The Mississippi River

Introduction

In “Life on the Mississippi”, Mark Twain described 19th century attempts to control the Mississippi River and concluded that humans “cannot tame that lawless stream” ([33]). William Faulkner’s observations of the 1927 Mississippi River flood, which provided the setting for the story “Old Man”, lead him to the same conclusion; “any time the Old Man wants to he can break the levee”. Faulkner used the African American name, Old Man, for the Mississippi River. The name Mississippi is derived from the 18th century French rendering of an Algonquin phrase meaning *Great River*. During the Civil War, President Lincoln celebrated Grant’s victory at the Battle of Vicksburg by noting that the “Father of Waters again goes unvexed to the sea” ([23]), repeating a common, but faulty, translation. Whether as Father of Waters, Great River or Old Man, the Mississippi River has always struck an impressive pose.

The Great Flood of 1927 in the Mississippi River was the most destructive in American history, inundating more than 27,000 square miles of land, resulting in hundreds of fatalities and leaving more than 700,000 people homeless ([26] and [1]). Damages from the flood were estimated at $1 billion in 1927, a loss that equaled a third of the federal budget ([26]). A repeat of the 1927 flood would result in damages far in excess of $100 billion ([32]). A consequence of the flood was the transformation of flood control policy in the Mississippi River from a *levees-only* approach to one of the most elaborate engineering systems in the world ([26]). Counter to the counsel of Twain and Faulkner, humans have doubled down on the wager that the Mississippi River can be controlled.

The Built and Natural Environment

The Mississippi River basin extends from the western provinces of Alberta and Saskatchewan in Canada to the southwestern corner of the State of New York along Lake Erie to the Crows Foot Delta of Louisiana in the Gulf of Mexico (Figure 1). The Missouri River, draining the Rocky Mountains and northern Plains region of the US, and the Ohio River, draining the Appalachian Mountains and the humid eastern US (Figure 1), are its principal tributaries. The Missouri River in its upper reaches is controlled by a series of massive earth dams, Fort Peck, Garrison, Oahe, Big Bend, Fort Randall and Gavins Point (Figure 2). The dams were designed to provide flood control, especially for the downstream cities of Kansas City and St. Louis, water for irrigated agriculture, recreation for the region, and hydropower for the nation. The Ohio River is controlled by a series of locks and dams which ensure year-round commercial navigation on the river.

The geologic history of the Mississippi River spans millions of years and has been profoundly shaped by tectonic, climatic and anthropogenic influences. Mountain building and erosion of the Rocky Mountains to the west and the Appalachian Mountains to the east have been the principal tectonic agents shaping the Mississippi River basin ([2]). An ancestral Mississippi River was in place more than 20 million years ago - separate drainages flowed to the Gulf of Mexico from the Rocky Mountains and from the Appalachians. Climate variation during the Pleistocene Epoch, which extended from 2.6 million years ago to around 11,700 years ago, was a major driver of the evolving form of the Mississippi River. Alternating glacial cycles during the Pleistocene produced large changes in the elevation of the Gulf of Mexico, with decreasing levels during periods of maximum glaciation and increasing levels during interglacial periods. The Laurentide Ice Sheet covered much of Canada and the northern United States during the Pleistocene. The most recent glacial period in North America extended from 75,000 to 11,000 years ago and the maximum glacial extent occurred between 25,000 and 21,000 years ago. The Holocene Epoch, which extends from 11,700 years ago to the present is an interglacial period, in which the current form of the Mississippi River has been shaped. Climate variation during the Holocene, including changing frequencies of extreme floods, continued to be an important driver in the development of the Mississippi River. The imprint of humans on the Mississippi River centers on the past several centuries.

A distinctive feature of rivers is their creation of floodplains. From the perspective of a geomorphologist the *floodplain* of a river is the flat area adjacent to the river channel, created by the river in the current environment and inundated during times of flooding ([20]). The channel and floodplain of the Mississippi River reflect the active role of the river in creating its environment. The meander bends of the Mississippi River near the confluence with the Arkansas River were mapped in 1944 by the geologist Harold Fisk (Figure 3; [9] and [10]). Albert Einstein noted that "it is common knowledge that streams tend to curve in serpentine shapes instead of following the line of maximum slope of the ground"; he participated, with little success, in a long line of research on river meandering ([7]).

