CHAPTER 2

Managing Floods in Large River Basins in the USA: The Mississippi River

Charles E. Shadie, Pilar Lopez-Llompart, Melissa Samet, Todd Strole, and G. Mathias Kondolf

Abstract The Mississippi River was the first theater in which the federal government sought to control floods and improve navigation through the efforts of the US Army Corps of Engineers, initially under a "levees only" philosophy, later revised (after the disastrous 1927 flood) to include multiple approaches, such as backwater areas and flood bypasses. The Mississippi River and Tributaries Project successfully conveyed the 2011 flood (with more rainfall than fell in 1927), but operation of critical

C. E. Shadie
Mississippi Valley Division, US Army Corps of Engineers, Vicksburg, MS, USA

P. Lopez-Llompart
University of California Berkeley, Berkeley, CA, USA

M. Samet
National Wildlife Federation, Washington, DC, USA

T. Strole
Consultant, St Louis, MS, USA

G. M. Kondolf (✉)
University of California Berkeley, Berkeley, CA, USA

University of Lyon, Lyon, France

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bypasses was threatened by encroachment of buildings within the bypasses, permitted by local governments. Structures designed to concentrate flow for the benefit of navigation can result in higher flood stages and thus can undermine flood control efforts. Allowing floodplains to flood naturally, as much as possible, can have benefits not only for the ecosystem but also for managing floods to minimize inundation of cities.

Keywords Mississippi River • Mississippi River 2011 flood • New Madrid Floodway • West Atchafalaya Floodway • Effects of navigation structures • Floodplain benefits

2.1 Introduction

Charles E. Shadie and G. Mathias Kondolf

2.1.1 The Mississippi River Basin

The Mississippi River Basin drains 41% of the 48 contiguous states of the USA. Its 3.2-million km^2 basin (1.25 million mi^2) extends from the Rocky Mountains to the Appalachian Mountains, the largest river system in North America and the third-largest river basin in the world (Fig. 2.1). Its basin roughly resembles a funnel with its spout at the Gulf of Mexico. The lower alluvial valley of the Mississippi River is a relatively flat plain of about 90,600 km^2 (35,000 mi^2), which historically flooded during times of high water prior to the construction of flood protective works, which were begun in the late 1700s. The Mississippi River system has an average flow into the Gulf of Mexico (via the Mississippi and Atchafalaya Rivers) of about 18,100 m^3/s (640,000 ft^3/s), much greater during floods. In one of the largest floods recorded on the Mississippi, in May–June 2011, the peak flow into the Gulf of Mexico was over 68,000 m^3/s (2.4 million ft^3/s). The Mississippi River has been extensively altered for navigation and flood control (Alexander et al. 2012).

The 2011 flood brought into focus many issues in the Mississippi River Basin, such as the role of the federal flood control project in this inter-state basin, the resistance of local interests to honoring flowage easements on their properties, and the conflict between structural approaches to flood

Fig. 2.1 The Mississippi River Basin

control and ecosystem services provided by naturally functioning floodplains. In this chapter, Charles Shadie of the US Army Corps of Engineers (Corps) points out that during the 2011 flood, the mid-twentieth-century flood control project worked largely as planned, preventing an estimated over $110 billion in flood damages (Sect. 2.2). In this section, he also notes that some navigation features of the Mississippi River and Tributaries (MR&T) Project (channel cutoffs, channel dredging, etc.) reduced the severity of flooding. The role of levees and navigation structures on flood heights has been contested for half a century, including Belt's (1975) conclusion that the record flood stages in 1973 were "manmade" due to "the combination of navigation works and levees." Melissa Samet considers the conflicts inherent between the Corps' objectives of navigation and flood risk management on the Mississippi, and argues that navigation works have increased flood risk (Sect. 2.4). Pilar Lopez-Llompart and Matt Kondolf consider land-use conflicts arising in the federally designated floodways (flood bypasses), where local jurisdictions have given building permits for structures within the floodways themselves, creating inevitable conflicts with the designated uses of the lands within the bypasses, not only exposing houses to flooding, but also compromising operation of the floodways (Sect. 2.3). Notably, in 2011 the state of Missouri sued to prevent a floodway from being activated, but was turned down by the Supreme Court just in time for the Corps to activate the floodway and avoid flood damages to settlements elsewhere. Todd Strole summarizes the benefits of connected floodplains and some successful efforts to restore these ecosystem functions along the highly altered Mississippi River system (Sect. 2.5).

2.1.2 Flood Risk Management in the Mississippi: History and Governance

With its major tributaries the Missouri, Ohio, Arkansas-White, and the Red Rivers, the Mississippi River drains all or part of 31 states and two Canadian provinces (Fig. 2.1). Given the multiple states in the basin, the potential for conflicting priorities among them, and the value of the assets exposed to flooding, the need for a federal role in controlling floods was obvious.

The 1927 Mississippi River flood was the greatest natural disaster up to that point in the US history, as many levees overtopped and breached, and between 120 and 225 crevasses developing, 17 of those being major crevasses on federal levees. The remainder of the breaks—ranging in size from half a mile wide to a mere trickle—occurred in state or local levees. By the time the flood finally subsided in August 1927, over 67,000 km^2 (26,000 mi^2) or 72% of the Lower Mississippi Valley had been inundated to depths up to 9.1 m (30 feet), levees were crevassed, and cities, towns and farms lay in waste. Where it reclaimed the floodplains the river was now in some places up to 160 km (100 miles) across. Crops were destroyed and industries and transportation paralyzed. The human loss was staggering as well, with up to 250 people killed directly, and deaths due to disease and exposure after the flood likely exceeding 1000. In addition, about 162,000 homes were unlivable, and 41,000 buildings were destroyed resulting in over 600,000 people being left homeless, with many having to live in tents for months following the flood. At a time when the federal budget barely exceeded $3 billion dollars, the flood, directly and indirectly, caused an estimated $1 billion dollars in property damage.

