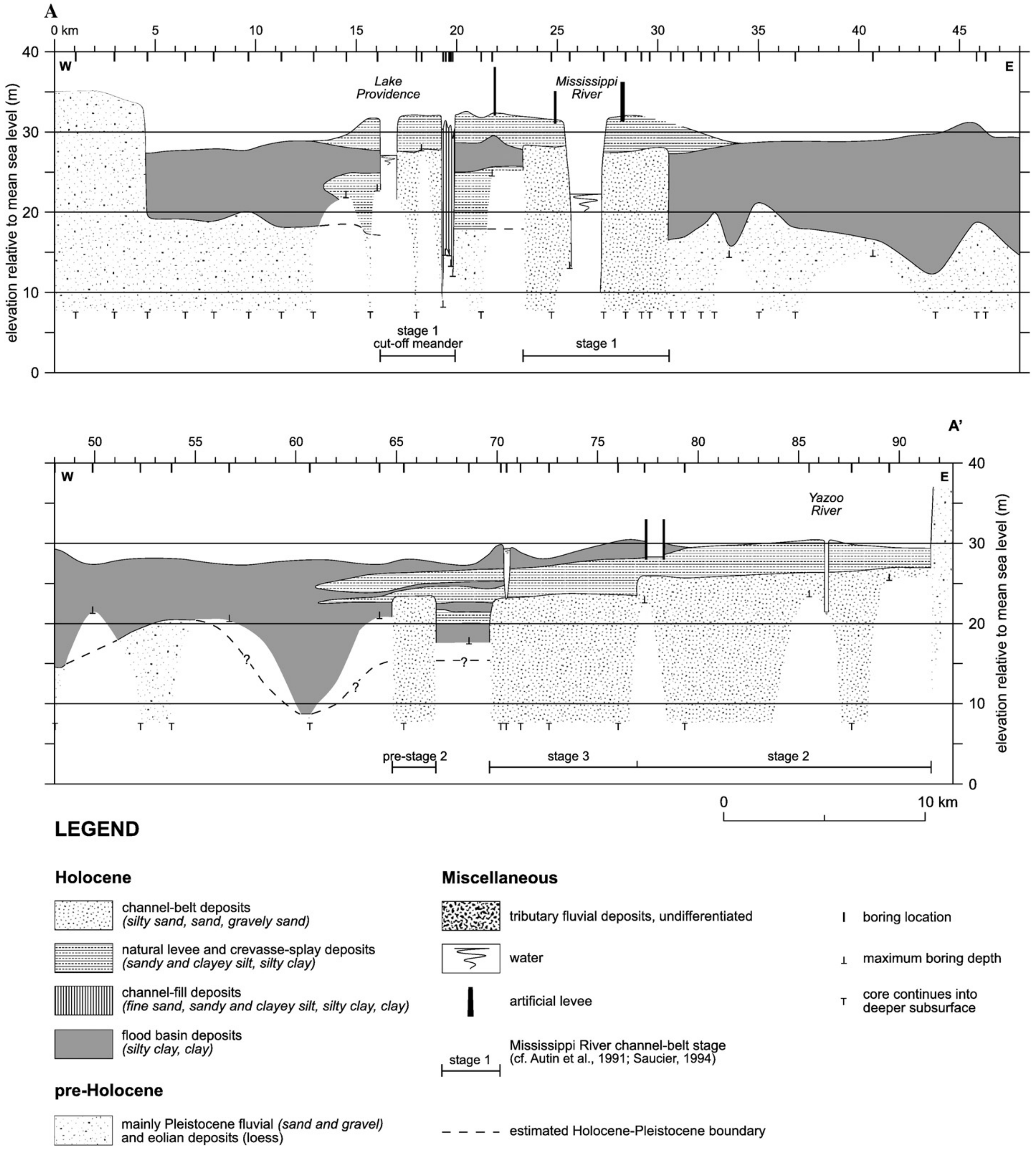


Fig. 2. Cross-section of the Lower Mississippi Valley, just upstream of Vicksburg (see Fig. 1-A). The valley cross-section displays considerable variability in topography and sedimentology associated with varying floodplain environments and the location of older channel belts. Modified from Gouw (2007).

delta, ranging from 3 to 28 mm/yr in the delta (Dixon et al., 2006; Shinkle and Dokka, 2006, Dokka, 2006; Törnqvist et al., 2008) to 3 to 5 mm/yr in the alluvial valley (Shinkle and Dokka, 2006, Dokka, 2006).

Humans have lived along the Mississippi River for millennia (Kidder and Fritz, 1993; Kidder, 1996; Arco et al., 2006; Bettis et al., 2008-this issue; Guccione, 2008-this issue). Extensive and prolonged human occupation occurred along the Mississippi Valley in sites such as Cahokia, the largest prehistoric earthen mound in North America (Holley et al., 1993). Many large prehistoric population centers contributed to extensive floodplain earth works, such as mounds and terraces, and floodplain borrow pits have been documented from

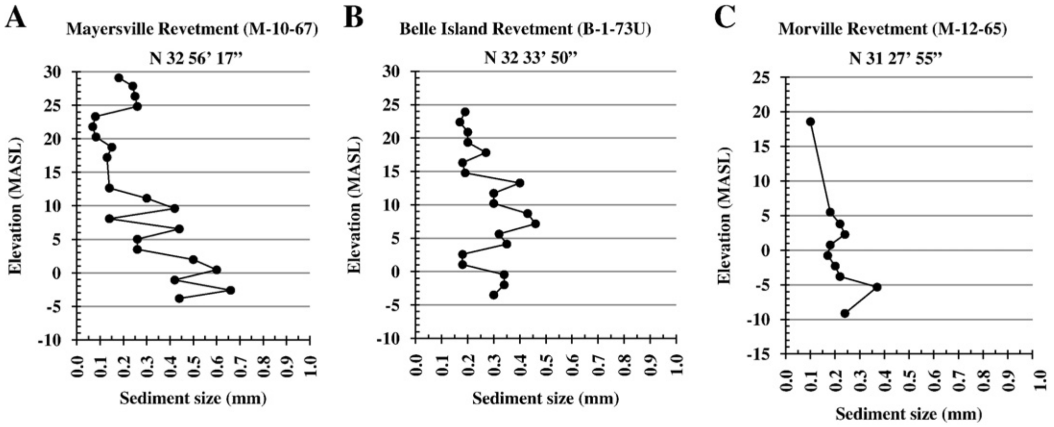


Fig. 3. Sediment size (D_{-50}, median grain size diameter in mm) of cores taken along the channel bank of the Lower Mississippi River. The corings are located within the Vicksburg District, which underwent the most intense changes because of flood management. Unpublished data from the US Army Corps of Engineers — Vicksburg District.

5200 BP (Middle Archaic) in northeastern Louisiana (Arco et al., 2006). But much of the evidence for prehistoric human modification of floodplain processes and forms is under-studied, and is likely buried in overbank deposits (Bettis, 2008-this issue; Guccione, 2008-this issue). European settlement and associated agricultural practices were responsible for considerable land degradation and accelerated sedimentation in the Upper Mississippi basin from the mid-1800s to early 1900s (Knox, 2006), and this sediment was likely making it into the Lower Mississippi River until the 1940s (Hudson and Kesel, 2006).

2.2. Rhine–Meuse

The Rhine and Meuse Rivers drain 221,000 km^2 of Western Europe (Fig. 1-B). With the headwaters in the Swiss Alps, the Rhine has a drainage of 185,000 km^2, receives runoff from six nations, and has an average annual discharge of 2300 m^3/s (Middelkoop and Van Haselen, 1999). The smaller Meuse begins in France, drains 36,000 km^2, and has an average annual discharge of 230 m^3/s. In general, both rivers have the same annual pattern of discharge, with peak events in January. Difference in size and source areas for the two rivers, however, results in Meuse discharge being much more variable. The two rivers join in the Netherlands and flow to the North Sea through a complex network of distributary channels, forming an extensive delta plain (Stouthamer and Berendsen, 2001). The distributary channels are perched above adjacent flood basins, which are near or below sea level because of subsidence associated with sedimentary compaction and human imposed land drainage. Combined with the high water table and North Sea storm surges, these conditions make over 60% of the Netherlands susceptible to floods of great duration (Middelkoop and Van Haselen, 1999).

The Rhine–Meuse delta was constructed as enormous volumes (~16 km^3) (Erkens et al., 2006) of sediments were deposited by various distributary channels in response to rapid Holocene sea level rise (Törnqvist et al., 1993; Berendsen and Stouthamer, 2001; Gouw and Erkens, 2007). While lateral migration is important to the floodplain geomorphology in the Rhine alluvial valley, upstream of the German border, in The Netherlands the dominant process responsible for the multiple distributary channels is avulsion, the switching of a river course to a new location on the floodplain. Channel avulsions may be caused by a variety of drivers (Aslan et al., 2005; Stouthamer and Berendsen, 2007), but the trigger is flooding and the formation of a crevasse at the breach in a natural levee. The amount of time required for channel avulsions to occur varies from decades to a couple thousand years, with the actual time probably controlled by gradient advantages and the depositional resistance of the flood basin in which the avulsion occurs (Stouthamer and Berendsen, 2007).

Sea level rise resulted in back-filling of the paleovalley during the Holocene, and an eastward shift in the point of avulsion (Stouthamer and Berendsen, 2001). This is key to understanding the development of the paleogeography, which provided humans with a distinctive hydrologic and topographic settlement context. Additionally, sea level rise resulted in a rise in the groundwater table, which resulted in thick peat formation. The formation of peat was most extensive in the western Netherlands, particularly after sea level rise abated, between 4000 and 3000 ^{14}C yr BP. Combined with the decreased stream power because of low channel gradients, few avulsions occur in the western reaches of the delta after the mid-Holocene. Neotectonics, and the differential movement of the Peel Horst and Roer Valley Graben, influence the orientation of meander belts and the location of avulsion nodes on a regional scale (Stouthamer and Berendsen, 2007).

Before river embankment the channel patterns and floodplain were controlled by variations in valley slope, sub-soil cohesion, and changes in river discharge. The meandering of the river Waal between Lobith and Nijmegen results from the presence of erodible sand and gravels of the eroded ice-pushed ridge in the sub-soil. The large meanders of the upper Ijssel River and the Meuse River can be associated with the presence of erodible sandy deposits (Weerts and Berendsen, 1995). Where tidal influence becomes important, the meander belts are embedded with in several meters of thick cohesive clays and peat (Berendsen, 1982), preventing lateral erosion and subsequent accretion, and as a result no meanders bend developed in this reach (cf. Fisk, 1947; Kolb, 1963). Weerts and Berendsen (1995) concluded that the meander length increased significantly between Roman times and 1200 AD, possibly because of increased peak discharge related to deforestation in the upper Rhine basin in the

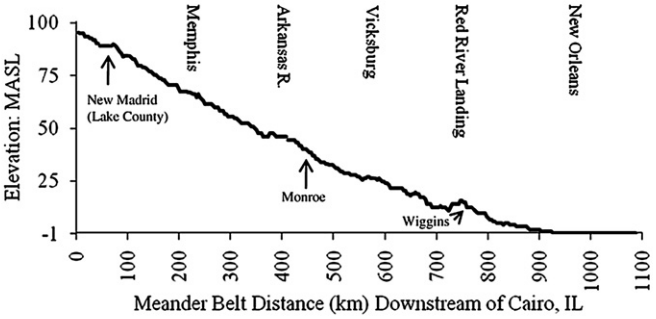


Fig. 4. Profile of the active Lower Mississippi meander belt (Hpm1). Valley elevation sampled along point bar surfaces (prior to US-ACE cutoffs) at 3.2 km (2 mi) intervals. The profile displays undulations associated with neotectonic controls and sedimentary wedges at the locations of major tributaries. Data source: Alluvial Valley of the Mississippi River, prepared by the Mississippi River Commission and US Army Corps of Engineers, 1930 (in two maps). Contour interval: 1.3 m (5 ft), map scale: 1:500,000.

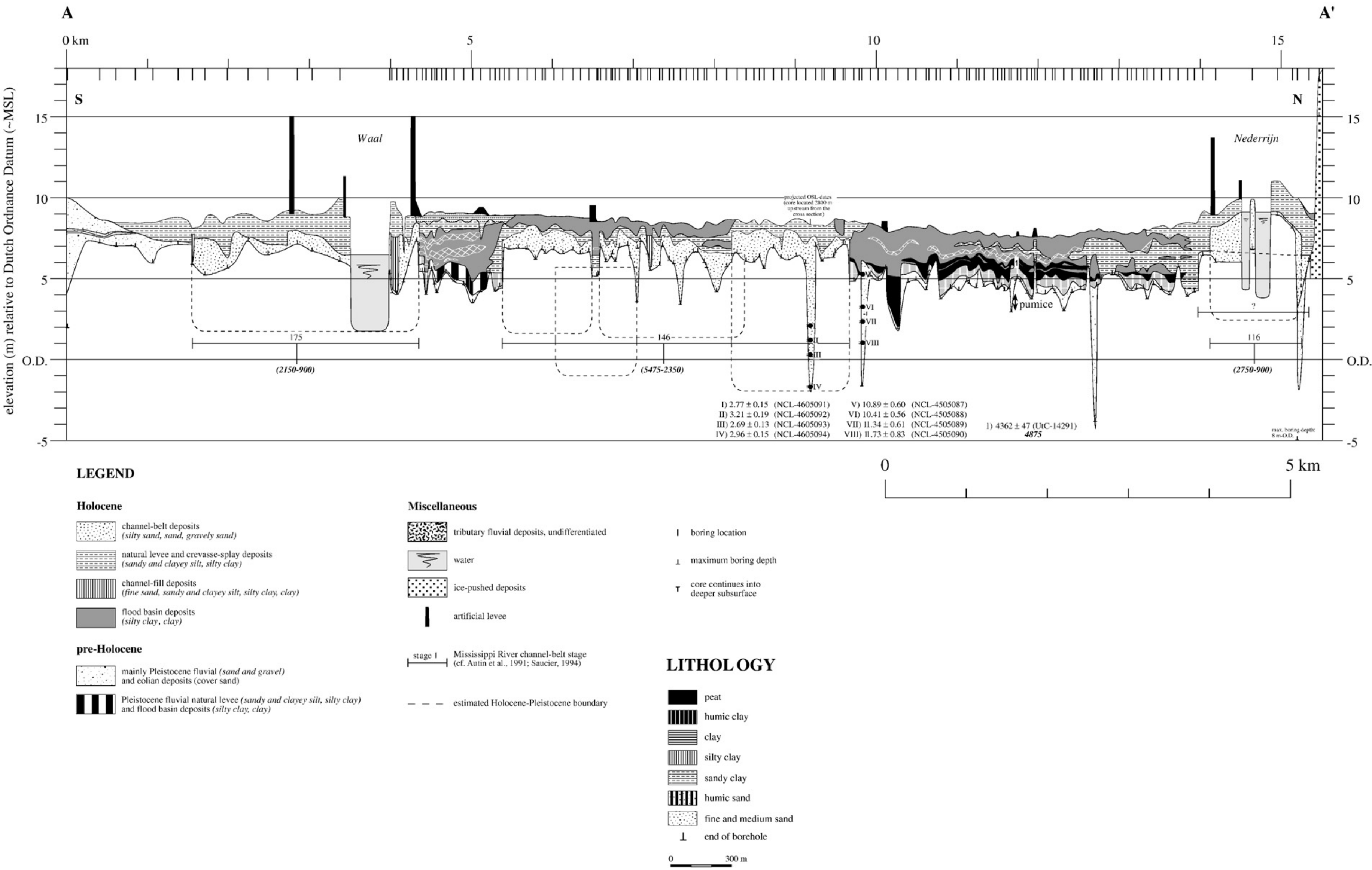


Fig. 5. Cross-section of the Rhine delta, displaying various channel belts of Rhine distributaries and depositional environments (from Gouw and Erkens, 2007). The Waal is the major distributary of the main-stem Rhine and transports ~66% of the discharge, while the Nederrijn transports ~22% of the main-stem Rhine discharge. See Fig. 1-B for location of cross-section.