Lateral migration, strikingly illustrated in Fisk's maps, is the process by which the channel bank is eroded along one side, with sediment deposition taking place on the opposite bank. The amplitude of meander bends expands by lateral migration, up to a point when a cutoff of the meander bend occurs, typically during a major flood. Meander development and floodplain formation reflect intrinsic internal adjustments made by the river system to maintain its form. One viewpoint on evolution of river morphology takes climate as largely a fixed driver and the river system as the principal actor, through internal adjustments, in creating its form ([2]). An alternative point of view places climate variation, in particular the magnitude and frequency of floods, in a more central position. The natural processes of lateral migration, expansion of meander bends and cutoffs shaped the Mississippi River prior to European colonization (as illustrated in Figure 3) and determined the form of channels and floodplains. Attempts to control the Mississippi River have often involved interventions to the cycle of lateral migration, meander formation and cutoff. Debates over the relative importance of internal river adjustments versus catastrophic floods on river structure have informed these interventions.

A natural feature of a meandering river whose channel is composed of unconsolidated sediment is development of *levees* along the margin of the channel. These elevated surfaces are created by deposition of coarse sediment, which is deposited closest to the river during times of flooding. Natural levees of the Mississippi River have been augmented by constructed levees beginning with French settlement in the 18th century - the term levee is taken from the French verb “to raise”. Failure of a levee during a period of flooding concentrates flow from the river through a *crevasse* and creates distinctive regions of scour and sediment deposition on the floodplain (see [13]).

The *discharge* of the Mississippi River at Vicksburg ranges from less than 200,000 cubic feet per second (cfs) during periods of drought to more than 2,000,000 cfs during extreme flood. Discharge is defined, and often directly computed, as the product of width (feet), depth (feet) and velocity ($ft\ s^{-1}$). In this formulation, width is the distance across the river, depth is the mean depth obtained as the ratio of the cross-sectional flow area to the width and velocity is the average flow velocity for the cross-section. Rivers construct their channels to accommodate changing discharge of water and sediment. Geometry of the channel and floodplain along a river reach dictate how width, depth and velocity adjust with discharge. Velocity for the Mississippi River at Vicksburg, for example, increases from 3.5 $ft\ s^{-1}$ at a discharge of 200,000 cfs to more than 7 $ft\ s^{-1}$ at a discharge of 2,000,000 cfs. Mean depth increases from 50 feet to 70 feet. Width increases from 2000 feet at 400,000 cfs to 3000 feet at 900,000 cfs, but does not vary much for flows greater than 900,000 cfs - unless the levee breaks.

Flow velocity, notoriously difficult to measure in the Mississippi River, is tied to slope of the river bed, which dictates the gravitational force that propels water downstream, the roughness of the channel bed, which determines the frictional forces that retard flow, and the discharge from upstream. Flow depth plays an important role in determining how much of the flow feels the roughness of the channel and consequently in determining flow velocity. The Chezy equation

$$v = C \, d^{\frac{1}{2}} \, S^{\frac{1}{2}} \tag{1}$$

is widely used for engineering applications and represents flow velocity v as the product of the square root of the water surface slope, S, the square root of flow depth, d, and a roughness coefficient, C, that is based on the composition of the channel. Smooth channels with fine sediment have lower roughness than channels with large sediment. The Chezy equation is semi-empirical, but captures the interrelated dependence of mean flow velocity on river slope, flow depth and roughness of the channel.

The built and natural environments of the lower Mississippi River intersect most strikingly through storage and transport of sediment, especially through their dependence on flow velocity. Low velocities provide an environment where all but the finest sediment particles will be deposited on the channel; high velocities can transport large sediment and erode material from the bed and banks of the channel. Dams on the Missouri River (Figure 2) have the unsurprising effect of reducing the flood peaks downstream in the Mississippi River. The more important, and perhaps less apparent, effect of these dams is changing the channel of the lower Mississippi River by trapping sediment in the reservoirs created by the dams ([24]).