In response to the 1927 flood, the US Congress passed the 1928 Flood Control Act, authorizing the MR&T project, which represented one of the first comprehensive public works projects within the Lower Mississippi Valley that would provide enhanced protection from floods while maintaining a mutually compatible and efficient Mississippi River channel for navigation. The project also represented a major departure from relying solely on levees for flood protection. Prior to 1927, local, state, and eventually federal agencies provided flood protection via a “levees only” approach, building levees higher and higher after larger floods overtopped the existing lines of protection. However, the 1927 flood demonstrated that "levees only" would not be adequate to provide the level of flood protection needed along the Lower Mississippi River Valley. The plan developed by the USACE Chief Engineer General Edgar Jadwin would provide flood protection for floods larger than the 1927 flood by acknowledging that, for some floods, measures in addition to levees would be required (Jadwin 1928; Barry 1997).

The MR&T Project consists of four primary components: (1) an extensive levee system to prevent overflows on developed alluvial lands, with a total of 6000 km (3727 miles) of mainstem and tributary levees and floodwalls that were authorized for the MR&T system, of which about 5600 km (3486 miles) have been built; (2) floodways and backwater areas to safely divert or store excess flows at critical reaches so that the levee system will not be unduly stressed. There are four floodways: one in Missouri (Birds Point—New Madrid Floodway) and three in Louisiana (Morganza Floodway, Bonnet Carré Spillway, and the West Atchafalaya Floodway) (see Sect. 2.3), and four backwater areas: St. Francis Backwater Area in Missouri and Arkansas, White River Backwater Area in Arkansas, Yazoo Backwater Area in Mississippi, and Red River Backwater Area in Louisiana (Fig. 2.2); (3) channel improvements and stabilization features (such as meander cutoffs, bank and channel revetments, channel bendway weirs and stone dikes, and dredging) to protect the integrity of flood control features and ensure proper alignment and depth of the navigation channel; and (4) tributary basin improvements, including levees, headwater reservoirs, and pumping stations, designed to expand flood protection and improve drainage into adjacent areas within the alluvial valley (Davis et al. 2017).

2.2 The 2011 Mississippi River Flood: What Worked

Charles E. Shadie

The 2011 flood in the Lower Mississippi River produced record flows throughout the 90,600 km² (35,000 mi²) river basin and resulted in record or near-record stages throughout the lower valley (Camillo 2012). The 2011 flood provides an opportunity to assess the effectiveness of the system of flood control structures in place in the region (Shadie and Kleiss 2012; Davis et al. 2017).

The 2011 flood set records for flow and stage over much of the Lower Mississippi River Basin, testing the MR&T Project as never before. Levees

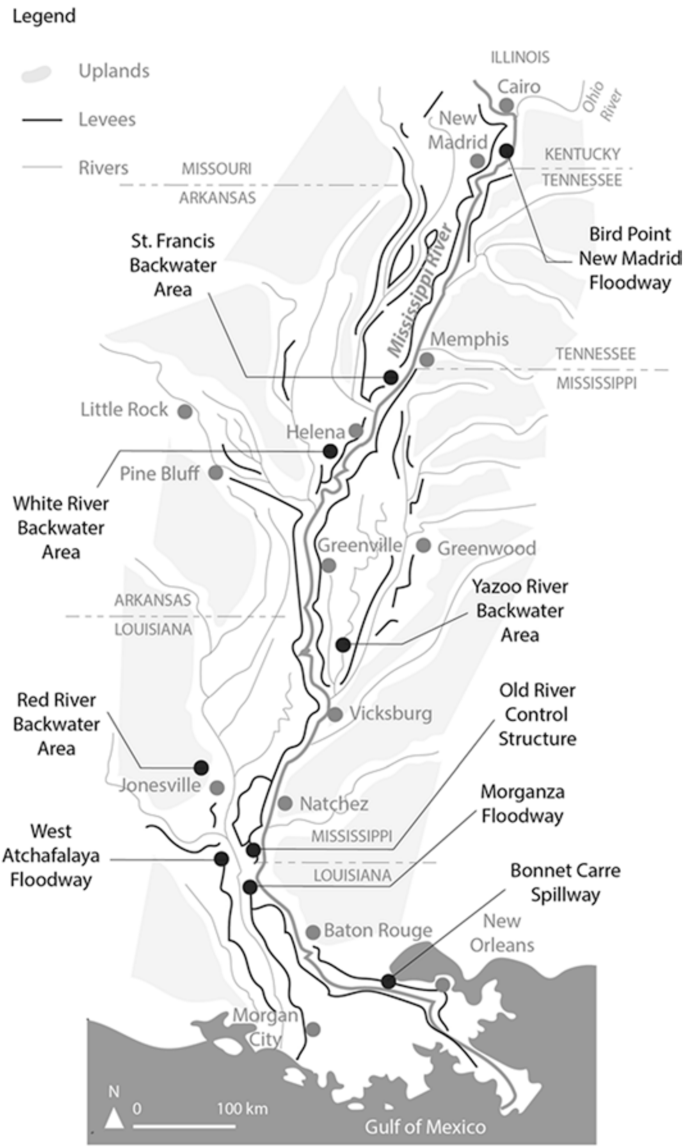

Fig. 2.2 Location of features of the Mississippi River and Tributaries (MR&T) Project. In addition to floodways, backwater areas and principal levees are shown (Source: Redrawn from US Army Corps of Engineers, Davis et al. 2017)

and floodwalls throughout the project experienced higher stages and pressures than from previous floods. In some areas, stages threatened to overtop the levees and floodwalls, requiring the USACE and local emergency crews to flood fight those areas with earthen berms, sandbags, and/or HESCO bastions (rectangular wire mesh containers) to prevent overtopping. While the levees and floodwalls held, hundreds of sand boils occurred throughout the system requiring emergency measures to stabilize the boils and prevent undermining and failure of the levee system. Sand boils had occurred before, throughout the MR&T system, in previous floods, but the 2011 flood placed higher pressures on the system (Shadie and Kleiss 2012).