Middle Ages, and to a lesser degree also to damming of smaller river channels.

The Holocene floodplain and channel geomorphology are illustrated by a valley cross-section (Fig. 1-B), and show the location of the Waal and Nederrijn Rivers, the larger of the active distributaries. Sedimentation of the Waal River began at 2160 cal yrs BP. During its initial phase, the Waal was located at the southern border of the floodplain and the residual channel is still topographically manifest on the floodplain surface. The channel belt complex in the area between 5.2 km and 9.7 km (Fig. 5) was formed between 5475 and 2350 cal yrs BP, and comprises at least four phases of channel belt development. The modern Nederrijn channel, initiated in 2750 cal yrs BP, is incised into an older channel belt located below 6.5 m + O.D (Berendsen and Stouthamer, 2001; Gouw and Erkens, 2007). Flood basin deposits, mainly consisting of clay, silty clay and humic clay occur between channel belt complexes. Between 9.6 km and 13.8 km (Fig. 5) the approximately 3 m thick succession of clastic flood basin deposits are underlain by a basal peat layer dated at 4362 ± 47 cal yrs BP.

3. Data and approach

This study employs a temporal framework to examine specific aspects of the extensive history of flood management along the Lower Mississippi and Dutch Rhine Rivers and its interrelations with fluvial deposits. The study includes analysis and synthesis of original and published data. The data sets include secondary sources from government agencies as well as primary data collected over several decades. These data pertain to sedimentary cores, hydrographic surveys, and historic maps. These data and further description of methods are available in digital format, published reports, government archives, and publications by the authors referenced throughout the text. The Holocene floodplain geomorphology has been established from numerous published radiocarbon dates and is presented as maps and cross-sections of fluvial depositional environments (e.g., Saucier, 1994; Berendsen and Stouthamer, 2001; Gouw, 2007; Gouw and Erkens, 2007). Geospatial data were integrated into a GIS for database management, and qualitatively and quantitatively analyzed using simple overlay analysis and measuring tools available in ArcGIS software.

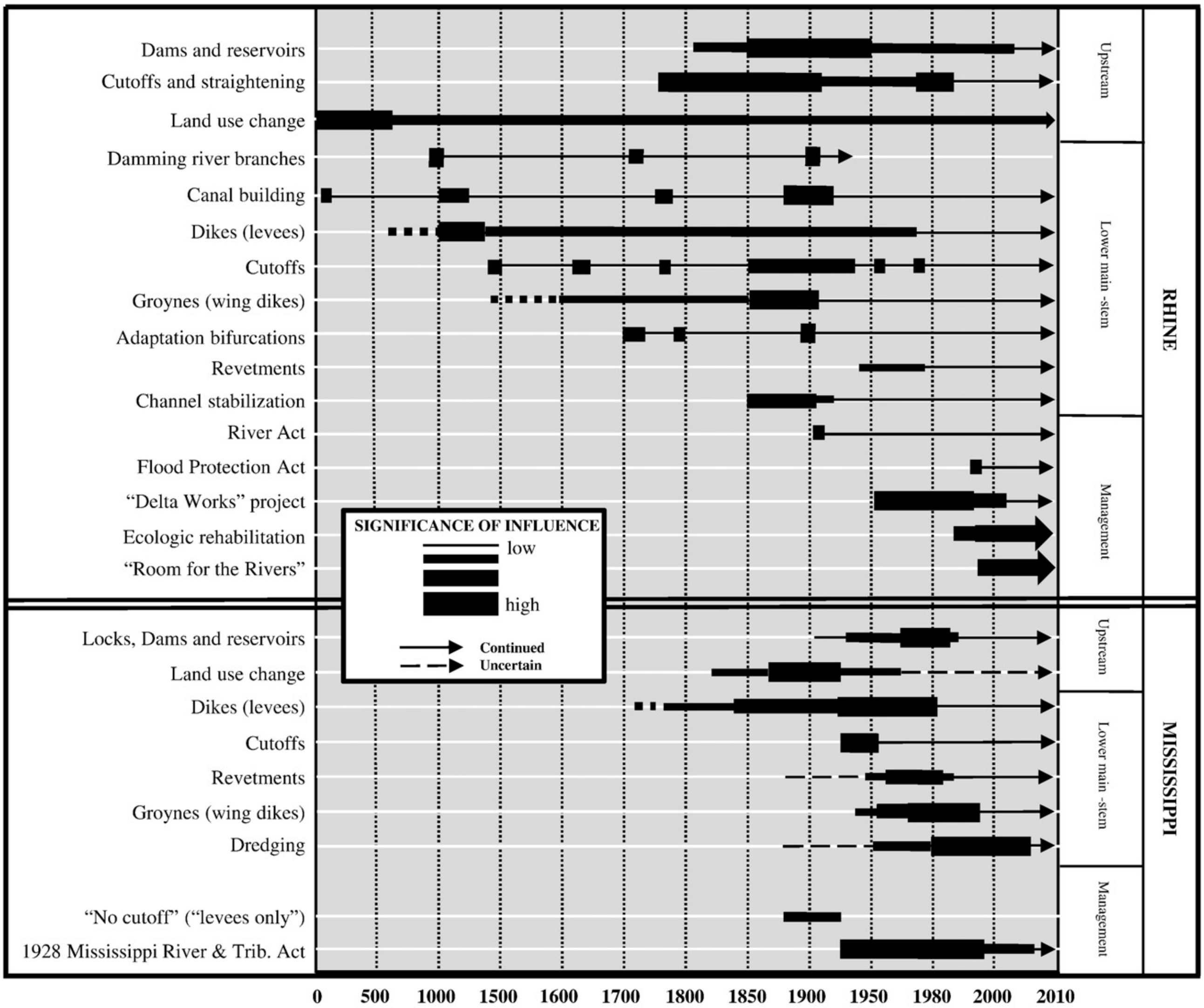


Fig. 6. Time-line qualitatively depicting major human influences on the Mississippi and Rhine Rivers. The bars indicate the timing of implementation and perceived significance of human influences. The arrows suggest continued or uncertain persistence of specific influences. Upstream influences includes the main-stem channel as well as tributary watersheds. Lower main-stem is limited to downstream of Lobith for the Rhine, and downstream of Cairo for the Mississippi. Management is limited to major national plans implemented by federal agencies. The Mississippi data does not include native American influences.

4. Historical overview: flood management along the Lower Mississippi and lowermost Rhine Rivers

While many differences exist between the Lower Mississippi and lowermost Rhine in terms of scale, they also have much in common. Both rivers include heterogeneous Quaternary deposits and a complex floodplain topography (Figs. 2 and 5). Additionally, the channel belt architecture, as characterized by scale-independent indices of meander belt geometry, has similar downstream spatial patterns (Gouw, 2007). Importantly, the fundamental engineering technology used in river management is actually quite similar, as both systems have primarily relied upon river groynes, meander bend cutoffs and channel bank stabilization, and earthen dikes; a ubiquitous approach to flood management since early civilization settled upon river banks in the Middle East (Butzer, 1976, 1982). To be clear, however, great differences exist in approach (De Bruin, 2006), with the initial major form of significant flood management along the Lower Mississippi emphasizing river channel engineering, while flood management along the lowermost Rhine has emphasized embankment and floodplain drainage. Great differences are also caused by the length of time that the systems have been managed, as well as important nuances in the implementation of major management schemes under the framework of policy (Fig. 6).

4.1. Lower Mississippi

Modern flood management along the Lower Mississippi River is distinguished by the scale of operations, the dynamic fluvial environment, the absence of coordinated management, and the US Army Corps of Engineers (US-ACE). Two major eras of modern flood management occurred along the Lower Mississippi River, with 1927 being the pivotal year and representing an abrupt change in approach and philosophy. The first dikes built by Europeans along the Lower Mississippi River were constructed in 1717 along the New Orleans waterfront, and the system progressed upstream to Baton Rouge along the east bank (Hewson, 1860). Prior to the 1800s flood management consisted of a patch-work system of local dikes lacking uniformity and coordination. Most dikes were placed adjacent to the river banks (Fig. 7) (Hewson, 1860), atop coarse natural levee deposits. By the early 1800s most of the Lower Mississippi was diked, but was managed by a consortium of land owners and municipalities representing early forms of levee boards. The US Civil War (1861–1865) and subsequent lack of recovery of the South disrupted repairs and fundamental maintenance for decades. By the late 1800s the dikes were woefully inadequate, and a series of devastating floods left the entire system in disrepair (MRC, 1880; Elliot, 1932). Congress was not aggressive in passing flood management legislation. An important

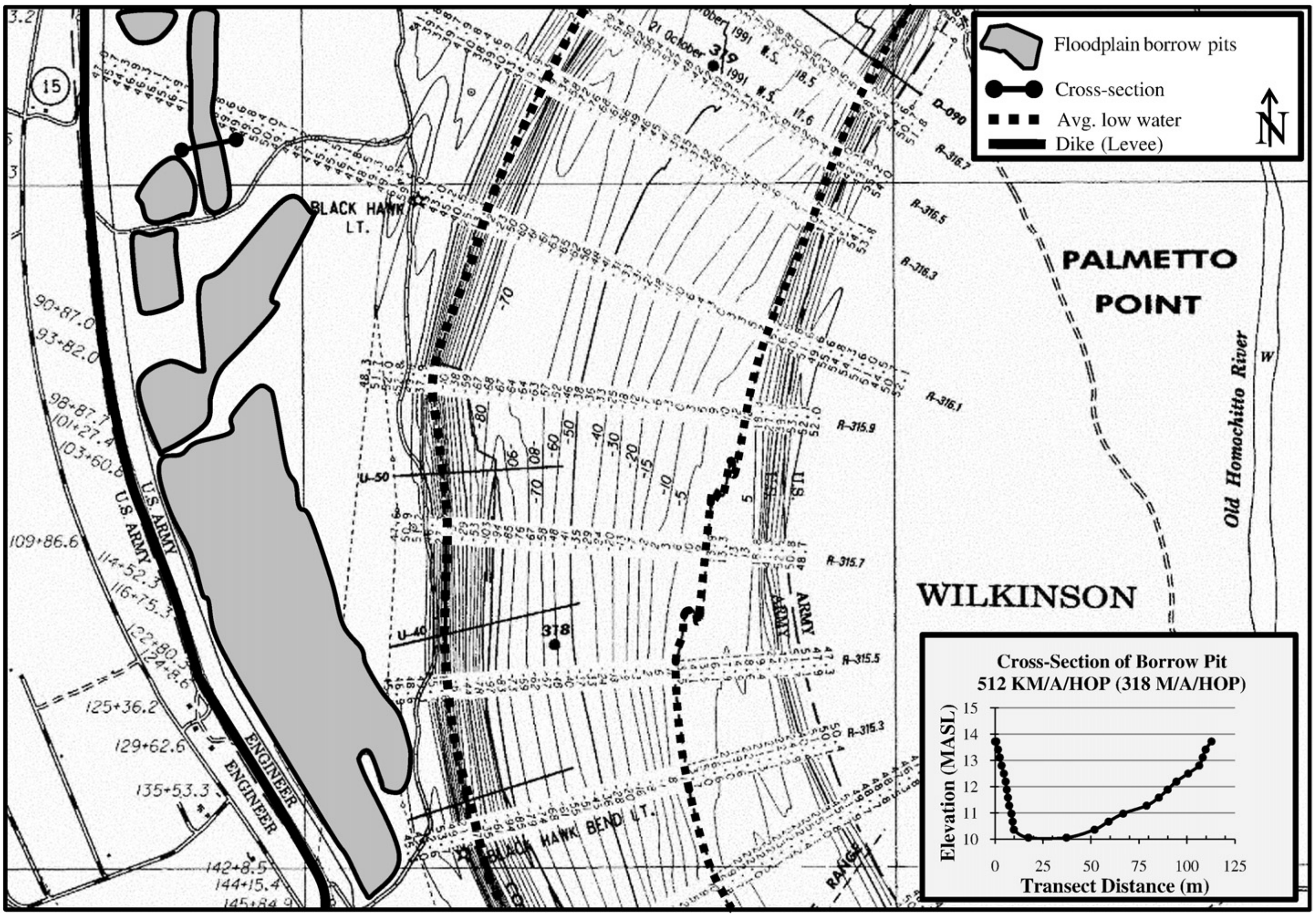


Fig. 7. Example of a 1991 hydrographic survey of the Lower Mississippi River, downstream of Red River Landing at 511 km above Head of Passes, LA (KM/A/HOP). The hydrographic survey shows the variable distance of the river dike (levee) placement and numerous floodplain borrow pits. Also shown are the elevation transects used to create long-profiles of the channel thalweg. Inset: Topographic profile of a floodplain borrow pit (data from Buglewicz et al., 1988). Most borrow pits are elongated and oriented parallel to levees. The design criteria of the US Army Corps of Engineers recommends that borrow pits should maintain a minimum of 0.91 m (3 ft) of cohesive fine-grained deposits to prevent levee underseepage (US-ACE, 2000).