Prior to European colonization, the Mississippi River transported approximately 400 million metric tons of sediment per year to the Gulf of Mexico (Figure 4). In the 21st century, sediment transport to the Gulf averages 145 million metric tons per year. The principal, but not sole, cause for the decrease in sediment loads to the Gulf has been trapping of sediment by the Missouri River dams, which were completed in the 1950s. The Missouri River dams capture approximately 100 - 150 million metric tons of sediment per year, or about half the decrease in sediment load. The remaining decrease in sediment load is due to soil erosion controls in the upland areas of the Mississippi River basin and to engineering activities such as meander cutoffs and structures to control bank and channel erosion ([24]).

Deforestation of the eastern US, principally during the late 19th and early 20th centuries, resulted in an increasing supply of sediment to the Mississippi River from its Ohio River tributary, at least through the early 20th century. Sediment production in the rivers of the eastern US peaked during the late 19th century, due to a combined peak in agricultural activity and the pervasive use of erosive agricultural practices. Soil conservation measures introduced after the Dust Bowl era of the 1930s dramatically altered the most erosive agricultural practices and reduced sediment loads ([18]). The time scales for sediment to move through a river system, however, can be quite long, decades to centuries for larger sediment. The legacies of land transformations on the form and function of rivers have similar time scales.

Sediment is crucial to the lower Mississippi River and the decrease in Mississippi

River sediment load has been a primary cause of accelerated land loss in the delta of the Mississippi River, where the boundary between land and water is blurred (Figure 5). Land loss along the Gulf Coast increases the hazards from hurricane storm surge and was one of the contributing elements to the catastrophic consequences of storm surge in New Orleans from Hurricane Katrina in 2005. Dams on the upper Missouri River in Montana and the Dakotas have made New Orleans more susceptible to storm surge hazards from hurricanes in the Gulf of Mexico!

Changing climate regimes during the past 2 million years have produced periods which are colder and drier than the present and periods that are warmer and wetter than the current climate. The glacial cycles of the Pleistocene have resulted in large changes in elevation of the Gulf of Mexico; sea level has increased more than 100 meters since the last glacial maximum 25,000 years ago. The changing *base level* of the Gulf of Mexico is one of the important aspects of climate variability for the evolving form of the Mississippi River. Major changes in the Mississippi River have also occurred since the last glaciation. Melt and retreat of the the Laurentide Ice Sheet from 12,800 to 8,500 years ago produced Lake Agassiz in what is now the upper Mississippi River basin; its extent exceeded all of the modern Great Lakes. *Megafloods* from Lake Agassiz sculpted portions of the Mississippi River during the early Holocene ([2]). Clustering of periods of flood and drought have persisted over the past several millenia ([17]).

The current meandering form of the the river, strikingly illustrated in Fisk's maps

(Figure 3), was largely in place over much of its extent 7,500 years ago. Since that time, however, there have been dramatic changes to the lower reaches of the river, where the channel has changed location multiple times (see Figure 6). The outlet of the main channel of the river is currently the Plaquemines - Balize Lobe, which was created approximately 1,300 years ago. The previous outlet was the Larourche Lobe to the west, which was created approximately 3,000 years ago and active until approximately 500 years ago. For a period of roughly 800 years, two lobes were active with the main channel switching from the Lafourche Lobe to the Plaquemines-Balize Lobe over this period. Two lobes are currently active, with the Atchafalaya Lobe having formed roughly 500 years ago. The mechanisms associated with *lobe switching* are not fully understood, with competing ideas stressing internal adjustments, like those described as central to floodplain formation, and catastrophic flooding. ([29]).