Floodways played a larger role during the 2011 flood than ever before. For the first time since the project's inception in 1928, a total of three of the four MR&T floodways were operated during a flood. The first floodway operated was the Birds Point—New Madrid Floodway (Missouri). On May 2, 2011, the US Army Corps of Engineers detonated explosives placed in the Birds Point—New Madrid Floodway fuseplug levee to open the floodway and reduce stages and pressures along the levee system. With a record flow of at least 59,500 m^3/s (2.1 million ft^3/s) in the river, a peak of about 11,300 m^3/s (400,000 ft^3/s) was diverted away from the river and down the floodway, providing floodplain storage of 525 km^2 (130,000 acres) with depths up to 6 m (20 feet) (Davis et al. 2017).

As the flood continued to flow down the Lower Mississippi Valley, new record flows and stages were set threatening the levee system in many areas. At Vicksburg, Mississippi, the new record stage of 31.5 m NGVD29 (103.3 feet NGVD29) came within 7–10 cm (3–4 inches) of overtopping the Yazoo Backwater levee, almost placing that backwater area into operation. Further south, the Bonnet Carré Spillway, about 48 km (30 miles) upstream of New Orleans, was opened on May 9, 2011, diverting flows away from the river into Lake Pontchartrain eventually reaching a peak diversion rate of about 8920 m^3/s (316,000 ft^3/s).

Finally, on May 14, the Morganza Floodway structure, about 64 km (45 miles) upstream of Baton Rouge, Louisiana, was opened (Fig. 2.3). At its peak, the structure diverted 5150 m^3/s (182,000 ft^3/s) from the river into the Atchafalaya Basin. This was only the second time the Morganza Floodway had ever been operated. The West Atchafalaya Floodway, with a design flow of 7080 m^3/s (250,000 ft^3/s), was not operated, as its fuseplug (i.e., control weir) did not overtop, both because the Red/Ouachita rivers were not flooding and because the Atchafalaya River channel had downcut in the preceding decades, meaning that a greater flow is now

Fig. 2.3 Morganza Floodway in operation during the 2011 Mississippi flood (Source: US Army Corps of Engineers)

needed to overtop the fuseplug (see Sect. 2.3). Of a total of 148,000 ha (366,000 acres) in the four MR&T floodways, 85,800 ha (212,000 acres) were flooded during this event while the three floodways were operated.

None of the four MR&T backwater areas were operated during the 2011 flood although the Yazoo Backwater levee came close to overtopping. However, because of high Mississippi River stages, the drainage structures in those backwater areas had to be closed. As a result, some flooding in those backwater areas occurred from internal runoff. Of a total 669,000 ha (1,652,000 acres) in the backwater areas, 135,600 ha (335,000 acres) experienced some flooding. However, the backwater areas clearly had excess capacity for a flood of an even greater magnitude than the 2011 flood (Shadie and Kleiss 2012; Davis et al. 2017).

Navigation improvements undertaken as part of the MR&T Project reduced water levels during the 2011 flood event as well. From 1933 to 1942, a total of 15 meander bends were artificially cut off (and an additional natural cutoff occurred). These cutoffs along with dredging chute enlargements and other modifications shortened the river by over 270 km (170 miles) between Memphis, Tennessee, and Baton Rouge, Louisiana. While the 2011 flood set new stage records from Cairo, Illinois, to Caruthersville, Missouri, and from Vicksburg, Mississippi, to Red River Landing, Louisiana, by 30–60 cm (1–2 feet), the middle reach from Memphis, Tennessee, to Greenville, Mississippi, ranged from about 0.6 to

1.8 m (2–6 feet) below previous records from 1927 or 1937. The cutoffs completed from 1933 to 1942 are primarily responsible for this middle reach not setting new records in 2011. In addition, other channel control features (dikes, bendway weirs, revetments, etc.) contributed to stabilizing the channel and protecting the levees, thereby helping the project perform as intended.

Tributary basin improvements also provided flood risk reduction benefits during the 2011 flood. Features such as the five MR&T-authorized reservoirs and the St. Francis Basin Huxtable Pumping Station (capacity 340 m^3/s (12,000 ft^3/s)) stored or evacuated flood waters, reducing flooding of interior areas.

By the time the flood subsided in late June 2011, over 25,640 km^2 (9900 mi^2) had been inundated. However, none of the project levees were breached or overtopped during the event (other than the Birds Point—New Madrid fuseplug levees which were detonated to activate the floodway). Even more important and remarkable, no deaths attributable to the flood occurred despite the fact that over 4 million people live and work within the Lower Mississippi Valley floodplains.

Since its initiation, the MR&T program has brought an unprecedented degree of flood protection to the project area within the Lower Mississippi Valley. The federal government contributed about $14.0 billion toward the planning, construction, operation, and maintenance of the project. The MR&T Project has provided a 44-to-1 return on that investment, including over $612 billion in flood damages prevented (including an estimated value of over $110 billion in 2011 alone), and waterborne commerce increases from 30 million tons in 1940 to nearly 500 million tons today. These figures place the MR&T Project among the most successful and cost-effective public works projects in the history of the USA.

2.3 Land-Use Conflicts in Floodways of the Mississippi River System

Pilar Lopez-Llompart and G. Mathias Kondolf

2.3.1 Introduction

Many national policies must be implemented by state and local governments, which have different motivations and constraints than the national government (May and Williams 1986). Local governments have primary responsibility for land-use planning, and many have permitted proliferation of development on flood-prone lands, in conflict with national policies, because they have "little fiscal stake…[and]… few incentives …to be fully involved in floodplain management" (Galloway 1995:11).

The National Flood Insurance Program (NFIP), authorized by the US Congress in 1968, provided federally subsidized flood insurance for residents of floodplains, effectively a "…'carrot-and-stick' philosophy – making federal benefits contingent upon local zoning…" (Houck 1985:78). However, the divergent motivations of local governments can undermine effective implementation of the program, resulting in further encroachments of housing and infrastructure into flood-prone areas. This "implementation dilemma" (May and Williams 1986) is brought into sharp focus in the land-use history of nationally designated floodways along the Mississippi River (Kondolf and Lopez-Llompart 2018).