Table 1
Major aspects of the 1928 Mississippi River & Tributaries Act[a]

Element	Engineering and associated activities	Activities and suggested response
Levees (dikes)	Construction and repair of 3200 km of main-stem earthen levees	Significant land use and land cover change along floodplain Creation of embanked floodplain; creation of floodplain borrow pits to obtain levee materials; direct change in floodplain morphology, change in flood hydrology and sedimentology
Channel improvement and stabilization	Channel bend cutoffs, construction of concrete channel revetments and channel groynes (wing dikes)	Vegetation clearing associated with drag lines and cutoffs, creation of new floodplain lakes and wetlands, increase in flood peaks and reduced travel times, channel incision, widening, and adjustment, loss of floodplain sediment
Floodways	Diversion of large flood crests into bypass corridors	Significant change in land cover and sedimentation within corridors; reduced flood peak
Tributaries improvement	Construction of dams and reservoirs in tributaries	Change in sediment supply to lower river, some reduction in flood peak

[a] Source: US Congress (1928).

exception with long lasting consequences, however, are the federal Swamp Lands Acts of 1849, 1850, and 1860. These acts specified that all seasonally inundated lands (between the Mississippi dikes) could be claimed by the state (Louisiana, Mississippi, Arkansas, Missouri) if used for dike construction and drainage channels (US-ACE, 1998a,b,c, V.1), resulting in policies which continue to be invoked. With navigation as the highest priority most efforts were directed towards removing river bed “snags” (trees, barges, and debris), local dredging, and channel bank protection to prevent meander neck cutoffs (MRC 1880; Elliot, 1932). Flood management was largely limited to repairing dikes and sealing off numerous breaches and crevasses that created persistent local flooding. In 1879 the flood problem resulted in Congress passing legislation to create the Mississippi River Commission (MRC), the first federal body dedicated to oversee management of the Mississippi River. The MRC, with cooperation from its partner institution the US-ACE Mississippi Valley Division (MVD), oversees the Memphis, Vicksburg, and New Orleans Districts of the US-ACE (Fig. 1) and is in charge of flood management along the Lower Mississippi River. The three US-ACE districts are loosely coordinated, and considerable autonomy remains within each district. A notable early accomplishment of the MRC, however, was the production of a detailed series of hydrographic surveys (e.g., Fig. 7) that spanned the entire Lower Mississippi River. But primarily the specific responsibilities and missions of federal government institutions in the late 1800s were still evolving, and most federal agencies had not developed an effective style of systematic data collection (Stegner, 1954; Graf, 1992). This is a trait that, at the scale of an enormous river like the Lower Mississippi, resulted in the MRC and US-ACE implementing large-scale experiments with technology, concepts, and philosophy.

The 1927 Mississippi flood is the largest historical flood in North America. Although widely recognized as an important event in US history (Barry, 1997), it should also be recognized as the beginning of major federal efforts in river management and engineering. Upon initiation, the 1928 MR&T Act triggered a time-dependent sequence of geomorphic change with significant environmental consequences to the Lower Mississippi, and many other US rivers. Indeed, following the heightened interest in flood control after the 1927 Mississippi flood, the Flood Control Act of 1936 extended the mission of the US-ACE to provide flood control for the entire country.

Comprehensive flood management of the Lower Mississippi abruptly began months after the 1927 flood waters receded, following US Congressional passage of the 1928 Mississippi River & Tributaries (MR&T) Act (Table 1). The 1928 MR&T Act involved fundamental changes in approach as the US-ACE changed its primary focus from navigation to flood control. But it was the *reversal* of philosophy which makes the MR&T Act so significant. The plan prior to the 1927 flood is often characterized as “levees only”, which included a “no cutoff” plan. The idea of the “levees only” approach was that flood waters contained within a narrower corridor would cause the river to essentially self-scour during large events (MRC, 1880). The impetus for this approach was laid out in the extensive study by Humphreys and Abbot (1861). While Humphreys and Abbot (1861) remain one of the most important studies concerning the Lower Mississippi River, it was flawed in arguing that flood waters within dikes would effectively result in a self-scouring (dredging) channel (Hudson and Kesel, 2006). Probably more significant was that the US-ACE implemented a “no cutoff” policy, which resulted in a patch-work construction of bank protection. The major effort in bank protection in the late 1800s and early 1900s was directed toward the engineering of channel bank revetments, constructed of common river willows fastened to wooden frames and ballasted along river banks (Fig. 8). The MRC borrowed and developed this approach following its success along the Dutch Rhine and other European rivers (MRC, 1880), but the approach was largely ineffective along the Lower Mississippi (Elliot, 1932). Indeed, bank erosion and channel migration remained high throughout the late 1800s and early 1900s (Hudson and Kesel, 2000).

While it has not yet been completed, implementation of the 1928 MR&T Act initiated a sequence of geomorphic disturbances to the Lower Mississippi channel and floodplain. The 1928 MR&T flood management plan was sweeping in terms of the magnitude and scope of engineering. The plan includes four major elements (Table 1): 1. Construction and repair of 3200 km of dikes; 2. River improvements, meander neck cutoffs (~straightening), dredging, groyne construction, and bank stabilization (Figs. 9 and 10); 3. Tributaries improvement, involving the construction of upstream dams and reservoirs; and 4. Floodways for routing of large flood events to reduce downstream flood crests. Since passage of the MR&T Act, numerous revisions were initiated by the various Flood Control Acts of 1936, 1938, 1941, 1946, 1950, 1954, 1962, 1965, 1968, and 1986. The 1928 MR&T Act, however, remains “the” management plan for the Lower Mississippi River and continues to be advocated by the MRC (2008) (hhttp://www.mvd.usace.army.mil/mrc/mrt/index.php). Indeed, all US-ACE technical reports and scientific investigations begin with a review of the 1927 flood and subsequent passage of the MR&T Act. The MR&T Act is approximately 85% complete with an anticipated date of completion in March 2010 (MVD, 2008).

In 1928 the MRC was in its infancy and had only recently started to analyze data pertaining to the modern system. Although significant improvement occurred in understanding the hydrology and hydraulics (Humphreys and Abbot, 1861; Elliot, 1932), little was known about the Quaternary geomorphology of the Lower Mississippi Valley, which is fundamental to understanding groundwater flow and dike underseepage (Mansur et al., 1956; Krinitzsky and Wire, 1964), river channel dynamics, and the sensitivity of the channel and floodplain to specific types of flood management (Winkley, 1977; Dunbar et al., 1999). Perhaps more significantly, the knowledge base concerning fundamental concepts and models about meandering river processes and alluvial architecture did not exist, because it was still a decade or more before the epic publications of Russell (1936) and Fisk (1944). Such was the status of knowledge concerning the floodplain geomorphology of the Lower Mississippi when the MRC embarked on its great plan.

Fig. 8. Construction of willow revetment mattress at Sunflower Landing, MS, the main technology used for bank protection from the late 1800s to the early 1900s. Although highly effective along the Dutch Rhine, the willow revetments were ineffective at controlling bank erosion along the more dynamic Lower Mississippi River (photo: US-ACE).

While the MRC lacked fundamental concepts and studies in floodplain geomorphology that would pertain to effective flood management of the Lower Mississippi, the practice of river engineering was moving forward with greater certainty (e.g., Graf, 1992) because, in part, US civil engineers held European examples in high esteem; the Rhine in particular.

The most abrupt and significant consequences to the Lower Mississippi channel and floodplain occurred as the US Army Corps of Engineers straightened the river by initiating a series of meander bend cutoffs (Table 2; Fig. 11). Following the 1927 flood there was considerable urgency in being able to manage flooding. Thus, in 1929 the US Army Corps of Engineers allowed a “natural” meander bend cutoff (at Yucatan bend) to develop, and studied the adjustment of the cutoff for two years (Ferguson, 1940; Winkley, 1977). In 1931 the MRC judged the cutoff to be successful and proceeded with their plan to cutoff over 250 km of channel. The final cutoffs in 1942 were at Hardin (1091 KM/B/C) and Sunflower (1006 KM/B/C) bends. Because of the size of the Mississippi River, the scale of engineering, and the brief amount of time in which the cutoffs occurred, the cutoffs represent among the most significant human induced geomorphic change to occur in North America during the twentieth century. Considerable historical precedent existed for developing the Mississippi River cutoffs. The introduction of this style of flood management in the US is largely because of the “apparent” successes with channel straightening along the German and Dutch Rhine in the early and mid 19th century. The implementation of this specific flood management plan to the Lower Mississippi, and subsequent diffusion to many other rivers throughout the world, has had sweeping consequences to

Fig. 9. Construction of articulated concrete revetment for bank protection (1964) at Goldbottom, Mississippi (photo: US-ACE).

Fig. 10. Creation of pilot channel for meander neck cutoff at Jackson Pt.—Sunflower Cutoffs, looking upstream (photo: US-ACE).

numerous river environments. Further, the approach has triggered a sequence of geomorphic and environmental disturbances associated with channel incision and bank failure, sedimentation, and flooding, particularly along coastal plain rivers (e.g., Yodis and Kesel, 1992; Toth et al., 1993; Shankman, 1996; Shankman and Smith, 2004).

Additional works associated with the 1928 MR&T Act included channel stabilization and improvement (Table 1), especially the construction of revetments and groynes (wing dikes). Although the willow revetments (Fig. 8) were not successful, experimentation with concrete resulted in the creation of a new type of articulated concrete revetment (Fig. 9). These structures are draped along the channel banks of the Lower Mississippi River, and were mainly put in place in the 1960s and 1970s (Hudson and Kesel, 2006). Concrete revetments are intensively utilized within the Vicksburg District (Fig. 11), which was undergoing high rates of adjustment and width enlargement after the cutoffs (Winkley, 1977; Smith and Winkley, 1996; Harmar et al., 2005; Hudson and Kesel, 2006). The next major phase of engineering were channel groynes (wing dikes). These features are generally oriented perpendicular to flow and are designed to trap bedload and reduce the channel width to ensure a deeper navigable channel (Smith and Winkley, 1996; Kesel, 2003; Pinter et al., 2006a,b). Thus, along the Lower Mississippi River channel groynes were constructed to offset the increase in channel width that occurred after cutoffs and channel straightening.

Table 2

Adjustment and Quaternary depositional environments of major Mississippi River meander neck cutoffs

Meander cutoff[a]	KM/A/HOP[b]	Cutoff year[a]	Bend dist.[a]	Cutoff dist.[a]	Reduced dist.[a]	Migration: 1880–1911	Migration: 1911–cutoff year	Migration: 1880 – cutoff year	Ch. width: 1911	Ch. width: 1996	Quaternary deposits[c]
(name)			(km)	(km)	(km)	(m/yr)	(m/yr)	(m/yr)	(m)	(m)	Dominance[d]
Glasscock	552	1933	25.1	7.7	17.4	71.4	25.2	52.2	690	605	HB
Giles	589	1933	22.5	4.7	17.9	86.1	20.7	59.0	950	643	HB, Hpm3, Hcom
Rodney	624.4	1936	16.1	6.6	9.5	78.6	74.8	76.9	510	2834	HB, Hpm1
Yucatan	656.6	1929	19.6	4.2	15.5	94.8	41.3	75.2	646	1205	Hpm1, Hchm
Diamond	682.4	1933	23.5	4.2	19.3	99.2	113.6	105.2	787	1051	Hpm1, Hpm2, Hchm
Marshall	721	1934	11.7	5.0	6.8	112.2	77.0	97.2	829	1803	Hpm1, Hchm
Willow	745.2	1934	20.0	7.6	12.4	26.4	30.0	27.9	644	1528	Hchm, Hpm1
Sarah	811.1	1936	13.7	5.2	8.5	88.8	48.0	70.6	517	1619	Hpm1, Hchm
Worthington	827.2	1933	13.0	6.1	6.9	20.5	6.3	14.6	843	1865	HB, Hchm
Leland	867	1933	18.0	2.3	15.8	52.2	15.8	37.1	1031	3256	Hpm1, Hchm
Tarpley	870.7	1935	19.6	5.8	13.8	6.8	6.0	6.5	700	1691	Hpm1, Hchm
Ashbrook	883.6	1935	21.4	3.1	18.3	37.3	11.7	26.1	533	1223	Hpm1, Hchm
Caulk	925.4	1937	27.7	3.2	24.5	18.6	6.0	12.9	612	645	Hchm, Pvl2, Hpm1
Sunflower	1005.9	1942	20.8	4.0	16.7	20.5	18.1	19.3	536	1227	Pve2, Hpm1
Jackson	1010.7	1941	17.9	3.9	14.0	28.0	30.4	29.1	799	882	Hchm, Hpm1
Hardin	1091.2	1942	30.3	3.1	27.2	55.2	52.3	53.7	576	1255	Hpm1, Hchm

[a] From Winkley (1977).

[b] Kilometers above Head of Passes, Louisiana, at mouth of delta.

[c] Quaternary depositional environment that was being reworked by meander bend at year of cutoff. Depositional environments based on Saucier (1994): HB = Holocene backswamp, Hpm1 = Holocene meander belt 1, Hpm2 = Holocene meander belt 2, Hpm3 = Holocene meander belt 3, Hchm = Holocene channel cutoffs (includes meander neck and chute cutoffs as "clay plugs" or lakes and wetlands), Hcom = Holocene abandoned courses, Pvl2 = late Pleistocene valley train, Pve2 = early Pleistocene valley train.

[d] In relative order of dominance along cutbank of meander bend.

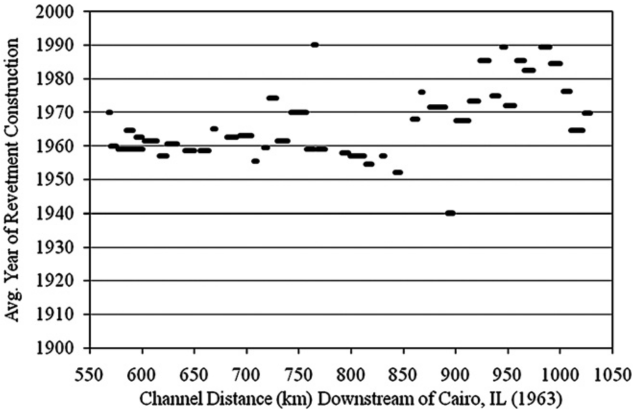


Fig. 11. The chronology and spatial extent of concrete revetment construction within the Vicksburg District (US-ACE). The data were obtained from large-scale (1:20,000) navigation charts along the most active portion of the Lower Mississippi River (Hudson and Kesel, 2000, 2006). The data for individual revetments are for the average date of construction, as most concrete revetments were built over a 10-year period (+ — several years).

4.2. The Dutch Rhine

In contrast to the US-ACE top–down approach as exemplified by the 1928 MR&T Act, the Dutch approach to flood management can be characterized as incremental, and locally adaptive. The Dutch lowlands are a product of step-wise management to a dynamic fluvial -deltaic environment over hundreds of years (Lambert, 1985; Van de Ven, 1993; Te Brake, 2002). This has resulted in a tremendously intricate landscape under the influence of an omnipresent flood management infrastructure that extends over much of The Netherlands. Although much of Holland is highly susceptible to flooding, people have lived in this setting for millennia, with the earliest settlements located on the higher natural levees and alluvial ridges of abandoned river branches. Systematic landscape modification for flood management in The Netherlands begins with the construction of thousands of terpen (built up earthen mounds) along coastal lowlands in ~2500 BP, many of which remain significant topographic elements upon the modern Dutch landscape (Lambert, 1985).