Distributaries are streams that branch off the main river and flow away from the river - they are important features in the deltas of many major rivers, including the Mississippi River. The principal distributary of the Mississippi River is the Atchafalaya River (Figures 7 and 8). The creation of the Atchafalaya River, which initiated the Atchafalaya Lobe (Figure 6), dates from approximately the 15th century and was caused by *capture* of the Red River by the Mississippi River. A growing meander bend of the Mississippi River reached the margin of the Red River and captured its flow. Much of the flow of the Red River exited the Mississippi River in the newly formed Atchafalaya distributary (Figure 8).

Another consequence of the capture of the Red River was creation of the *Great Raft of the Red River*, a logjam that formed at the confluence of the Red River and Mississippi River ([9] and [29]). The logjam expanded during the annual spring flood in the Mississippi River when the Red River was backed up by the flow of the larger river. The logjam grew upstream and extended for more than 100 miles at its maximum extent.

The Great Raft was a natural feature of the Mississippi River and predated European colonization. During the 19th century, extensive efforts were made to remove the logjam, principally to promote navigation on the Red River ([27]). A consequence of removing the Great Raft was a shift in flow from the Mississippi River to the Atchafalaya, which is the shorter, higher gradient path to the Gulf (Figure 7). The fraction of flow carried by the Atchafalaya increased steadily during the 20th century and by 1950, the Atchafalaya was carrying 30% of the Mississippi River flow, on average, to the Gulf of Mexico. Congress instructed the Corps of Engineers to keep it so: "the distribution of flow and sediment in the Mississippi and Atchafalaya Rivers is now in desirable proportions and should be so maintained" ([22]). This has proven to be a Herculean task.

A “Significant Nexus”

The 1803 Louisiana Purchase expanded the territory of the US into much of the western portion of the Mississippi River basin, but most importantly it expanded the territory of the US to include the west bank of the Mississippi River. From a geopolitical and military perspective, a river is not secure unless both banks are controlled. Navigation on the Mississippi River was a principal benefit of the Louisiana Purchase in the early 19th century and from the 18th century to the present, the river has played a pivotal role in the US economy.

Navigation on the Mississippi River was no small matter in the deliberations that produced the US Constitution. The Treaty of Paris, which ended the American Revolutionary War in 1783, made the Mississippi River the western boundary of the United States and guaranteed open access for Americans to navigation on the river. Spain attempted to close the river for navigation in 1784, entering into negotiations on a treaty that would eliminate the American right to navigate the river in return for a commerce treaty that would benefit American exports. Southern states were adamant in opposing the treaty and northern states supported the treaty because of its commercial benefits to developing US industry, which was concentrated in northern states. John Marshall, later to become Chief Justice of the Supreme Court and author of its most important ruling on rivers and the environment, noted that southern leaders like Patrick Henry would rather “part with the confederation than to relinquish the navigation of the Mississippi”. When the Philadelphia Convention met in 1787, southern states demanded that the Constitution require a two-thirds vote rather than a simple majority when ratifying treaties. A two-thirds majority gave southern states veto power over any treaty that endangered their access to navigation on the Mississippi River.

The Mississippi Valley has long been viewed as a breadbasket for the US. For much of US history, this has been more potential than reality. The main requirements for agricultural development of the lowlands of the Mississippi Valley are land clearance, flood protection and drainage ([13]). All three elements have been challenging and engaged different players. Land clearance has always been viewed as a private activity and the responsibility of land owners. Flood prevention responsibilities have evolved from private, with state law in Louisiana requiring *front holders* of land along the river to build and maintain levees, to a shared state and local system and finally to federal programs ([13]). Drainage projects address the problems of excessive water in soils adjacent to lowland rivers; they have typically involved both private and state efforts. The appropriate mix of private and governmental activities for economic development of the Mississippi River and its environs has been a challenging problem throughout US history.