As described in Sect. 2.1, the MR&T Project included four designated flood bypasses (termed "floodways" in MR&T parlance), areas of floodplain designated to accommodate part of the river's flood flow, thereby reducing stage in the main river (Fig. 2.2). Since the initial planning of the MR&T, the Birds Point—New Madrid (New Madrid) and West Atchafalaya Floodways were opposed by residents who did not want their properties flooded to protect other lands along the valley (MRC 2007a). The US Army Corps of Engineers purchased flowage easements from the owners of all the affected private properties. However, the easements included no restrictions on the use or development of the land, and local jurisdictions have permitted many structures in these floodways.

2.3.2 The Birds Point: New Madrid Floodway

Completed in 1932, the New Madrid Floodway is designed to divert flood flows from the mainstem Mississippi River, thereby reducing the river stage and preventing overtopping of levees elsewhere. It is activated by blasting a breach in the levee at the upper end of the floodway when a peak stage of 18.3 m (60 feet) is forecast for Cairo, Illinois, to produce a decrease in stage on the Mississippi and Ohio rivers along the east bank opposite the floodway (MRC 2007b).

Despite the US government's flowage easements over all the lands within the floodways, during the record flood of 2011, activation of the New Madrid Floodway by the national government (US Army Corps of Engineers) was delayed by a lawsuit brought by the State of Missouri attempting to prevent inundation of lands within the floodway. Lower courts and finally the US Supreme Court rejected the suit and confirmed that the floodway should be operated as established in the MR&T Project (Camillo 2012). On May 2, 2011, the levee was detonated and water diverted through the floodway (Olson and Morton 2012a; Londoño and Hart 2013), lowering river stage at Cairo and elsewhere along the east bank of the river (Luke et al. 2015; Olson and Morton 2012b).

At the floodway's downstream end, a 460-m (1509 feet) gap in the levees allows floodwaters to return to the main Mississippi channel, and during smaller floods when the bypass is not activated, the gap allows backwater flooding from the Mississippi River to inundate the lowest one third of the floodway, providing shallowly flooded habitat of high value to fish and other wildlife (MRC 2007b). Agricultural interests have long called for this gap to be closed to prevent the backwater flooding and thereby permit farming in the floodway during high flows. However, the inundated floodplain habitat that exists now (and which would be lost if the gap were closed) is the kind of habitat now widely recognized as critically important for riverine ecosystems (Opperman et al. 2009; Dorothy and Nunnally 2015). The St. Johns-New Madrid Floodway project, originally authorized in 1954 to close the gap, was finally started in 2003 but was halted by a federal court ruling that the project had violated the Administrative Procedure, Clean Water, and National Environmental Policy Acts (Taylor 2007; Morton and Olson 2013; USACE 2015). Continued pressure for the project from local interests in Missouri (Dorothy and Nunnally 2015) met strong objections from the conservation community and from elected official representing residents along the river (on the opposite bank and upstream, in other states) whose risk of flooding would be increased (Barker 2014). In a multi-agency decision issued in January 2017, the US Army Corps agreed not to proceed with the project unless the project's impacts could be fully mitigated through advance restoration of a comparable area of frequently inundated floodplain, effectively meaning that to close off this connected floodplain area the Corps would have to open a comparable floodplain area to frequent flooding elsewhere (Wittenberg 2017).

2.3.3 The Atchafalaya Floodway System

The Atchafalaya River is the principal distributary channel of the Mississippi. From its bifurcation at the Old River Control Structure, the Atchafalaya flows westward, is joined by the Red River, turns southward, paralleled by and then receiving discharge from the West Atchafalaya Floodway as well as from the Morganza Spillway (from the mainstem Mississippi). Downstream, the combined floodway is termed the Atchafalaya Basin Floodway, ultimately discharging into the Gulf of Mexico (USACE 1938). The 69-km-long (42.9 miles) West Atchafalaya Floodway covers a surface of 610 km^2 (235.5 mi^2), mostly swampland, separated from the Atchafalaya River by a levee. The floodway was designed to be activated at 19,300 m^3/s (681,600 ft^3/s) by passive overtopping of the levee's northern end (MRC 2007a; FEMA 1980), to lower stages in the Atchafalaya and Red rivers, and in the Mississippi River itself. Under the MR&T plan, this floodway is the last component of the MR&T system to be activated (MRC 2007b), and in fact, it has never been used.

The Atchafalaya River channel has incised in recent decades, attributed to increased and sediment-starved flows (due to the water diverted into the Atchafalaya from the control structure having disproportionately lower sediment loads), and the effects of river engineering such as dredging, channel straightening, revetments, and wing dikes (Mossa 2016). Due to the increased capacity of the Atchafalaya River from channel incision, a much larger flow is probably needed now to passively overtop the fuseplug levee section and initiate flow through the West Atchafalaya Floodway.

Describing the situation in the early days of the NFIP, Houck (1985) documented extensive building within designated floodways of the Atchafalaya Floodway system. One community lay half within the Atchafalaya Basin Floodway, but local officials were "reluctant to limit growth in so large an area." In Point Coupee Parish, which includes the Atchafalaya River itself east of the West Atchafalaya Floodway, the Federal Emergency Management Agency found local official had allowed extensive development, evincing a "…'total lack of understanding' of the NFIP program, and gross neglect of FEMA's regulations" (Houck 1985:99).

To document recent trends in land use within the West Atchafalaya Floodway, Lopez-Llompart and Kondolf (2016) mapped the buildings and other structures (which are considered *encroachments* within the designated path of floodwaters) and found that the number had tripled (from 1439 to 4324) from 1968–1969 to 2008–2009, mostly after 1994 (Fig. 2.4 a–c). The highest density occurred around the town of Simmesport, which lies outside of the floodway within a ring of levees, but whose growth has "spilled over" into the floodway itself.