The Rhine distributaries in the Netherlands have known a long history of systematic management (Fig. 6). While much early water management in The Netherlands is characterized as local or regional scale, extensive centralized administration of water and flood management actually began with the Romans at about ~2000 BP (Van Veen, 1962). Large-scale engineering modifications included canal building to connect distributary channels. But the construction of settlements and fortresses atop the flanks of natural levees of the Kromme Rijn (Oude Rijn), the northernmost branch of the Rhine (Fig. 1-B), would have required construction of dikes and embankments. Little is known about the period of water management between about 2000 BP and 900 BP, and no historical evidence suggests substantial coordinated flood management. Instead, small settlement raised embankments along upstream borders to protect against flood waters (Van de Ven, 1993). The initial framework for coordinated flood management developed in the early medieval period by newly established water boards (*waterschappen*) (Van Dam, 2002). These community based entities were highly sophisticated, and each had an intricate knowledge of its local river and flood basin hydrology. One of the major accomplishments that occurred under the framework of local water boards included damming of the river branches to concentrate discharge within a few larger channels, rather than division of flow across numerous smaller channels. For example, an avulsion of the Kromme Rijn occurred in 1900 BP (Fig. 1-B), resulting in a gradual switch to the River Lek. In 1122 AD the Kromme Rijn was still partially active, but problems with low water and sedimentation were persistent. In 1285 AD the system was finally dammed, resulting in a complete switch to the River Lek, and an abrupt end to the northern most main-stem Rhine.

An additional major accomplishment of the local-scale water boards involved drainage of the flood basin areas with ditches and canals, and protecting flood basins from river flooding by construction of dikes. Embankment of the delta and river polders initially occurred at about 1000 AD in western Holland, near the coast. All rivers in the western Netherlands were diked by 1150 AD. Over a couple centuries embankment moved eastward, towards the German border, and the last dike ring was closed around 1350 AD (Lambert, 1985; Van Veen, 1962; Van de Ven, 1993; Berendsen, 2005). As a consequence of embankment, river flood waters remained trapped in the 0.5–1 km wide embanked floodplain zones along the main channels and infrequently inundated the more extensive flood basins. By the mid 14th century the Dutch lowlands had been greatly transformed by various forms of hydraulic engineering, including drainage channels, canals, sluice gates, and dikes (Van Veen, 1962; Van Dam, 2002; Te Brake, 2002). By the middle medieval period the increasing number of local water boards necessitated greater coordination, and although the Netherlands was not yet politically unified, regional water boards with greater authority became the standard model (Kaijser, 2002). The

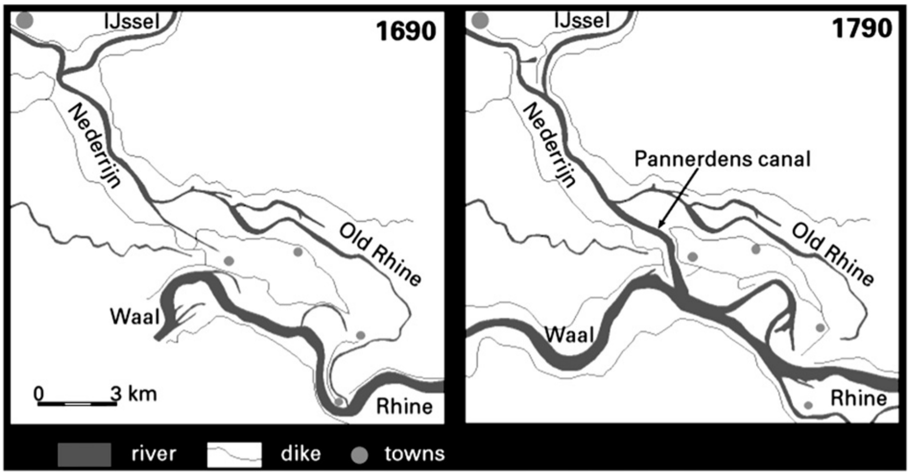


Fig. 12. The bifurcation of the Dutch Rhine near the German border (after Van de Ven, 1993). The Pannerdens Canal improved discharge distribution between the three major Rhine distributaries, with the Waal, Nederrijn, and Ijssel transporting 2/3, 2/9, and 1/9 of the total main-stem Rhine discharge, respectively. The discharge allocation has been maintained since creation of the Pannerdens Canal in 1701–1707.

pace of dike construction and fortification (heightening and strengthening) was renewed with the onset of a period of large floods in the 15th century, particularly the great St. Elizabeth's Day flood of 1421 (Lambert, 1985). By the mid-1600s this had produced a rural landscape which had become incredibly rectilinear in pattern as land subsidence and increasing demands for agriculture necessitated continued land drainage, resulting in the creation of an extensive polder landscape (Van Veen, 1962; Van de Ven, 1993).

A major accomplishment by increasingly centralized water management was in the adaptation of the bifurcations of the three major Rhine distributaries in the eastern Netherlands. This involved the construction of the Pannerdens Canal in 1701–1707 and the reconstruction of the IJssel bifurcation in 1775 (Fig. 12). This major engineering project effectively fixed the discharge ratios of the Waal, Nederrijn, and IJssel Rivers at 2/3, 2/9, and 1/9, respectively, and resulted in a sustainable discharge distribution that continues to be maintained. Furthermore, large spill-over areas and bypasses were established along the Ijssel and Meuse rivers for siphoning flood waters. An additional example at the federal scale was river normalization that occurred after 1850, which included straightening rivers and engineering to improve discharge capacity, alleviate floods, reduce the impact of ice jams, and in the construction of groynes to narrow the river channels.

Besides land drainage and polder management, large-scale “hard” engineering approaches have been important to water and flood management in The Netherlands, particularly over the past 150 years. Although a comprehensive review is beyond the scope of this paper (see Fig. 6), some major engineering works include the improvement of the drainage capacity of the lower Rhine (Waal and Meuse) branches into the North Sea. This involved excavating the New Merwede — connecting the Waal to the Haringvliet estuary — and the Bergsche Maas to achieve direct drainage of the lower Meuse into the estuary. In the 1930s several meanders in the Meuse were cutoff, reducing the length of this river reach by 30%. Furthermore, the Nieuwe Waterweg was created in 1872, connecting Rotterdam to the North Sea. The ultimate example of modern Dutch flood management, however, occurred following the devastating flood of 1953 that resulted in numerous dike breaches and over 2000 deaths in rural areas. The Dutch response was the implementation of the extensive “Delta Works” project (Van de Ven, 1993), a comprehensive flood management plan that included storm surge barriers. Completed in the mid 1990s, the Delta Works is widely considered one of the most effective and sophisticated flood management models for large coastal draining rivers (Bijker, 2002).

Contemporary flood management in The Netherlands is highly centralized by the Rijkswaterstaat, formed in 1798 to coordinate over 3000 local water boards (Kaijser, 2002). In the nineteenth century numerous Dutch water boards were consolidated into larger spatial units responsible for dike maintenance, land drainage, and emergency coordination during floods. By the early twentieth century only twenty-seven water boards remained.

In recent decennia major shifts in water management vision and strategy have occurred (Fig. 6). In the 1980s local interests increasingly advocated protection of the unique culture of floodplain areas, while nongovernmental organizations (NGOs) encouraged protection of embanked floodplains areas for environmental concerns, particularly as nature corridors across a densely populated and cultivated landscape. Large floods in 1993 and 1995 (with a recurrence interval of 50 to 70 years) almost breached the dikes (Fig. 13), and exposed weaknesses in the Dutch flood management system. The threat of such a major inundation, the first since the devastating 1953 event, had a sobering effect, and in 1996 the Dutch developed a new national flood management plan entitled “Room for the Rhine” (Silva et al., 2001) (Fig. 14). A major element of the plan is that embanked floodplain storage is increased. This is accomplished in several ways, including the movement of dike sections further back from the river, removing flood deposits to lower the floodplain surface, and the creation of secondary floodplain channels (Middelkoop et al., 2002). Although the minimization of flood risk is the priority, secondary motivations are principally environmental. Moreover, this plan recognizes some of the faults of past approaches to flood and water management that influence floodplain inundation, including subsidence, dike placement and accelerated sedimentation, and the loss of secondary channels to store floodwaters. Thus, the important lesson is that older historical styles of flood and water management resulted in unintended geomorphic and hydrologic impacts on the modern Rhine floodplain, and have necessitated additional measures to ensure safety from flooding.

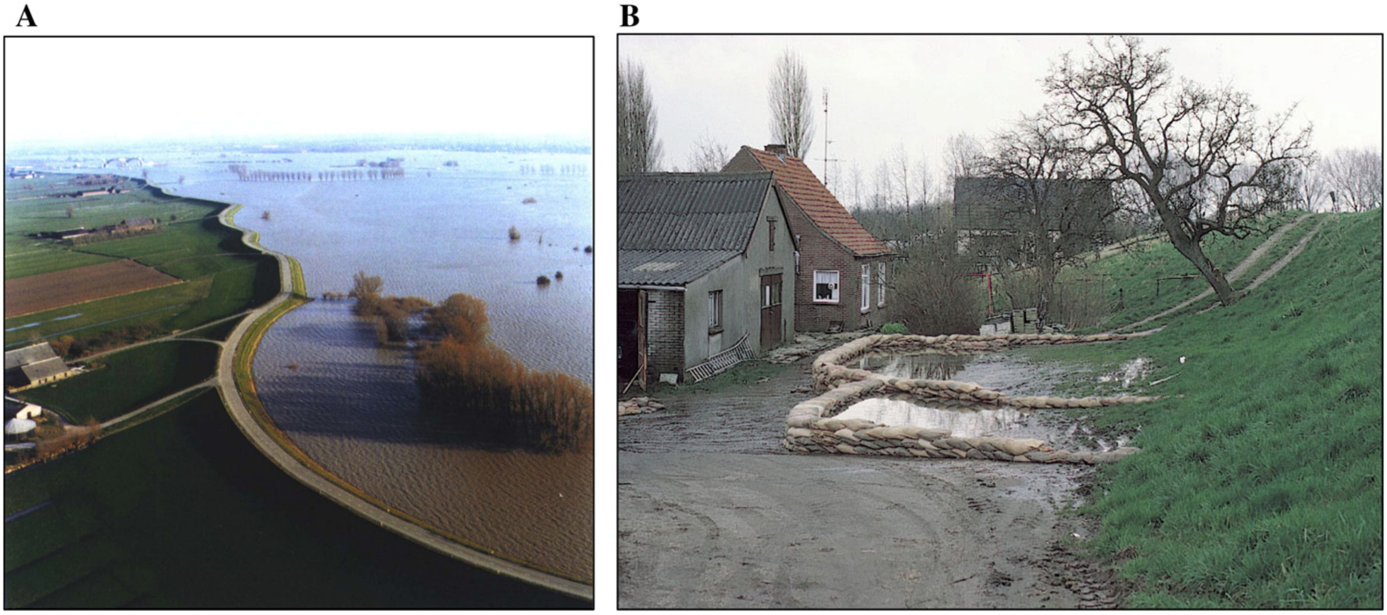


Fig. 13. High stage events in 1993 and 1995 with a recurrence interval of 50 to 70 years were important for developing new flood management approach. A. High water of the River Waal. The event did not breach the dikes. Photo: Rijswaterstaat. B. Seepage beneath a Wall River dike, which threatens dike stability. Photo: Rijkswaterstaat.

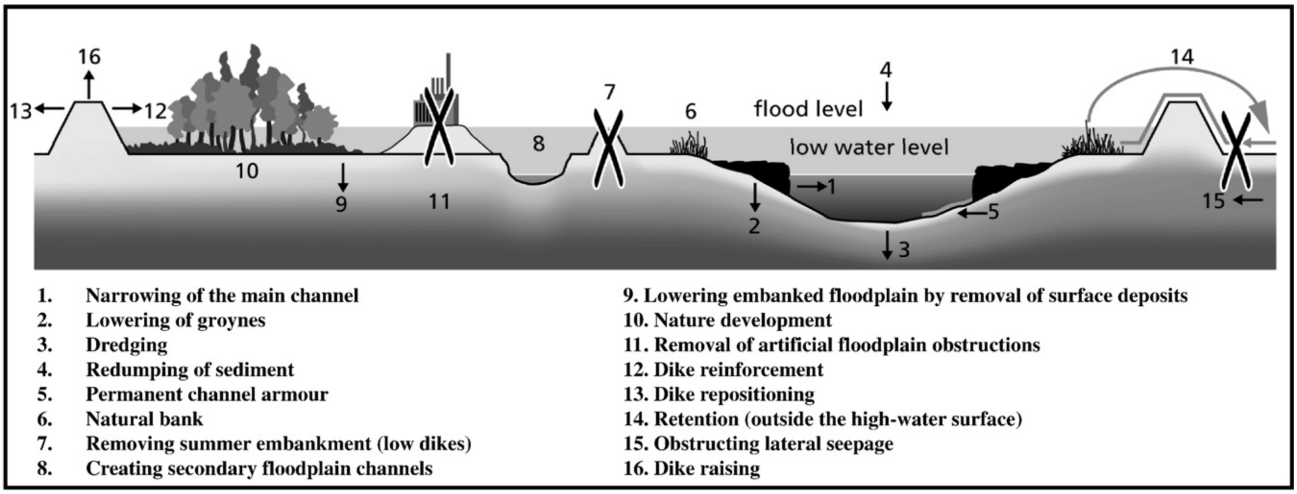


Fig. 14. Model of the “Room for the Rhine” floodplain modification program, designed to reduce flood risk by increasing the floodplain storage space for flood waters. Fundamental to the plan is to relocate dikes further away from the channel and to remove thick overbank deposits within the embanked floodplain. From Middelkoop and Van Haselen (1999).