In the 21st century a large segment of the US economy, especially from the agricultural and energy sectors, is either directly or indirectly linked to the lower Mississippi River. A profile of economic activity in the lower Mississippi Valley (i.e. the Mississippi River below the confluence with the Ohio River) assessed the total revenue of the region at \$128 billion in 2001 ([6]). The largest single generator of revenue was manufacturing with the \$87 billion revenue concentrated in petroleum refining and chemical production along the river in the reach from Baton Rouge to New Orleans, which is downstream of the Atchafalaya distributary. The concentration of manufacturing along the Mississippi River is based on ready availability of water from the Mississippi for industrial processes, the access to shipping through navigation along the Mississippi River and close proximity to oil and natural gas production sources along the lower Mississippi River in Louisiana. Agricultural products from the central US and the Mississippi Valley and energy products associated with oil and natural gas dominate total cargo shipped in the lower Mississippi River. Congress's directive that the course of the river past Baton Rouge and New Orleans be maintained is an economic imperative; a rapid switch to the Atchafalaya would have devastating impacts.

Commerce has played a major role in development of river basins of the US through the *Commerce Clause* of the Constitution, which states that Congress shall have the power to "regulate Commerce with foreign Nations, and among the several States, and with the Indian Tribes." The Commerce Clause provides the foundation for the federal government to manage and regulate rivers of the US. Chief Justice John Marshall and the Supreme Court ruled in the 1824 steamboat monopoly case, Gibbons vs. Ogden, that "the power of Congress, then, comprehends navigation, within the limits of every State in the Union; so far as that navigation may be, in any manner, connected with commerce with foreign nations, or among the several States". Following the 1824 Gibbons v. Ogden case, *navigable waterways* were in the purview of the federal government.

Core elements of environmental legislation, including the Clean Water Act and Endangered Species Act, have been grounded in the 1824 Supreme Court decision. The central role of the Commerce Clause for environmental management was highlighted in a 2006 challenge to the Clean Water Act, Rapanos v. United States. The case centered on federal jurisdiction to regulate wetlands in the upper Mississippi River basin under the Clean Water Act. The plaintiff in the case, Rapanos, filled a wetland to build a shopping mall in violation of existing Environmental Protection Agency (EPA) regulations and was fined by the U. S. Army Corps of Engineers. The case hinged on competing definitions and interpretations of navigable waterways, each of which was grounded in particular views of how rivers work.

The plaintiff's viewpoint was articulated by Justice Antonin Scalia in a succinct summary of the complicated position of the drainage network within a drainage basin: "The Corps has also asserted jurisdiction over virtually any parcel of land containing a channel or conduit through which rainwater or drainage may occasionally or intermittently flow. On this view, the federally regulated waters of the United States include storm drains, roadside ditches, ripples of sand in the desert that may contain water once a year, and lands that are covered by floodwaters once every 100 years. In fact, the entire land area of the United States lies in some drainage basin, and an endless network of visible channels furrows the entire surface, containing water ephemerally wherever the rain falls. Any plot of land containing such a channel may potentially be regulated as a water of the United States."

The government viewpoint was articulated by Justice John Paul Stevens: "The Army Corps has determined that wetlands adjacent to tributaries of traditionally navigable waters preserve the quality of our Nation's waters by providing habitat for aquatic animals, keeping excessive sediment and toxic pollutants out of adjacent waters, and reducing downstream flooding by absorbing water at times of high flow. The Corps' resulting decision to treat these wetlands as waters of the United States is a quintessential example of the Executive's reasonable interpretation of a statutory provision."

The controlling view in the case was issued by Justice Anthony Kennedy: "The Court [has] held that to constitute navigable waters, a water or wetland must possess a **significant nexus** to waters that are or were navigable in fact or that could reasonably be so made". The decision reflects the difficulty in sharply drawing boundaries at interfaces of the water cycle. Subsequent attempts to define significant nexus have proven challenging.

Arguments for a broad interpretation of Commerce Clause powers for federal regulation of land use rest heavily on the downstream impacts of soil erosion and environmental contaminants from agricultural lands. The impacts of sediment on navigation from erosive agricultural practices have been recognized since the late

18th century and stimulated the long history of channel dredging projects carried out by the Corps of Engineers under Congressional authorization through the *Rivers and Harbors* acts. Downstream effects of agricultural practice in the midwest have significant impacts on commerce in the lower Mississippi River and Gulf of Mexico. Nitrogen and phosphorus from fertilizer application in the midwest and along the Mississippi River Valley are transported to the Gulf of Mexico producing a zone of low dissolved oxygen, or hypoxic zone, in the northern Gulf of Mexico (Figure 9). The accelerated growth of algae that decay and consume oxygen is the principal cause of the Gulf of Mexico hypoxic zone. Low dissolved oxygen can cause death in bottom-dwelling organisms, resulting in large economic losses to one of the nation's most important fisheries and damaging a fragile ecosystem. Land and water management activities throughout the Mississippi River basin have impacts on commerce that are connected over large distances by the Mississippi River.