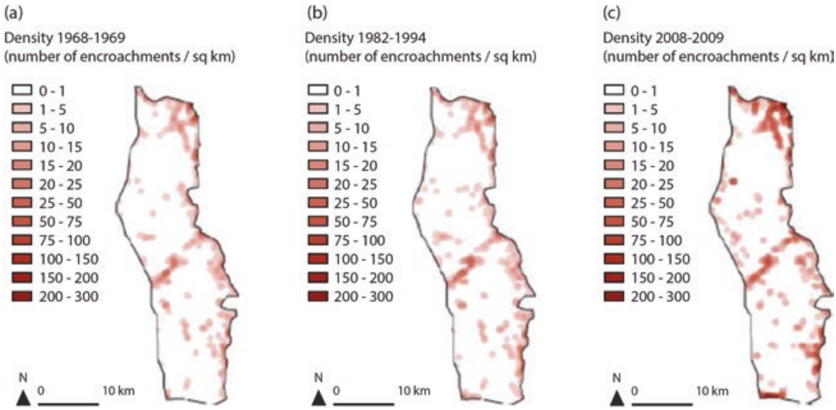

Fig. 2.4 Density of encroachments (number of encroachments/km^2) in West Atchafalaya Floodway at the three studied time periods: (**a**) 1968–1969, (**b**) 1982–1994, and (**c**) 2008–2009 (Source: Lopez-Llompart and Kondolf 2016)

While the widespread construction within flood-prone areas is not unique, reflecting as it does a lack of enthusiasm by local governments to enforce land-use restrictions associated with the federal flood insurance program, the encroachments within the floodways have implications that go beyond inundation of the poorly sited structures themselves. Although the structures and their parcels occupy less than 2% of the total area of the West Atchafalaya Floodway, the encroachments concentrate along east-west trending roads traversing the floodway normal to the flow direction (Fig. 2.5). This linear pattern may have implications for hydraulic roughness during a flood, potentially decreasing the conveyance of the floodway during large floods.

2.3.4 Risk Perception and Implications for Floodway Operation

Although the federal flowage easement has been part of the deeds of the lands within the floodways for decades, the fact that the land is explicitly designated for inundation did not prevent local interests from attempting to stop use of the New Madrid Floodway in 2011, nor has it discouraged the explosion of residential development within the West Atchafalaya Floodway over the past two decades. Residents in the West Atchafalaya Floodway may consider its chances of being used for its designated purpose

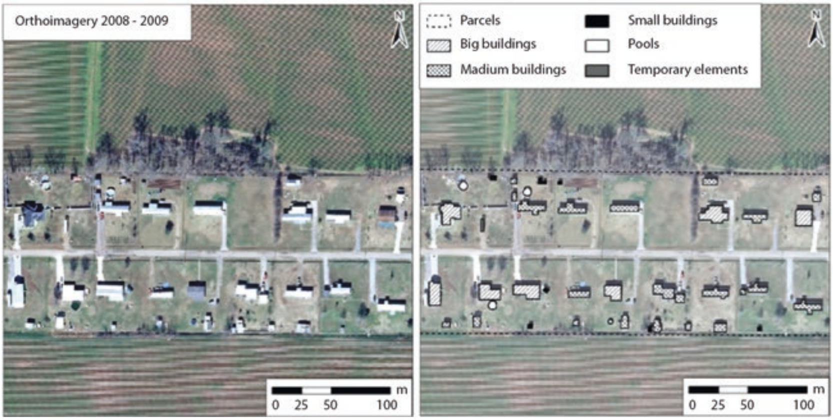

Fig. 2.5 Orthoimage of 2008–2009 of an area of residential development within the West Atchafalaya Floodway (*left*) and same view with various types of encroachments identified (*right*), at coordinates 91°50'9.288"W and 30°59'13.533"N (Source: US Geological Survey; accessed at earthexplorer.usgs.gov, used by permission)

to be low, or may simply be fatalistic about the potential of flooding, a common reaction to flood risk (May and Williams 1986: 5). The West Atchafalaya Floodway now contains houses and swimming pools, besides the original swampland. Such encroachments can interfere with the operation of the floodways (1) by making flood managers reluctant to activate floodways, because of anticipated public resistance, and (2) because of the potential for buildings within the floodway to locally increase hydraulic roughness and reduce conveyance of the floodway. In urban areas, buildings strongly affect flood flow paths (Schubert and Sanders 2012), but the potential effect of buildings on flow resistance in a broad floodway has not (to our knowledge) been analyzed.

2.3.5 Conclusion

While there have been many attempts in the USA at the national level to reduce flood losses through land-use planning, these have not always been supported at the state level and commonly have been circumvented at the local level where land-use decisions are made. Following the disastrous 1993 Upper Mississippi flood, a federal interagency floodplain management review committee (IFMRC 1994) concluded that "The federal government certainly must provide leadership and be a financial supporter of appropriate activities. States, and, as delegated to them by the states, communities, must accept responsibility for land-use planning and should be guiding development in the floodplain" (Galloway 1997: 84–85).

The roles of states in managing floodplains have varied widely across the nation and over time. The NFIP specifies that development be regulated within floodplains inundated by the 100-year flood, but in California, the Central Valley Flood Protection Act of 2008 required a higher standard (the 200-year flood) for urban areas in the Central Valley. NFIP guidelines prohibit new construction in the floodplain that would raise flood elevations by more than 30 cm (1 foot). While some states have legislated stricter standards, in 2004 the state of Missouri took the opposite step and "passed legislation that prohibits any county from setting any threshold stricter than the 1.0-foot limit," thereby contributing to extensive recent floodplain development near St. Louis and elsewhere in the state (Pinter 2005). In contrast to the lack of national-local coordination in the USA, ongoing implementation of the recently adopted Floods Directive in the European Union illustrates a systematic, supra-national approach, which requires systematic mapping of flood risk in all member states and development of measures to reduce risk (Serra-Llobet et al. 2016).

While the basic dilemma of national-local conflicts in land-use management on floodplains is not unique to the examples presented here, conflicts over land use in the New Madrid and West Atchafalaya floodways are particularly compelling (Kondolf and Lopez-Llompart 2018). These are essential components of a river-wide system to manage floods on a large, inter-state river, whose operation reflects national interests. Despite the government's flowage easements, landowners in the New Madrid Floodway objected to inundation of their lands and, through their elected state representatives, attempted to prevent operation of the bypass during the 2011 flood, and have sought to prevent backwater flooding during smaller floods. Despite the government's flowage easements, there has been a threefold increase in residential and commercial development within the West Atchafalaya Floodway since the late 1960s. These new buildings are permitted by local jurisdictions under their land-use authority, but these local decisions have potential to compromise effective operation of a flood control system of national importance.