Implementation of the “Room for the Rhine” flood management plan includes considerable coordination and integration across different scales of government agencies and stakeholders, including international, federal, provincial, water boards, and individual property owners. The result is that specific elements of the plan are highly customized and variable. Nevertheless, implementation

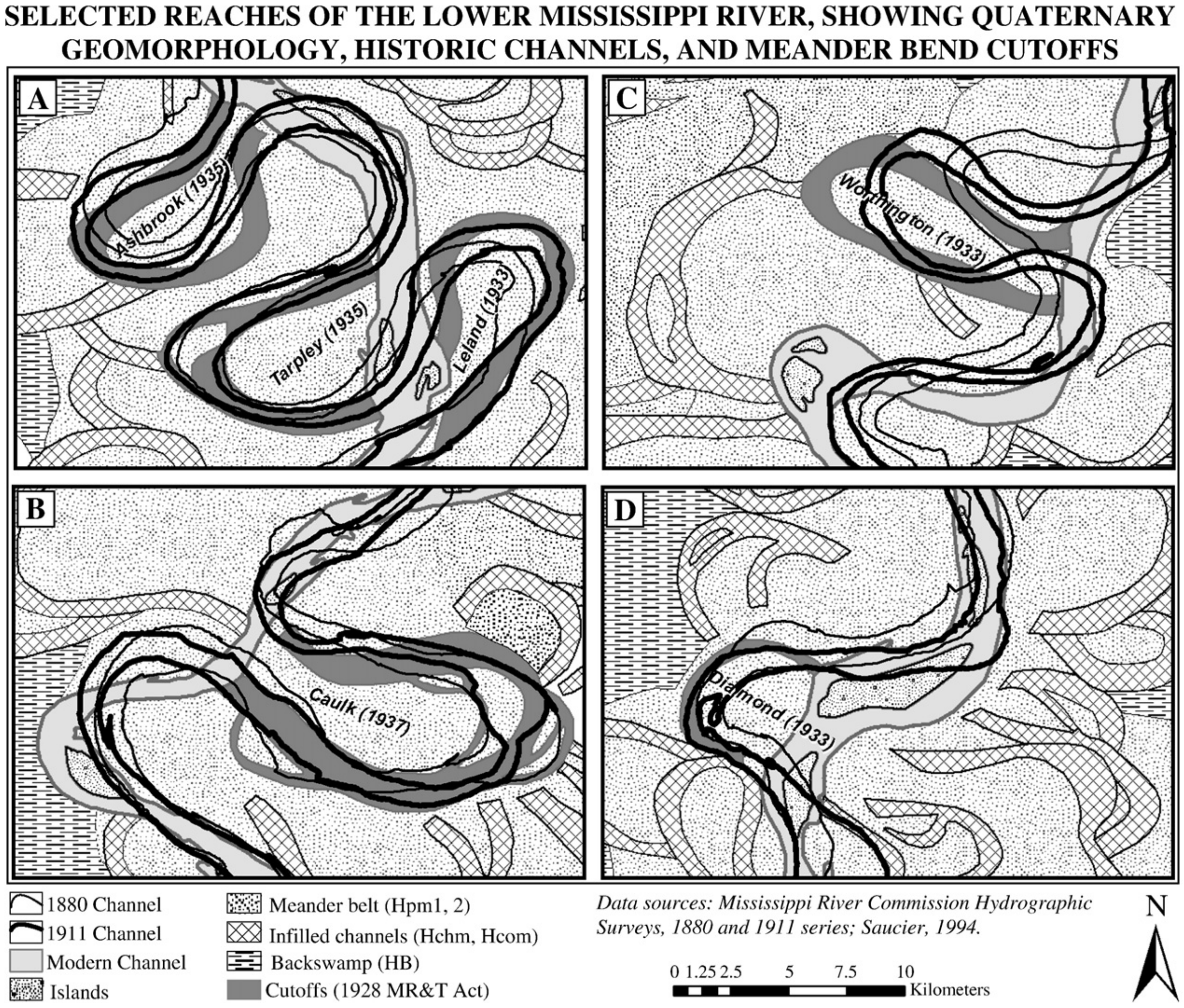


Fig. 15. Examples of meander bend cutoffs and floodplain geomorphology along the Lower Mississippi River within the Vicksburg district. Index to cutoffs: A. Ashbrook (884 km), Tarpley (871 km), Leland (867 km); B. Caulk (925 km), C. Worthington (827 km), D. Diamond (682 km). The migration rate and adjustment of meander bends is related to the floodplain geomorphology, with resistant deposits depicted as Holocene backswamp and clay plugs (infilled cutoffs). At some meander bends the river is incised into Pleistocene or Tertiary deposits, such as depicted by the relatively stable bends at Ashbrook, Tarpley, and Leland. Detailed hydrographic surveys from the 1880s and 1911 allow the position of the historic channel overlaid in GIS with the meander bend cutoffs and floodplain geomorphology data. Further reference for cutoffs and floodplain geomorphology is provided in Table 2.

requires consideration of a floodplain geomorphology that was highly altered by older (historical) styles of flood and water management.

5. Flood management consequences, interrelations with floodplain geomorphology

5.1. The Lower Mississippi

The first major element of the 1928 MR&T Act to be implemented were the meander neck cutoffs within the Vicksburg District. Although fundamentally a channel engineering procedure, the argument for cutoffs was that a straighter channel would reduce flood stages and convey flood waters more quickly downstream (Ferguson, 1940; Winkley, 1977). Prior to the meander bend cutoffs the Lower Mississippi River was actively reworking its floodplain deposits, resulting in typical cutbank erosion and point bar aggradation associated with downstream translating meander bends (Table 2; Fig. 15). The rate of meander bend migration between 1880 and the year of cutoff varies from 6 to 105 m/yr. These rates span a greater period than reported by Hudson and Kesel (2000), between 1880 and 1911, but generally maintain the same trend. As might be expected, there is greater variability in migration rates for meander bends with higher rates of migration (Fig. 16), and the relation is best fit with a power function. For several meander bends, rates of migration were constrained by floodplain deposits, such as fine-grained Holocene backswamp deposits or infilled channels and cutoffs which represent resistant “clay plugs” (Fig. 15; Table 2). Several of the meander bends (Leland, Tarpley, Ashbrook cutoffs) with the lowest rates of migration occurred along a very sinuous reach where the Mississippi was incised into Eocene Yazoo Clay (Jackson Group), emplaced into the channel because of the Monroe Uplift (Schumm, 1986). The cutoffs resulted in a shorter channel, which immediately started to erode and widen. The new channels were cut into (formerly active) sandy point bar deposits (e.g., Fig. 3). With few exceptions the new post cutoff channel is substantially wider than the pre-cutoff channel width (Table 2). These reaches typically include a mid-channel island and result in a local-scale braided channel pattern (Fig. 15). Exceptions exist in some reaches where the new channel is impinged against fine-grained (cohesive) Holocene backswamp deposits, such as in several lower reaches of the alluvial valley between Vicksburg and downstream of Natchez (e.g., Fig. 3). Indeed, upstream of Natchez the Giles cutoff channel is within backswamp deposits (Winkley, 1977; Smith and Winkley, 1996), and the resistant cohesive deposits resulted in much lower rates of channel adjustment. At this reach the river has maintained a relatively low channel width of about 650 m (Table 2).

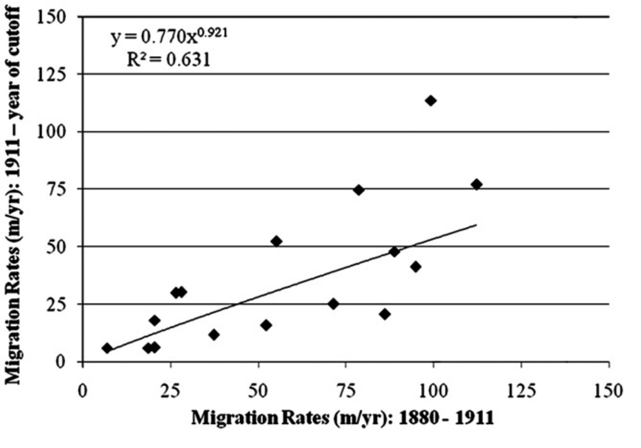


Fig. 16. Relationship of migration rates for meander bend cutoffs associated with the 1928 MR&T Act for two periods: 1880–1911 and 1911 to the year of meander neck cutoff.

The channel straightening by artificial cutoffs introduced a channel knickpoint, a local increase in channel bed slope, which caused channel incision (Winkley, 1977; Smith and Winkley, 1996; Biedenharn et al., 2000; Harmar et al., 2005; Hudson and Kesel, 2006). A comparison of long-profiles of the channel thalweg for different hydrographic surveys shows that the Lower Mississippi abruptly incised (vertically) after the cutoffs (Fig. 17). The thalweg data plotted in Fig. 17 include the 1948, 1963, 1975, and 1999 hydrographic surveys for 100 km reaches within the alluvial valley. The 1948 hydrographic survey is not a true base-line survey (pre-cutoff), as the river was already adjusting to the cutoffs. Nevertheless, a comparison of trend lines for the four reaches between 1948 and 1999 (Fig. 17) show that most of the incision occurred between the 1948 and 1963 surveys, with appreciably little adjustment in subsequent years (surveys). The average incision (along the trend lines) between the 1948 and 1999 survey ranged from 3.5 m along the 0–100 km (Fig. 17-A) to 6 m along the 600–700 km reach (Fig. 17-B). Average trends mask local variability, and in a number of reaches incision exceeded 10 m, such as upstream of Greenville (610 to 630 km, Fig. 17-B) and downstream of Vicksburg (825 km, Fig. 17-C). Several cutoffs represent an exception. For example, the Leland, Tarpley, and Ashbrook cutoffs were already incised into resistant Tertiary Yazoo Clay (630–670 km, Fig. 17-B), and did not undergo as much overall channel incision (e.g., Winkley, 1977). Spatial variability exists, however, particularly between the upstream- and downstream-most reaches. Fig. 17-A includes thalweg data upstream of the meander neck cutoffs (Table 2). This reach was aggrading until at least the 1948 survey (Hudson and Kesel, 2006), and the 1963 trend displays greater incision downstream (towards 100 km) than in the upper reaches of the channel segment (towards 0 km). This may be caused by the length of time required for channel knickpoints to migrate to this upstream channel reach. The downstream-most reach, 975–1025 km (Fig. 17-D) shows slight incision between the 1963 and 1975 surveys, but displayed slight aggradation between the 1975 and 1999 surveys. An additional characteristic to note is that after cutoffs the channel began to adjust its sinuosity, resulting in shifting of channel reaches. This can be observed in the thalweg data by comparing a number of the deep pools that are moving along the channel bed between successive surveys, with examples at 685 km (Fig. 17-B), 825 km (Fig. 17-C), 930 km (Fig. 17-D), and 1010 km (Fig. 17-D).

A significant oversight in flood management along the Lower Mississippi River concerns the synergistic effect of various elements of the 1928 MR&T Act (Table 1). The channel cutoffs initiated a distinct sequence of geomorphic adjustments, invoking a continuum of river management activities that effectively resulted in the US-ACE placing as much emphasis on channel management as flood (dike) management. An additional mode of geomorphic and environmental change introduced by an embanked floodplain, however, is trapping of fine-grained deposits, particularly within the numerous secondary channels, sloughs, and cutoffs. Winkley (1994) suggests that embankment has resulted in an increase in sedimentation and height of channel banks, but there has been limited research on this for the Lower Mississippi embanked floodplain.

By creating sixteen new oxbow lakes the meander neck cutoffs resulted in an abrupt alteration of the Lower Mississippi floodplain geomorphology and hydrology. The change in this environment, however, must be considered within the overall context of the 1928 MR&T Act (Table 1). In particular, the oxbow lakes are located within a much narrower embanked (diked) floodplain that ranges from 1.1 to 30.2 km in width (Winkley, 1994). The vast majority of research concerning human impacts on the Lower Mississippi has solely concerned the channel, but the inherent lateral connectivity between alluvial channels and floodplains suggests that floodplain environments should also be impacted. After cutoffs, newly formed oxbow lakes along the lower Mississippi responded rapidly, with many

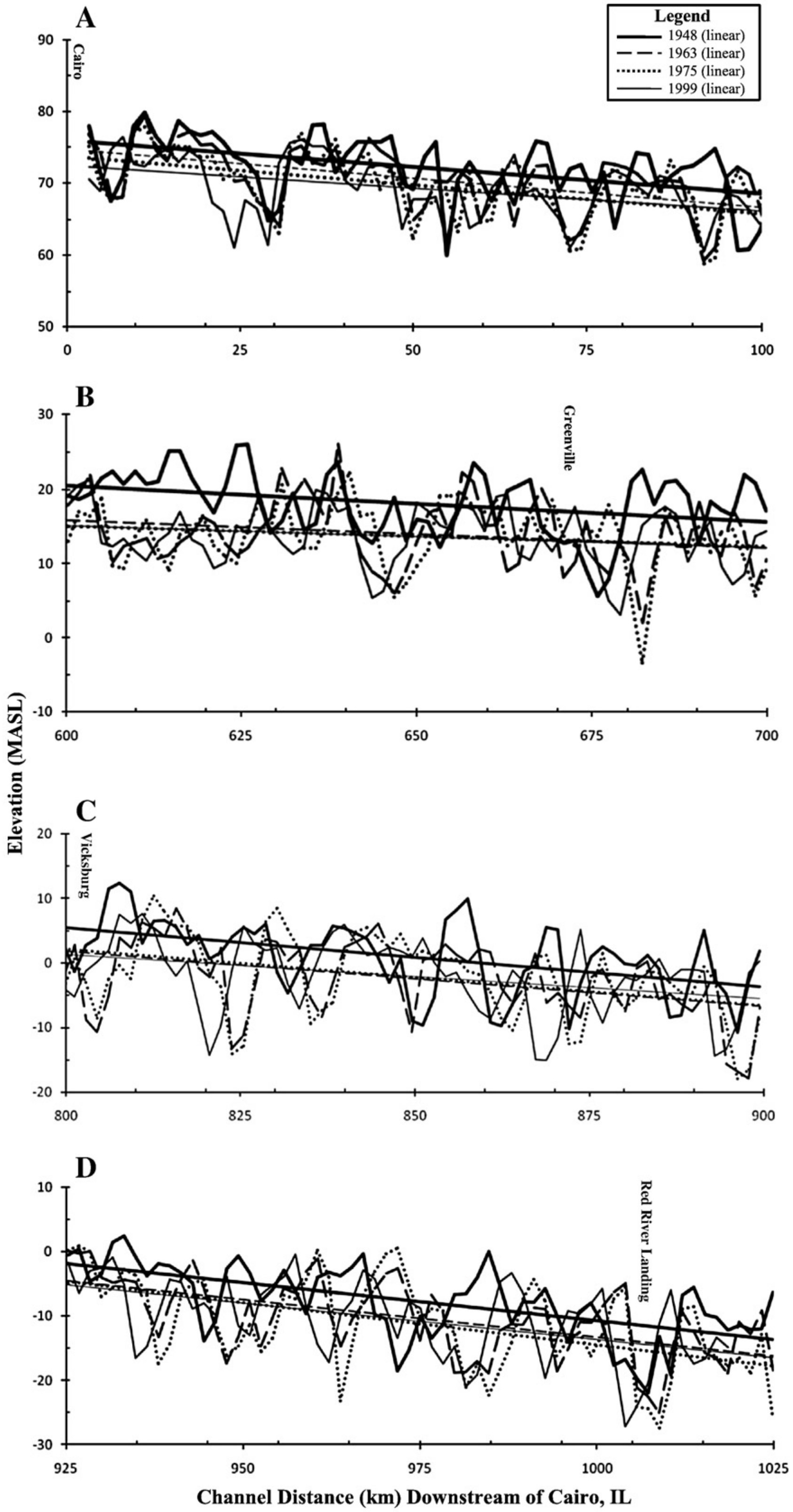


Fig. 17. Long profile of Lower Mississippi River thalweg comparing the 1948, 1963, 1975, and 1999 hydrographic surveys. The data are of soundings of the channel bed thalweg averaged over 1.6 km (1 mile) reaches. The channel distance is referenced to kilometers downstream (below) Cairo, IL (KM/B/C). A. 0–100 KM/B/C, B. 600–700 KM/B/C, C. 800–900 KM/B/C, D. 925–1025 KM/B/C. The field surveying to compile each hydrographic survey was collected over several years (see Kesel, 2003, Table 1 for survey years). Data source: Mississippi River Commission, hydrographic surveys, Vicksburg, MS.