A direct consequence of the 1824 Gibbons vs. Ogden ruling was the elevation of the U. S. Army Corps of Engineers to a role of principal responsibility in river development for the US. The Corps of Engineers was created in 1802 by President Thomas Jefferson and stationed at West Point as part of the U. S. Military Academy. Jefferson created the Military Academy as an engineering school following the model of the Ecole Polytechnique in France. Although the mission of the Military Academy expanded beyond the Corps of Engineers, the elite graduates of the Academy traditionally joined the Corps through much of the 19th century.

Following the Gibbons vs. Ogden Supreme Court decision, Congress gave the Corps its first directive to "improve the navigation of the Ohio and Mississippi Rivers" in 1824. *Rivers and Harbors* acts of Congress became the routine mechanism for directing COE activities in managing the nation's rivers. The Mississippi River Commission, which was created in 1879, combines COE personnel with citizen engineers and provides an executive body for developing and implementing navigation and flood control programs on the Mississippi Rver.

Early attempts to control the Mississippi River consisted primarily of levee construction, literally building on the natural levees the river had created. New Orleans and its constructed levees were both built upon this natural high ground. In 1724 the levees around New Orleans stood only 3 feet high and protected local areas of development; by the turn of the 20th century levees covered most of the lower Mississippi River from Cairo, Illinois down to the Gulf of Mexico and had consistently increased in size (Figure 10) in response to major floods ([13]).

By the mid-19th century control of the waters of the Mississippi River had fallen more or less completely to the Corps of Engineers, who filled in gaps in the levees and enforced quality and height standards. The Corps subscribed to a *levees-only* approach to controlling the Mississippi, which involved closing outlets and straightening the river channel to increase current velocity. By the 1860's, hydrologic surveys, especially those of Charles Ellet and Andrew A. Humphreys ([16] and [8]), had established that prior understanding of rivers, developed largely for European rivers, was not adequate for developing flood control plans for the Mississippi. Ellet advocated mixed approaches involving both levees and outlets, as well as headwater dams and reservoirs. Humphreys and Abbot ([16]) pointed to problems with the levees-only approach to flood control, but criticized Ellet's proposals for outlets and dams ([13]; see also [1] for discussion of Humphreys and the evolution of his policies for Mississippi flood control). The outcome was that the levees-only approach remained official policy of the Corps of Engineers and Mississippi River Commission until well into the twentieth century ([13], [27] and [1]).

The Humphreys and Abbott report ([16]) was an important contribution to the science of rivers, based on the extensive measurements on the river that were carried out during the 1850s. The most lasting impact of the report would be in supporting the levees-only approach to flood control ([1]). The level of the channel bed of the Mississippi rose slowly over much of the 19th and early 20th centuries as outlets were closed, levees were expanded, and human development in the vast drainage area of the Mississippi increased runoff and sediment into the river and its tributaries. By the 1920's levees stood as high as thirty feet; in towns along the river they often towered several stories over the city streets.