2.4 Mississippi River Navigation System: A Major Contributor to Flooding

Melissa Samet

2.4.1 Introduction

As described in prior sections of this chapter, the Mississippi River system has been highly altered by agricultural, industrial, and urban land uses, and by extensive modifications for flood control and navigation. As noted above, the modifications to the river system for flood control have been undertaken principally by the US Army Corps of Engineers. In addition to its responsibility to protect communities from flooding, the Corps is charged with restoring portions of the Mississippi and its inland and coastal floodplain, and with reducing impacts to the river and its wetlands when issuing permits for activities of other entities. Notably, the Corps is also responsible for constructing, maintaining, and operating a major navigation channel on the river, extending from the Gulf of Mexico to Minnesota. The navigation responsibility typically conflicts with the Corps' flood damage reduction and restoration responsibilities because the structures built to improve navigation have deleterious impacts on riverine habitats and can increase flood risks by raising water levels during floods.

The Corps' significant level of control and oversight over the river places it in a unique position to advance comprehensive ecological and hydrological restoration of the river and its floodplain to benefit riparian communities and important populations of fish and wildlife. The Corps could make significant progress toward such restoration by developing a fundamentally new approach to operating and maintaining the navigation system.

2.4.2 The Upper Mississippi River Navigation System

The Upper Mississippi River navigation system runs 1394 km (866 miles) from Minneapolis, Minnesota, to the confluence of the Ohio River at Cairo, Illinois (USACE 2017c). The Upper Mississippi River navigation system includes a stretch of river that the Corps refers to as the Middle Mississippi River. The Middle Mississippi runs 314 river km (195 miles) from the confluence of the Missouri River north of St. Louis, Missouri, to the confluence of the Ohio River near Cairo, Illinois (USACE 2017a).

Above St. Louis, the Corps has created a commercially navigable channel through the construction of 29 locks and dams that have transformed the once free-flowing river into a series of highly manipulated pools (Fig. 2.6). There are no locks and dams on the Middle Mississippi River portion of the navigation system. Instead, the Corps has created a commercially navigable channel by heavily constricting the river through hundreds of miles of river training structures (wing dikes, bendway weirs, chevrons) and revetment.

Navigation is maintained through this Upper Mississippi River system by regular dredging of the navigation channel (and disposing of those dredged materials), regulating water flow through the system's locks and dams, constructing new river training structures to force the river into a deeper and narrower channel, placing additional revetment on the river's banks to eliminate natural lateral movement, and operating and maintaining the system's locks and dams.

Construction, maintenance, and operation of the Upper Mississippi River navigation system has fundamentally changed the way the river functions, causing highly significant and well-recognized harm to the environment. A 1999 US Geological Survey report concluded that the Army Corps' navigation management practices have destroyed critical habitats including the rivers' backwaters, side channels, and wetlands; altered water depth; destroyed bathymetric diversity; severely impacted native species; and caused the proliferation of non-native species (USGS 1999). A Biological Opinion issued by the US Fish and Wildlife Service in 2000 determined that key protections were needed to prevent the ongoing management of the river's navigation system from jeopardizing the continued existence of the pallid sturgeon and the Higgins eye pearly mussel (USFWS 2000). The adverse impacts of navigation management were highlighted again in a 2008 US Geological Survey report, which found that the Army Corps' management continued to fundamentally alter the river's hydrologic regime, cause a loss of connectivity to the floodplain, and create high sedimentation rates that had already caused "a substantial loss of habitat diversity" in the system over the past 50 years (USGS 2008).

These adverse impacts are not limited to damage caused by the Upper Mississippi River locks and dams and regular dredging. Significant environmental damage has also been caused by extensive construction of river training structures and revetment in the Middle Mississippi River (USGS 1999, 2008; USFWS 2000).

Fig. 2.6 Mississippi River Lock and dam 27, oblique aerial view from the north (Illinois on the *left*, Missouri on the *right*) (Source: US Army Corps of Engineers, reprinted from Alexander et al. 2012)

2.4.3 River Training Structures in the Middle Mississippi River

The Corps has constructed more than 1375 wing dikes, bendway weirs, chevrons, and similar structures in the Middle Mississippi River (between river km 290 and 60 (miles 180 and 37)), which amount to 2.4 km (1.5 miles) of river training structures for each mile of this river reach. More than 12,192 m (40,000 feet) of wing dikes and bendway weirs were added in the three years leading up to the great flood of 1993. Many more structures have been added since then, including at least 23 new chevrons between 2003 and 2010.

River training structures are used to reduce the need for, and costs of, navigation dredging by creating a "confined and accelerated flow in the central channel," which causes the channel to incise (downcut), which in turn leads to lower water levels during low flows at most locations (Pinter et al. 2010).

However, at flood flows (flows equal to four or more times the average annual discharge level), these same structures increase water levels by creating "backwater effects upstream of these structures" across a full spectrum of discharges (Pinter et al. 2010). These flood impacts are typically overlooked when evaluating flood risks and flood damage reduction solutions for the Mississippi River, but they should not be, as they pose very real risks to Mississippi River communities.

In the Middle Mississippi, river training structures are responsible for flood height increases of up to 4.5 m (15 feet) in some locations and 3 m (8 feet) and more in broad stretches of the Middle Mississippi where the structures are prevalent (Pinter et al. 2010; Remo et al. 2009). These river training structures contributed to the record crests in 1993, 1995, 2008, 2011, and again in 2015. Dangerously, river training structures and levees have so constricted the Middle Mississippi that it now suffers from the flashy flooding typical of a much smaller river (Criss and Luo 2016).

Analysis of a database of more than 8 million discharge and river stage values and a geospatial database of historical engineering infrastructure (locations, emplacement dates, and physical characteristics of over 15,000 structural features constructed along the study rivers over the past 100–150 years) demonstrates that "the largest and most pervasive contributors to increased flooding on the Mississippi River system were wing dikes and related navigational structures" (Pinter et al. 2008a, 2010). The flood stage impacts of river training structures are cumulative; in the Middle

Mississippi, flood stages have increased by more than 10 cm (4 inches) for each 1000 m (3281 feet) of wing dike built within 32 river km (20 miles) downstream. Progressive levee construction and climate- and/or land-use changes have also contributed to stage increases in the Middle Mississippi, but to a much lesser extent (Pinter et al. 2008a, 2010).