oxbow lakes already having infilled by >75% of their surface area (Table 3). The cutoff lake with the least amount of infilling, as a percentage of the original surface area, is Hardin cutoff (1942), which has infilled 52% of its basin. Of the sixteen meander neck cutoff lakes, only three have greater than half of the original lake area remaining. On average, 67.7% of the total lake surface area has been converted to

Table 3
Infilling of meander neck oxbow lakes along the Lower Mississippi River

Name	1963 KM/A/HOP	Year of cutoff	Area (km^2) of cutoff*	Oxbow lake area (km^2)*	% Infilled*	Embanked (yes/no)
False River	417	1699–1722[a]	29.1	12.9	55.7	No
Racouri-Old River	481	1848[a]	32.1	20.6	35.9	Yes
Lake Mary	518	1776[a]	16.4	11.3	31.1	No
Glasscock Cutoff	552	1933[b]	17.3	7.7	55.8	Yes
Giles Cutoff	589	1933[b]	21.4	5.4	74.6	Yes
Lake Saint John	610	Prehistoric[a]	17.2	9.2	46.6	No
Rodney Cutoff	624	1936[b]	8.2	2.8	65.3	No
Lake Bruin	642	Prehistoric[a]	15.3	12.2	20.4	No
Yucatan Cutoff	657	1929[b]	12.7	8.5	32.5	Yes
Diamond Cutoff	682	1933[b]	18.5	4.3	76.7	Yes
Marshall Cutoff	721	1934[b]	9.7	0.5	94.8	Yes
Eagle Lake	744	1866[a]	26.9	17.9	33.5	No
Willow Cutoff	745	1934[b]	12.9	3.7	71.4	Yes
Lake Providence	784	Prehistoric[a]	12.4	6.0	51.5	No
Sarah Cutoff	811	1936[b]	7.1	1.3	81.5	Yes
Worthington Cutoff	827	1933[b]	11.0	1.6	85.4	Yes
Lake Lee	847	1858[a]	13.5	7.3	46.3	Yes
Lake Chicot	856	Prehistoric[a]	22.1	17.4	21.3	No
Leland Cutoff	867	1933[b]	18.6	8.5	54.0	Yes
Tarpley Cutoff	871	1935[b]	13.7	2.3	83.5	Yes
Ashbrook Cutoff	884	1935[b]	11.4	5.1	55.0	Yes
Caulk Cutoff	925	1937[b]	17.0	6.0	64.5	Yes
Sunflower Cutoff	1006	1942[b]	17.1	6.5	62.0	Yes
Jackson Cutoff	1011	1941[b]	14.3	3.7	73.9	Yes
Hardin Cutoff	1091	1942[b]	32.4	15.5	52.0	Yes

*The area of infilling expressed as a percentage of the oxbow lake area. Oxbow lake area (km^2) estimated from historic hydrographic surveys and large-scale USGS National Hydrographic Data (NHD) in ArcGIS.

[a] Source: Gagliano and Howard (1984).

[b] 1928 Mississippi River & Tributaries Project.

wetlands since the year of cutoff. This represents a dramatic overall reduction in floodplain lake environment, and is of considerable significance to riparian ecology dependent upon high levels of channel and floodplain connectivity associated with the annual flood pulse. As perhaps expected, considerable differences occur in the infilling of embanked and non-embanked oxbow lakes (Fig. 18). In comparison to the oxbow lakes created by the 1928 MR&T Act within the embanked floodplain, older oxbow lakes that are not within the embanked floodplain have infilled on average by 37% (Fig. 19; Table 3). Prehistoric oxbow lakes, such as Lake Chicot, Lake Providence (Fig. 2), and Lake Saint John (Fig. 17) have infilled by 21%, 47%, and 52%, respectively. Thus, the influence of floodplain embankment is to arrest the oxbow lake sequence (e.g., Gagliano and Howard, 1984) outside of the dikes, but accelerate the infilling of oxbow lakes within the embanked floodplain.

The high rate of oxbow lake infilling within the embanked floodplain occurred during a period in which considerable spatial variability was observed in discharge–stage relationships along the Lower Mississippi River (Smith and Winkley, 1996; Biedenharn and Watson, 1997; Wasklewicz et al., 2005; Pinter et al., 2006a,b). Because of the variety of local factors that influence oxbow lake sedimentation (e.g., main-stem channel and lake geometry, position, distance, size, management) there is no clear relation between the spatial pattern of oxbow lake infilling (Fig. 19) and changes in river stage. USGS gauging stations at Memphis, Helena, Arkansas City, and Vicksburg (Fig. 1-A) underwent a reduction in stage for specific discharge magnitudes. Stage levels have increased since the mid 1980s, but have not returned to pre-cutoff levels. In contrast, stage–discharge relationships in the southern portions of the alluvial valley did not exhibit pronounced reduction following channel cutoffs (Smith and Winkley, 1996; Wasklewicz et al., 2005). Data at the Natchez USGS gauging station reveals little reduction in stage following channel engineering, and stage is now higher than pre-cutoff levels. Wasklewicz et al. (2005) report an increase in flood frequency and duration for Natchez, and an opposite pattern, reduced frequency and duration, just upstream at Vicksburg. Indeed, the 2008 flood at Natchez was the highest flood stage since the record flood stage of 1937. Further downstream, at Red River Landing, stage levels did not reduce following major engineering activities, and instead have increased (Smith and Winkley, 1996). Although the incision caused by the meander neck cutoffs likely initially reduced overbank sedimentation of floodplain environments because of lower stage levels for specific discharge magnitudes, sedimentation into oxbow lakes via the cutoff channels (or batture channel) may have increased. For example, the oxbow lake at Marshall cutoff (1934), upstream of Vicksburg, is

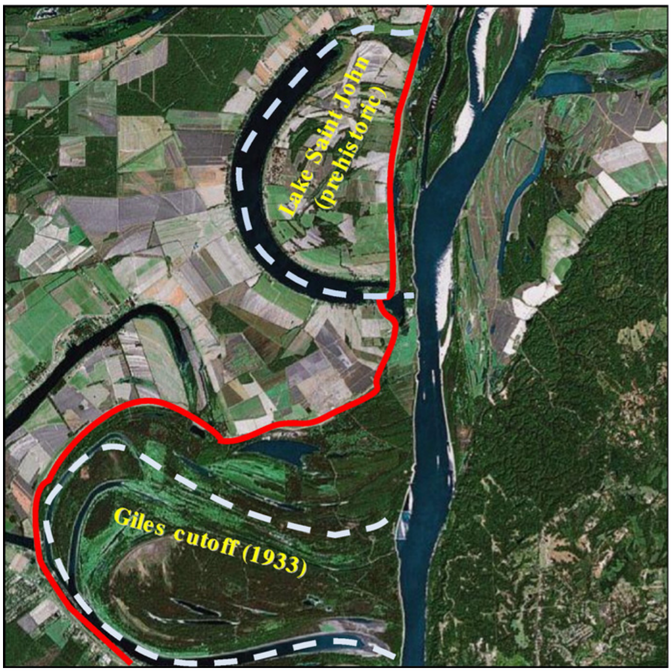


Fig. 18. Example of two meander neck cutoffs (dashed lines), illustrating the influence of embankment on infilling of oxbow lakes, near Natchez. Lake Saint John is a prehistoric meander bend cutoff (Gagliano and Howard, 1984) and is located outside of main-stem river dikes (solid line), while Giles cutoff (1933) is within the embanked floodplain. In comparison, oxbow lakes within the embanked floodplain have undergone much higher average rates of infilling.

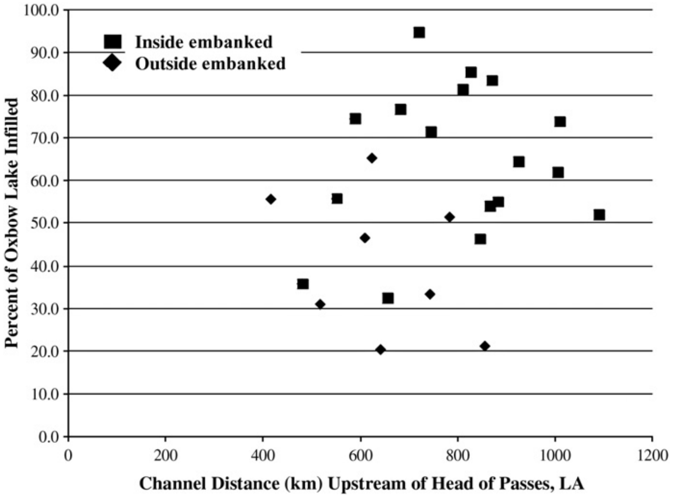


Fig. 19. Relationship between the percentage of oxbow lake infilling with channel distance, expressed as kilometers above Head of Passes, LA (KM/A/HOP). The oxbow lakes depicted as solid squares are associated with the 1928 MR&T Act. The solid diamonds represent oxbow lakes located outside of the embanked floodplain and include natural and anthropogenic cutoffs (created before the US Army Corps of Engineers cutoff program). See Table 3 for reference.

essentially completely infilled with 95% of the lake surface area converted to floodplain wetlands.

The dikes along the Lower Mississippi River are constructed upon a framework of Holocene floodplain deposits having considerable variability in permeability (Mansur et al., 1956; Krinitzsky and Wire, 1964). Groundwater seepage beneath dikes and sand boils behind dikes represent a persistent problem throughout the alluvial valley during high stage events and requires constant monitoring and fortification (US-ACE, 1998a,b,c, 2000; Li et al., 2003; US-ACE, 2005). An important issue confronting flood management along the Lower Mississippi concerns the design and construction of local floodplain "borrow pits" usually located within the batture (riverside of dike) (Hewson, 1860; US-ACE, 1998a,b,c, 2000) (Fig. 7), created as floodplain deposits are excavated for adjacent dike construction and maintenance. Floodplain borrow pits do not represent a significant amount of the total floodplain area within the embanked floodplain, but they do represent distinctive anthro-geomorphic floodplain features. Floodplain borrow pits are generally elongate in shape and oriented with adjacent dikes. Most borrow pits exceed 100 m in width and extend for hundreds of meters (Fig. 7). The average depth of floodplain borrow pits is 2.1 m, while the average area and volume of floodplain borrow pits is 7.8 ha and 78,510 m^3, respectively (Fig. 20-A) (Buglewicz et al., 1988). Borrow pits are highly connected to floodplain aquifers, but the major control is flooding and slackwater sedimentation of fine-grained sediments (Fig. 20-B). It is acknowledged that floodplain borrow pits enhance levee underseepage and require additional flood management measures, such as seepage wells, berm construction, and drainage ditches landward of the levee where fine-grained top stratum lacks sufficient thickness (<~1.0 m) (US-ACE, 1998a,b,c, 2000). Although the creation of borrow pits has become controversial and associated with floodplain destruction (US-ACE, 1998a,b,c), after a few decades floodplain borrow pits develop "environmental" attributes associated with floodplain lakes (US-ACE, 1998a,b,c). Nevertheless, the clayey topstratum of overbank (clastic) floodplain deposits are essential for limiting levee underseepage and piping, but is also the desired sedimentary deposit for modern levee construction and maintenance. Organic rich swamp clay, prevalent in the lowermost alluvial valley and delta plain, is prone to compaction and decomposition, thereby increasing the risk of levee failure. The need for suitable clay is a major challenge confronting flood management in the New Orleans metropolitan area, as identified by the US-ACE (US-ACE — New Orleans, 2007), setting forth a wave of borrow pit creation and selective stripping of floodplain clay as the US Army Corps of Engineers attempts to finish the 1928 MR&T Project ahead of the scheduled year of completion in 2010.

5.2. The Dutch Rhine

The consequences of specific elements of flood management along the Lower Mississippi are well observed within the channel, but are just beginning to be observed within the floodplain. Other fluvial systems influenced by similar procedures over longer periods of time, however, may provide comprehensive insight into the longer term impacts of flood management to floodplain geomorphology. In contrast to the Mississippi, the Rhine River distributaries in The Netherlands have been embanked (Fig. 1-B) for almost 800 years and have been influenced by a number of flood management activities (Fig. 6). The modern Dutch Rhine is embanked by dikes designed to withstand floods having a recurrence intervals of 1:1250 years in the east, and increasing to 1:10,000 years in the western Netherlands. Nevertheless, a number of issues confront flood management in The Netherlands that relate to the floodplain geomorphology. As a consequence of embankment, flood waters only reach the distant flood basins during extreme conditions. During the more frequent minor floods, the water remained between the dikes. As a result, natural vertical accretion of floodbasins ceased, while overbank sedimentation of silty clays became limited to 0.5–1 km wide zones along the main channels (Fig. 1-B).

The influence of river dikes on floodplain geomorphology also results in distinctive morphologic and sedimentary features, which represent a flood archive. Dikes were breached during extreme discharge events. But the occurrence of coastal surges driven inland by

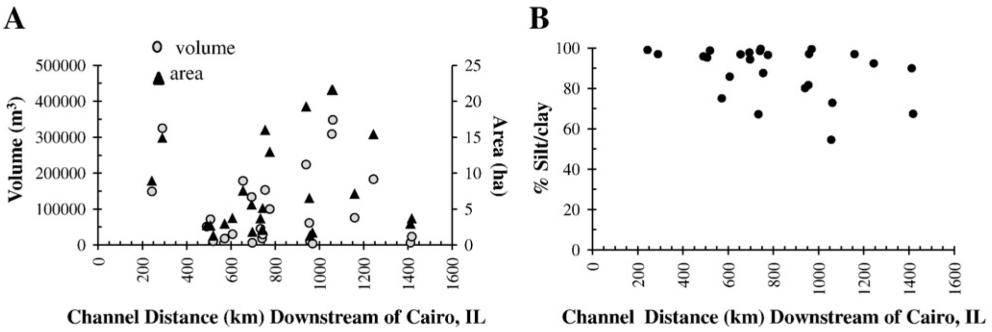


Fig. 20. Geomorphic characteristics of selected floodplain borrow pits along the embanked floodplain of the Lower Mississippi. Data from Buglewicz et al. (1988). A. Morphologic dimensions of "average" active floodplain borrow pits along the Lower Mississippi River. The average area and volume of floodplain borrow pits is 7.8 ha and 78,510 m^3, respectively. B. The percent silt-clay (<0.063 mm) of "average" active borrow pits deposits along the Lower Mississippi River. The fine-grained sediments result from slack water sedimentation.

Fig. 21. Examples of wielen (dike breach ponds) along the River Waal (major Rhine distributary). A. An infilled wiel along the inside of the embanked floodplain. Note that the dike was routed around the pond, resulting in rapid sedimentation and infilling. Picture: H.J.A. Berendsen. B. Open dike breach pond located along the dike of the River Waal along the outside of the embanked floodplain. The absence of flood sedimentation ensures that these features remain as small floodplain lakes for centuries.

northwesterly storms, and ice jams during extremely cold winters, also resulted in high flood stages and represented important dike breach mechanisms. The floodplain sedimentology was also important to the occurrence of dike breaches. Dikes crossing over the sand body of an older alluvial ridge were more susceptible to seepage and subsequent breaches. At the location of a dike breach, the flood waters eroded deep scour holes (called wielen in Dutch). Consequently, a repaired dike section was built around the breach holes. The eroded material from the scour hole is typically deposited as a fan-shaped splay of poorly sorted, coarse grained sediment overlying the fine-grained overbank deposits (breach deposits located at 4.3–5.5 km, Fig. 5). River dikes reconstructed between the channel and wiel, however, prevent sedimentation and create a lake environment that persists for hundreds of years (Fig. 21-B).

The ponds (“wielen”) that became located at the river side of the repaired dike have been functioning as natural traps for overbank fines and organic detritus (Middelkoop, 1997). A floodplain segment along the Waal River, downstream of Nijmegen, provides excellent examples of active ponds on the modern floodplain in different stages of development, which were historically reconstructed through a combination of floodplain corings and analysis of archival documents.

At Wamel, the oldest of the two ponds (WU) was formed in 1726 and is situated within the embanked floodplain. Hydrologic connectivity and sedimentation from the Waal occurs when the discharge at Lobith exceeds a threshold of about 7900 m^3/s. The total depth of the WU breach is about 8.5 m (Fig. 22), and contains a +5 m thick body of fine, humic lake-fill sediment beneath about 3 m of pond water (which varies seasonally). The laminated clays in this dike breach fill consist of 1–5 cm thick dark-grey to black layers in which 0.2–3.5 cm thick brown-grey laminae are embedded. The density of the sediment increases between 50 and 200 cm depth from about 0.4 g/cm^3 to 0.9 g/cm^3. The sediment is compacted in the lower section of the profile. The total sediment load in the pond is about 370 g/cm^2. The clay contents of the sediment are between 30% and 60%, and they are highly variable due to the lamination. In the upper 110 cm, the organic matter contents range between 9 and 12%. At greater depths the organic matter content is about 6%. A sharp erosional contact between the humic lake-fill deposits and the underlying coarse sandy channel bed deposits is identified at a depth of 5.5 m (Fig. 22).

The second pond (WI) was formed when the Waal dike breached during the night of 27–28 January, 1781 (Fig. 22). After the flood, the dike was rebuilt between the pond and the river, and, as a result, no sedimentation occurs during seasonal flood pulses. The WI pond is characterized by 7.0 m of water overlying 2.35 m of sedimentary fill. The base of the dike breach fill is marked by a sharp transition to coarse sand. The upper 2 m of sediment consists of non-laminated black humic clays, and in the lower 35 cm of the fill, the sediment is more silty. The sediment densities vary between 0.35 and 0.65 g/cm^3 in the upper part of the profile. In the lower section they increase to nearly 1.2 g/cm^3 (Fig. 22). This increase is not caused by compaction, but is related to changes in the sediment composition. The organic matter contents in the upper part of the profile are between 6 and 15%, but appreciably decrease in the lower 0.35 m of the core, as the silty clays contain less than 2% organic matter.

It is important to note that the examples shown here represent a small segment of the larger Rhine–Meuse floodplain distributary system that has been embanked with over a thousand kilometers of dikes for over eight centuries. During the centuries that followed embankment, numerous dikes breaches occurred. The cumulative result is a distinctive type of antho-geomorphic floodplain feature, with the ponds (wielen) representing flood archives for centuries of extreme events generated by different flood mechanisms (e.g., high discharge, ice jam, coastal surge). Considering the sedimentary infilling of the “natural” morphologic features (e.g., ride and swale, sloughs, old channels) within the embanked floodplain, wielen represent one of the major morphologic elements of the embanked floodplain geomorphology, and represent important riparian ecological niches (Middelkoop, 1997).

During the 16–18th century the Waal River became the main branch in the Rhine delta. Medial channel islands and lateral bars were common (Fig. 23). The embanked Waal River had a low-sinuous meandering channel (wave length ~7 km, amplitude 2.5 km) with meander bends translating downstream at a rate of about 2 km per century. Shifting meanders eroded the downstream banks and floodplain, while scroll bars formed upstream of bends (Fig. 24). The accretion of the scroll bars was artificially accelerated by local residents who built small dams to enhance sedimentation to reclaim land from the channel (Middelkoop, 1997; Hesselink, 2002). The newly reclaimed land was used for cultivation of reed, willows, and, after a period of vertical accretion, as meadow for more intensive agricultural practices (Fig. 24). Along eroding banks, groynes were constructed to divert flow and increase sedimentation.

As a result of this step-wise land reclamation a typical geomorphologic floodplain pattern developed, characterized by an almost parallel oriented array of ridges and swales (Fig. 24). The bars that developed in these floodplain sections consist of medium to coarse sands, with median grain sizes typically varying from 210 to 300 μm in

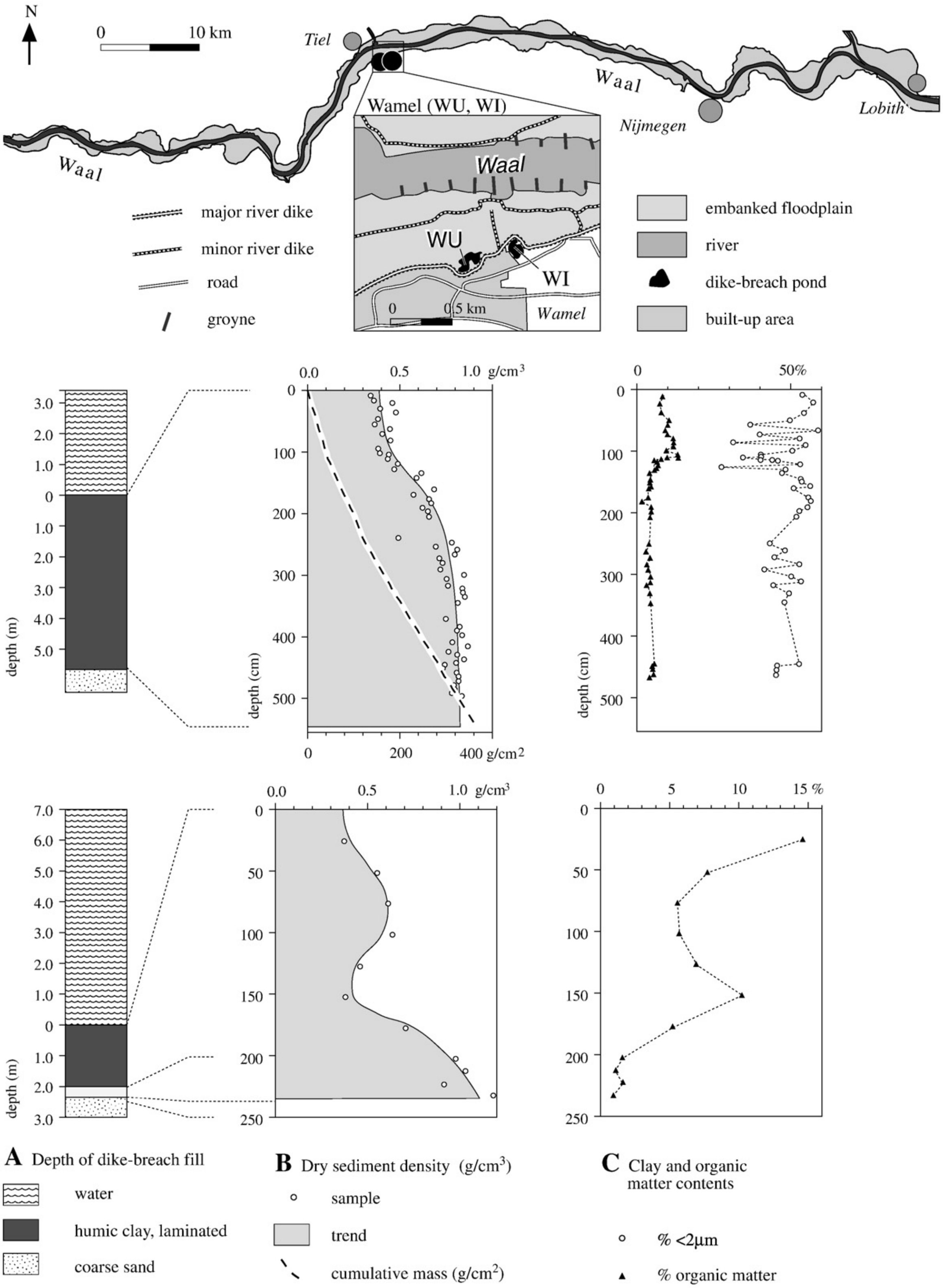


Fig. 22. Sedimentary characterization of wielen (dike breach ponds) along the Waal River, downstream of Nijmegen. The WU wiel was formed in 1726 and has undergone 5.5 m of infilling, while the WI wiel was formed in 1781 and is outside the dike, and has under 2.0 m of infilling (modified from Middelkoop, 1997).

the upper dm, increasing to 400 and over 800 μm at greater depths. These channel bed deposits are covered by 1 to 2 m thick overbank deposits, mainly consisting of sandy and silty clay. The fills of deep residual channels consist almost entirely of dark-grey clay and silty clay, which is humic over several dm. The secondary channels have silted-up with humic clays, clays and silty clays, which are generally less humic than the deep channels along the river dike. Occasionally, the upper parts of the channel fill consist of silty and sandy clay that cannot be distinguished from the overbank deposits. Thus, where the main channel migrated and eroded its outer banks, these silted-up

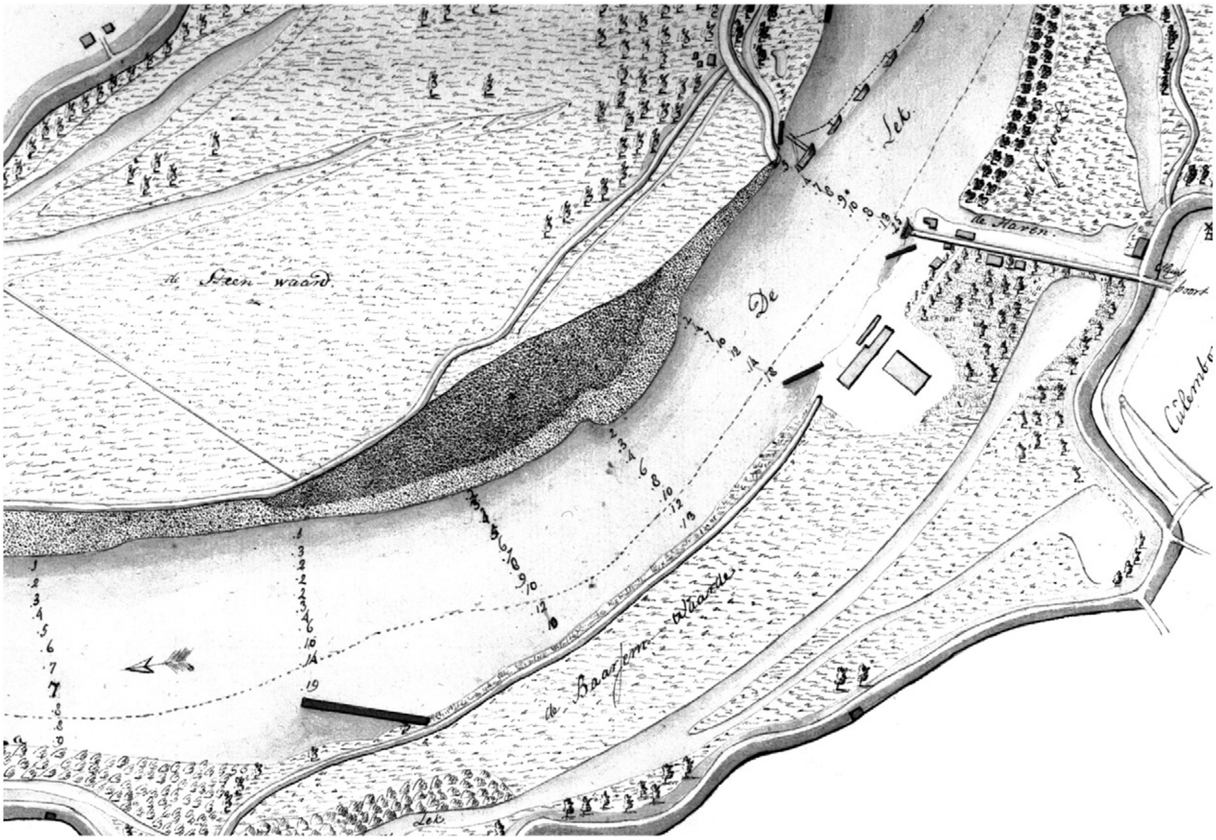


Fig. 23. Hydrographic survey of the Lek distributary in the 1820s, showing details of embankment and river groynes (modified from Hesselink, 2002).

floodplains were eroded, while lateral accretion continued along the inner bends. In this way the river continued to rejuvenate its floodplain, and reworked its floodplain deposits about two centuries after deposition.

The prevention of lateral erosion by revetment and groyne construction (Fig. 25) has led to a continued accumulation of overbank deposits on the embanked floodplains over the past century. As a consequence of the limited sediment storage capacity the embanked floodplain is elevated locally more than 2 m relative to the pre-embankment floodplain level. In addition, the embanked floodplain deposits are coarser grained than the pre-embankment overbank deposits. Before embankment, floodplain deposits mainly consisted of clay and silty and humic clay (see 9.8–13.9 km, Fig. 5). After embankment, floodplain deposits consisted of fine sand, silty and sandy clay and clay (see embanked floodplains of the Waal and Nederrijn, Fig. 5). This difference can likely be explained by the limited space available for sorting (e.g., Pizzuto, 1987; Middelkoop and Asselman, 1998). Classic sedimentary sorting of grain size requires adequate space. Because of embankment the space for lateral sediment sorting substantially decreased. The resulting overbank deposits were coarser, and represented a local control on the overbank floodplain facies, rather than being controlled by changes in climate or upper basin land use.

The accelerated phase of floodplain sedimentation is also responsible for altering the floodplain topography, as low depressions and swales were infilled. Further, very little open water remains associated with the artificial oxbow lakes that were created from meander neck cutoffs and channel straightening in the 1800s. As the river has not been able to rework recent overbank deposits, the aggraded floodplains have caused an increase in flood stages, which has increased flood risk and prompted the creation of the Room for the Rhine flood management plan that comprises a range of landscaping measures (Fig. 14 and 26) (Silva et al., 2001; Middelkoop et al., 2002).