2.4.4 *Scientific Consensus Regarding Effects of River Training Structures and the Agency Response*

More than 50 peer-reviewed studies support the conclusion that river training structures increase flood stages (e.g., Huthoff et al. 2013; Azinfar and Kells 2007, 2009, 2011; Bormann et al. 2011; Yosseff and de Vriend 2011; Paz et al. 2010; Pinter et al. 2008a, 2010; Theiling and Nestler 2010; Criss 2009; Doyle and Havlick 2009; Pinter 2009; Remo et al. 2009; Jemberie et al. 2008; Ehlmann and Criss 2006; Huang and Ng 2007; O' Donnell and Galat 2007; Remo and Pinter 2007; Yosseff 2005; Ettema and Muste 2004; Wasklewicz et al. 2004; Criss and Schock 2001; Smith and Winkley 1996; Belt 1975 and others). Indeed, a recent theoretical analysis shows that increased flood levels caused by wing-dike construction are "consistent with basic principles of river hydro- and morphodynamics," and that even with extremely conservative parameters used in modeling, "the net effect of wing dikes will be higher flood levels" (Huthoff et al. 2013).

Despite the fundamental hydrological science principle that river training structures increase flood stages, and the extensive empirical evidence that this has occurred on the Middle Mississippi River, the Army Corps' St. Louis District has rejected the scientific consensus of this effect. In contrast, the Corps' St. Paul District recently reached an opposite conclusion more in line with hydrological principles, rejecting a river training structure proposal precisely because that district's modeling showed the structures would produce "significant" and "unacceptable flood stage increases" (USACE 2017b).

Corps leadership and the St. Louis District have rejected numerous requests for a National Academy of Sciences study to guide the agency in its evaluation of this critical public safety issue, requests made by independent scientists in 2008 and subsequently by the St. Louis Post Dispatch editorial board, the conservation community, and thousands of members of the public (e.g., Pinter et al. 2008b; St. Louis Post Dispatch 2010; NWF 2012; ASA 2012; USACE 2017a). A National Academy of Sciences study, which would likely cost less than a single river training structure, could provide vital input for protecting river communities and could help restore the public's confidence in the US Army Corp of Engineers' decision-making.

Instead, the US Army Corp of Engineers' St. Louis District has recently recommended that it continue to build new river training structures in the Middle Mississippi through at least 2034, to further reduce dredging costs (USACE 2017a). This recommendation was based on an environmental impact statement that, once again, explicitly rejected the validity of the science demonstrating the flood stage impacts of river training structures. Not surprisingly, this recommendation is strongly opposed by the public, the conservation community, independent scientists, the US Fish and Wildlife Service, and others (USACE 2017a).

The proposed construction of new river training structures will compound the very real risk of catastrophic flooding that already plagues Mississippi River communities. Dangerously, the next wave of river training structure construction is planned for areas that are already at significant risk. The planned Dogtooth Bend project will be built just downstream from a segment of the Len Small Levee that failed during the 2011 floods (on the Illinois side of the river, 32–64 km (20–40 miles) upstream of the Ohio River confluence). The planned Grand Tower project will be built adjacent to the Big Five Levee System, which has been designated as deficient by Corps inspectors (on the Illinois side of the river near Wolf Lake, 107–118 km upstream of the Ohio River confluence).

The proposed construction would also add to the already extensive losses of fish and wildlife habitat by, among other things, destroying at least another 440 ha (1087 acres) of vital border channel habitat. This would bring the total loss of border channel habitat to 40% in the Middle Mississippi River since 1976 alone, without counting losses prior to this year (USACE 2017a).

2.4.5 Conclusion and Recommendations

The US Army Corps is charged with multiple objectives in its management of the Mississippi River. Notably, the Corps' construction and operation of the navigation system have created striking conflicts with the Corps' flood damage reduction and restoration objectives, and the agency continues to utilize technologies and methodologies that favor navigation at the expense of these other vital interests. The Corps has multiple authorities to protect the public and the environment, which could be more effectively used to advance comprehensive restoration of the river and its floodplain. The critical importance of these issues argues for a halt to new structures, and an independent assessment by the National Academy of Sciences.

To initiate a more balanced and sustainable approach to managing the river and its resources, prioritizing public safety, the Army Corps should:

1. Adopt a moratorium on new river training structures that will remain in effect unless it can be proven that new structures will not increase flood risks for Mississippi River communities.
2. Initiate a National Academy of Sciences study on the role of river training structures on increasing flood heights to inform the Army Corps' decision-making.
3. Conduct a scientifically and legally sound environmental review of the full suite of actions carried out by the Army Corps to maintain navigation on the Upper Mississippi River system and develop and adopt a navigation management plan that will protect people and wildlife. To comply with the Congressionally established National Water Resources Planning Policy (42 USC 1962–3), the measures adopted must protect the environment, including by restoring the river's natural hydrologic and ecosystem functions and by mitigating any harm that cannot be avoided.

   This new plan should (1) abandon the construction of new river training structures, unless it has been demonstrated that they will not increase flood risks; (2) abandon the construction of new revetment that will lock more of the river in place and thereby further harm the river's natural functions; (3) remove and/or modify some of the existing river training structures and revetment to reduce flood risks and restore habitat; (4) restore habitat that has been lost to navigation activities over at least the past four decades; and (5) fully mitigate the adverse impacts of past and future navigation maintenance activities.
4. Advance the wide-scale use of natural infrastructure (healthy rivers, floodplains, and wetlands) as a primary tool for water resources management for the Mississippi River and its floodplain, and throughout the country. Natural infrastructure provides a host of vital benefits, including natural flood protection, clean water, wildlife habitat, and recreational opportunities that are a significant economic driver.

2.5 Floodplains: Meeting the Needs of People and Nature

Todd Strole

Floodplains are among the most fertile and biologically rich lands on earth. Floodplains are a vital component of a healthy river system that supports a diversity of species and a dynamic mosaic of habitats including open water, submersed/emergent aquatic vegetation, wet meadows/prairies, and bottomland hardwood forests. With rich soils, abundant water, and verdant plant growth, river floodplains are tremendously productive. Today, a river's natural floodplain is often separated from the river using levees that protect the land from flooding and provide access to this productivity for agriculture but often protect municipalities and other infrastructure as well. Levees effectively disconnect the river from its floodplain, and while often successful for flood protection, there is an environmental cost. Natural floodplain functions that are reduced dramatically from levee construction include storage and conveyance of floodwaters, natural river hydrology, nutrient cycling, carbon sequestration, sediment management, water filtration/purification, groundwater recharge, habitat for plants and animals, and recreation. The river/floodplain connectivity and the functions it supports have largely been ignored in the past, but we are increasingly aware of the need for functional floodplains in healthy river systems.

People have exploited floodplains and their riches to the detriment of nature, and this use and development in floodplains has often resulted in great loss during floods. Today, we have the understanding, the tools, and the opportunity to change our use of floodplains, reduce such tragedies, and improve the balance between nature and people. We understand that floodplains and rivers in a more natural condition play a critical role in meeting our needs. We can make communities safer, restore critical ecosystem functions, and reduce long-term costs of flood control and disaster relief.

A vision for integrated management of floodplains starts with two premises regarding the needs of nature:

1) We must maintain and restore the key natural processes and functions that sustain floodplain and river systems.
2) We can accurately define the areas, features, and conditions that a floodplain and their associated rivers must have in order to maintain healthy ecological systems.

There are also two premises regarding the needs of people:

1) Floodplains and rivers must provide a significant amount of the goods and services necessary to meet human needs.
2) Understanding flood risks and desirable floodplain functions is not enough to change traditional activities and behavior in the floodplain. Rather, economic incentives, disincentives, and multiple benefit solutions are needed.

As we move toward this vision, there are several examples of research and planning efforts that can guide our work. In the context of flooding, engineers and hydrologists are continually improving the ability to model floods and the impacts that various land-use practices and geomorphic changes will have on a river's ability to store and convey floodwaters. A good example of this is modeling work being conducted on the Missouri River, led by the USGS, where differing land management scenarios have been tested for their impact on flood heights (Bitner 2012). They found that levee setbacks (or removal) and river channel widening can significantly lower flood heights for moderate-sized floods, but this impact is diminished as floods become larger. Using this model, the researchers were able to measure the impact that land-use changes following a record flood in 1993 had on flood heights during the flood of 2007. Work like this demonstrates that we have the ability to design landscape changes that will achieve a target flood-carrying capacity in a river.

So if we can design what we need, then the next step is looking for places to apply these landscape changes. When looking for locations where floodplain restoration can be targeted, there are data sets that are wildly available that can be used to guide floodplain mangers. An example of this is a database for the Upper Mississippi River that was developed in a partnership between the Nature Conservancy and the USACE (Strole 2011). The effort produced a database of information regarding floodplain characteristics that would be useful for screening, planning, mapping, and project identification and included data regarding infrastructure, ownership patterns, and natural resource features.

The restoration of natural floodplain habitat features requires additional information, beyond the hydraulics and hydrology used in the design of flood conveyance. An excellent example of using existing data over large geographies in floodplain management and planning is a technique known as hydrogeomorphic modeling or HGM (Heitmeyer 2008). This method has been used extensively in the Mississippi River Valley, producing detailed maps and information on the historic floodplain vegetation, measuring the changes that have occurred over time, and identifying the options for restoration. This method uses elevations, soils, geomorphic surfaces, historical accounts, and hydrology to produce incredibly detailed maps on historic and current conditions in the floodplain. There are other examples of less intense evaluations such as the Land Capability Potential Index used in the Missouri River floodplain to rapidly assess the current land use and its capacity for other uses (Jacobson et al. 2007).

Broader application of these models, data sets, and assessment methodologies will be needed as we move toward floodplain management that integrates both the needs of people and nature. There are differing approaches and strategies that could move society's understanding, appreciation, and ultimately management of floodplains. However, all would likely include some common elements. For example, demonstration projects that provide research opportunities for measuring floodplain functions including their impact and value in conservation and in flood risk management planning would be required. These projects would provide the foundation of information used to communicate these values to floodplain occupants, stakeholders, and decisions makers. This heightened understanding could lead to a political strategy and ultimately inform a national policy that would improve our management of floodplains through regulation, programs, and market systems that connect the provider of floodplain functions to those receiving the benefit in a real market scheme.

This is a monumental task, and change will be slow and difficult due to the number and complexity of state and federal policies, programs, and regulations. These include but are not limited to executive orders that guide the federal government's role in floodplain development; the NFIP; USDA programs from the "Farm Bill" that provide restoration and insurance programs; numerous projects, authorities, and policies of the US Army Corps of Engineers that exert tremendous influence on the management of floodplains; and state and local management and zoning programs. There are good examples of well-intentioned steps, from legislation to government reports, which have urged us toward wise use of floodplains but have fallen short on implementation. Take, for example, *Sharing the Challenge: Floodplain Management into the 21st Century*, otherwise known as the "Galloway Report," which was an extremely comprehensive report following the 1993 flood in the Upper Mississippi and Missouri River system (Galloway 1994). It provided detailed recommendations that would integrate compatible floodplain uses with appropriate flood protection measures in an effort to reduce flood risk in the future. While some progress has been made, nearly 25 years later, we have failed to reach the vision provided in this report. It remains a much respected document that provides relevant guidance for today regarding many of the issues described above.

Wise use of our nation's floodplains is critical as we continue to face increasing flood losses, a climate that is producing more extreme events and a burgeoning population in need of space to live and land to provide food, fiber, and fuel. However daunting the task may be, the information, technologies, and methodologies are available to guide us. Coupling this with new regulations, programs, and markets that build from our successes and apply lessons learned from our past will be the key to success.

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