6. Synthesis: a general model of large lowland fluvial adjustment to flood management

The adjustment of the Rhine and Mississippi Rivers to flood management provide interesting lessons in comparative historical analysis of major fluvial systems and elucidate several "general" conclusions regarding the continuum of adjustment of large rivers and floodplains to flood management (Fig. 27). Understanding the sequence of change that occurs within a particular river influenced by these activities may provide river managers with guidance to implement more effective management and policy, particularly if it is known at what stage in the model a particular river is within. This model may apply to the lower reaches of large alluvial valleys and delta plains (Fig. 27, I) with a complex floodplain geomorphology influenced by a combination of dikes, land drainage, straightening (e.g., cutoffs), and channel bank protection by groynes and revetments. These individual engineering options are usually implemented within a specific sequence because of river engineering initiating an unintended geomorphic response.

With few exceptions the first significant human impacts along rivers are dikes for flood protection, triggering an abrupt alteration of fundamental floodplain processes that segments the floodplain into two distinctive zones: Embanked floodplains which undergo higher overbank stages and higher rates of sedimentation, and distant flood basins effectively cutoff from active main-stem overbank sedimentation except during dike breach events (Fig. 27, II). The outer floodplain (outside of the dikes) also includes abandoned channels and oxbow lakes. Along the margins of the dikes the floodplain is altered because of the creation of floodplain borrow pits and dike breach ponds. Although dikes effectively eliminate overbank flood pulses from reaching the distant floodplain, except during dike breach events, the hyporheic connectivity between the main-stem channel and distant

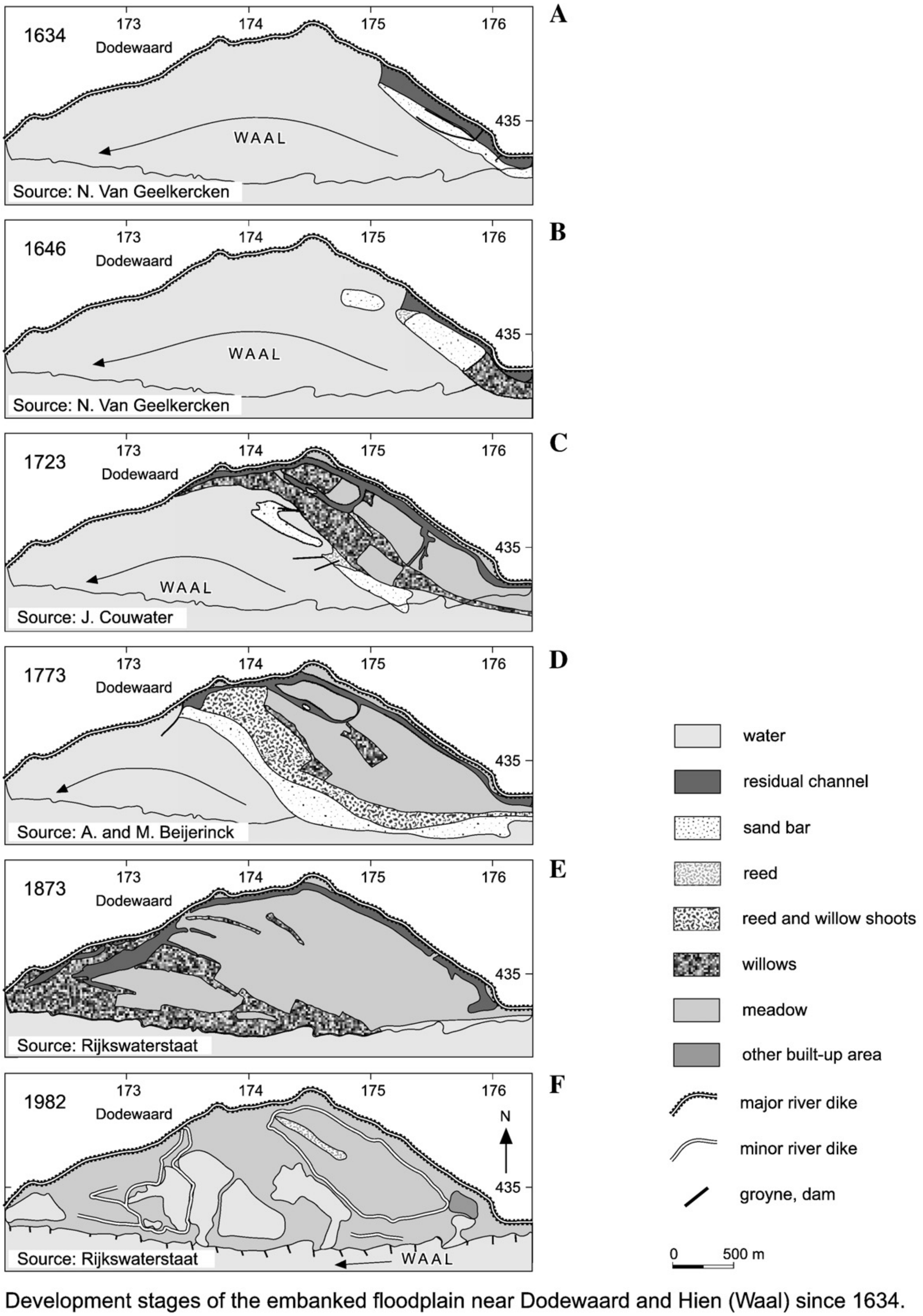


Fig. 24. Model of embanked step-wise floodplain development along the Waal distributary caused by river stabilization, particularly in response to groyne construction and channel narrowing. Modified from Middelkoop (1997).

floodplain aquifer and lakes is likely enhanced during high stage events by the presence of dikes. A fundamental component of dike construction and management is the construction of drainage channels within the distant floodplain reaches (US-ACE, 1998a,b,c, 2000, 2005), while the frequency of sand boils may increase (Mansur et al., 1956). The influence of land drainage is less abrupt and more variable because of the underlying stratigraphy and the type and intensity of land use, but can lead to rapid subsidence associated with

Fig. 25. The restrained Waal River. Photo showing river groynes and side channels within the embanked floodplain.

dewatering and oxidation of organic rich soils, which is not buffered by addition of flood deposits.

The most common approach to river straightening involves channel shortening by meander neck or chute cutoffs (Fig. 27, III). This results in a direct alteration of local-scale hydraulics and initiates a channel knickpoint, which frequently results in rapid channel incision. Channel bed incision initiates an unintended geomorphic response, because oversteepened banks frequently result in bank erosion and an increase in channel width. Channel reaches within coarser grained floodplain deposits appear to be more sensitive than channel reaches within cohesive deposits. The sediment added to the active channel by bank erosion may buffer incision, but bank erosion threatens river dikes and requires further engineering measures to ensure a stable and navigable channel (Fig. 27, IV). Thus, a common engineering solution after river straightening is revetment construction to stop bank erosion. An additional measure, particular where the channel is excessively wide, is in the installation of river groynes (commonly referred to as wing dikes in the U.S). These measures trap coarser bed sediments, which over long periods can result in the development of a new low floodplain surface (Fig. 27, V).

The lack of channel mobility implies that recent embanked floodplain deposits are not reworked, and rather, the rate of aggradation accelerates following channel stability (Fig. 27, VI). Thus, over long time periods the channel and floodplain have been fundamentally altered. The floodplain has been segmented into two distinct zones. The embanked floodplain can be seen as evolving towards an endmember condition characterized by a higher surface and reduced topographic complexity, with artificial oxbow lakes being essentially infilled. Further, the sedimentary facies are altered, and overbank deposits consist of coarser flood deposits because of the

Fig. 26. Photo of wielen and nature development along the Waal (Source: Ten Brinke, 2005).

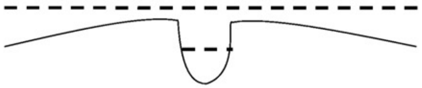
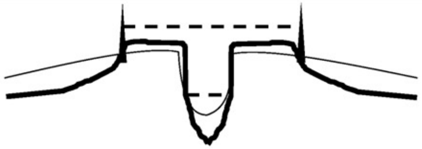
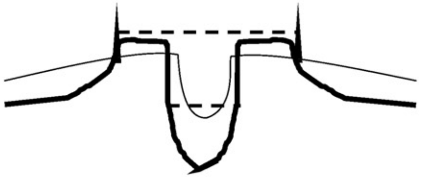
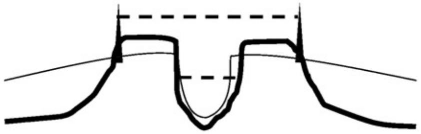
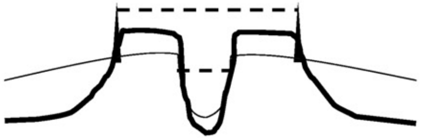
Era	Management / Engineering	Condition / Response	Valley Cross-Section
I. Natural	**N/A**	**Channel:** relative stability, sediment exchange (erosion/aggradation) with floodplain **Floodplain:** comprehensive suite of floodplain environments with complex topography, lateral hydrologic connectivity (surface and hyporheic)	
II. Embankment	**Dikes and land drainage**	**Channel:** no strong response to dike construction **Floodplain:** embanked and distant floodplain, creation of floodplain borrowpits and dike breach ponds associated with dike construction, increased stage and sedimentation of embanked floodplain during large events, dikes result in loss of surface lateral connectivity with channel and associated floodplain processes, land drainage results in subsidence of distant floodplain, which retains hyporheic connectivity with the channel (perhaps increased at high river stage)	
III. Channel Disturbance	**Channel straightening (cutoffs)**	**Channel:** knickpoint formation (increase in slope and stream power) associated with meander bend cutoffs, rapid channel bed incision within noncohesive floodplain deposits **Floodplain:** creation of artificial oxbow lakes within embanked floodplain, embanked sedimentation results in infilling of low swales and sloughs and diminished floodplain topography	
IV. Complex Adjustment	**Bank protection, Monitoring**	**Channel:** knickpoint migration (upstream), bank erosion (lateral) is dominant due to over-steepened banks, particularly along noncohesive floodplain deposits, rapid floodplain reworking, differential upstream – downstream response (timing and magnitude) **Floodplain:** continued aggradation of low depressions and rapid infilling of artificial oxbow lakes within the embanked floodplain, continued subsidence and hypoheic connectivity of distant floodplain require further land drainage	
V. Channel Stabilization	**Bank protection, Groynes, Revetments**	**Channel:** narrowing and greater stability (locked in place) **Floodplain:** absence of floodplain reworking and accelerated aggradation with coarser floodplain deposits, infilling of embanked oxbow lakes and depressions decreases surface connectivity paths (sloughs, swales)	
VI. Floodplain Response	**Dike stability and fortification**	**Channel:** moderate incision due to loss of sediment from floodplain reworking, but lateral stability maintained with groynes and revetments **Floodplain:** infilling of oxbow lakes and smoothing of embanked flood plain topography by accelerated aggradation of coarser deposits within embanked floodplain, reduced floodplain storage capacity and higher flood (overbank) stage	

Fig. 27. Simplified model of the continuum of geomorphic adjustment of the lower reaches of large river channels and floodplains to flood management from dikes and channel stabilization (groynes and revetments). The dashed line indicates low and high stage. The "Natural" floodplain profile provides a reference to compare the geomorphic adjustment caused by incision, bank erosion, floodplain aggradation, and subsidence. The figure does not portray individual floodplain environments or the full range of floodplain topography (swales, abandoned channels, lakes, borrow pits, dike breach ponds).

greater energy of flood waters within embanked floodplains and the lack of suitable space to induce lateral sediment sorting. Floodplain alteration reduces the capacity for the floodplain to store floodwaters, and increases the stage of overbank events. The threat of floods overtopping dikes may lead to new flood management strategies that increases lateral connectivity between channels and floodplains, which is favorable for geomorphic integrity and for environmental management of riparian corridors (Thoms, 2003; NRC, 2005; Day et al., 2008).

7. Conclusions and implications

The Lower Mississippi River and lowermost Rhine River represent large fluvial systems intensively regulated for flood management and stability. Although flood management between the Rhine and Mississippi varies on many accounts, the actual methods of flood (and river) management are somewhat similar, with the fundamental elements of management including dikes, groynes, cutoffs, and bank protection. The implementation of these specific types of activities, however, varies considerably. And, the historical analysis provided by this study illustrates that flood management is associated with unintended geomorphic consequences that have required additional management solutions, and in some cases have further increased flood risk.

The adjustment of rivers and floodplains, influenced by fundamental approaches to flood management (dikes, groynes, cutoffs, etc…), is inherently scale-dependent and adjusts along a time–space continuum. Finer elements of the fluvial system, such as channel cross-sections, adjust over smaller temporal-scales. Larger elements of the system, such as the floodplain geomorphology, requires longer periods for significant change to occur. This has management implications, as disturbances introduced into the system decades ago (or longer) may require significant amounts of time to be observed on the floodplain. While the direction of adjustment is scale-dependent, the style of adjustment involves positive feedbacks and unintended consequences, which can require further management options. Meander bend cutoffs initiate channel incision, which destabilizes channel banks and causes bank widening. Floodplain embankment results in accelerated sedimentation within a narrower floodplain corridor, which eventually reduces floodplain inundation capacity. The manner in which the system adjusts to this consequence is likely to be dependent upon the floodplain geomorphology, and probably requires further management options.

Although most large river floodplains impacted by flood management may be seen to exhibit many elements of the fore presented model, the exact character of adjustment of the fluvial system to flood management is largely dependent upon the specific manner in which the engineering is implemented, as well as the floodplain geomorphology and sedimentology. For example, the adjustment of the Lower Mississippi River in response to cutoffs was constrained by clayey backswamp and older bedrock within the channel bed by neotectonic controls. Alternatively, dikes that overlay sandy channel belt deposits, such as shown for the Rhine, are more likely to experience seepage and be breached, resulting in substantial alteration to the floodplain geomorphology.

Modern flood management of large rivers is fundamentally an experimental science, carried out by large government agencies in trial and error operations that initiate extensive geomorphic change with long lasting environmental consequences. Specific procedures are applied based on perceived achievements in different settings or laboratory analysis, but the ultimate success of such applications can only be understood through historical analysis, such as this study has (partially) provided. Specific flood management options are frequently associated with unintended geomorphic and hydrologic consequences, which over time become important to modern flood management in the context of a changing environment.

The Dutch Rhine represents a tremendous historical lesson in flood management science. By taking a long-term perspective this paper illustrates an intriguing dimension of flood management: over long time-scales the actions to reduce flooding influence processes that can reduce the effectiveness of flood management. The activities and style of response associated with implementation of the 1928 MR&T flood management plan are only now being realized. At the same time, the recent Hurricane Katrina–Rita flood in New Orleans has renewed a call for looking to the Rhine as a "model" for flood management, and frequent delegations of US scientists, engineers, and policy makers tour the Delta Works project in coastal Holland. The sequence of geomorphic response to flood management provided by this study, however, suggests that the longer historical perspective offered by the Rhine is also important to consider. Flood management science has traditionally emphasized understanding modern hydraulics and hydrology, with the older floodplain geomorphology viewed as the "historical" framework in which modern processes operate. This study illustrates, however, that the floodplain geomorphology represents an active and dynamic control on the modern system, and should be carefully implemented into comprehensive flood management for large lowland floodplains.

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