The Great Mississippi River Flood of 1927

"The water dug out, Lordy, levee broke, rolled most everywhere
The water at Greenville and Leland, Lord, it done rose everywhere
I would go down to Rosedale, but they tell me there's water there."
High Water Everywhere, ***Charley Patton***

The 1927 Mississippi River flood was the most destructive in US history and it was the largest. A peak discharge of 2,472,000 cfs for the Mississippi River near Arkansas City, Arkansas appears in the flood records of the U. S. Geological Survey (USGS; see Figures 11 and 12 for locations). It is listed as occurring in May of 1927 - no day is given. The USGS has operated more than 12,000 stream gaging stations across the United States since 1888 and no measurement has exceeded the Arkansas City peak on the Mississippi in 1927. Unlike virtually all of the other flood measurements in the USGS archive, there is no evidence in the records of the USGS, the Corps of Engineers or the Mississippi River Commission concerning the source of the 2,472,000 cfs peak (5). Many features of the 1927 flood are crystal clear, while others, like the Arkansas City peak discharge and the nature of the storms that were responsible for the flood, are, like the Mississippi River in flood, murky.

On April 21, 1927, a massive crevasse opened along the main channel of the Mississippi River near Mounds Landing, just upstream of Greenville, Mississippi (Figures

11 - 13). The crevasse at Mounds Landing occurred on the outside of the first major meander bend downstream of the confluence with the Arkansas River (Figure 12), a location that would have the highest velocities impacting the overtaxed levees. As Charley Patton observed in *High Water Everywhere*, floodwaters that poured through the crevasse covered much of the Yazoo River Delta region of the state of Mississippi and would do so for weeks to follow (Figure 11). Multiple levee failures along the lower Arkansas River and White River, resulted in extensive flooding in Arkansas around the same time (Figures 1 and 11).

Floodwaters moved down the main channel of the Mississippi River and the Delta region, with flooding at Vicksburg and points south including both the main channel flow and flow from the Mississippi Delta region that rejoined the river at Vicksburg. The river level at Vicksburg decreased from April 22 to April 26, as the Mounds Landing crevasse reduced flow in the main channel of the Mississippi, then began to increase on April 27 as flow from the Delta began to reenter the main channel. On 3 May 1927 the *Cabin Teele crevasse* on the west bank of the Mississippi River put large areas of Louisiana under water, including the village of Waterproof, named for its prior history of surviving Mississippi River floods. The Mounds Landing crevasse on April 21 set in motion a chain of events which resulted in the inundation of more than 27,000 mi^2 of land in Mississippi, Arkansas and Louisiana (Figure 11) .

The day after the Mounds Landing Crevasse, the Daily Democrat-Times of Greenville, Mississippi reported the levee failure and noted the "unprecedented rise of the Mississippi River" at Greenville in the preceding three days. The conclusion of the Daily Democrat-Time still holds; the rise of the Mississippi River in the days prior to the crevasse at Mounds Landing has not been surpassed. The four largest flood stages that have been measured for the Mississippi River at Greenville occurred on 21 April 1927 (65.4 feet), 16 May 2011 (64.2 feet), from 13 - 16 February 1937 (61.6 feet) and 12 - 14 May 1973 (58.2 feet). The increase in stage from 15 - 21 April 1927 of 4.1 feet in 6 days is far larger than other floods, with the 2.1 feet in 6 days in May 2011 placing second to 1927. The rapid rise in the Mississippi River at Greenville preceding the crevasse on 21 April 1927 is a signature of extreme flooding in the lower Mississippi River basin, close to the Mounds Landing crevasse.

Storms produce floods and the April 1927 storms concentrated their rainfall in Arkansas and southern Missouri (Figure 14), principally engaging the drainage networks of the White River and Arkansas River. Rainfall analyses in Figure 14, which are based on reconstructions using a regional climate model (31), show extensive areas with monthly accumulations exceeding 20 inches (500 mm) in the White River basin of Arkansas and Missouri and the Arkansas River basin in Arkansas and Oklahoma. Rain gage observations, which were sparse in 1927, also include monthly accumulations exceeding 20 inches.

Daily discharge observations from the USGS during April 1927 for the White River at Beaver, Arkansas (Figure 15), which principally drains the Missouri portion of the watershed (including the present-day Mark Twain National Forest) highlight the development of flooding in the White River basin. The peak daily discharge was 69,400 cfs on April 16, which translates to 6,000,000 cubic feet of water flowing past the gage over the course of the day, or 2.1 inches of water spread uniformly over the 1238 square mile drainage basin. Accumulating depths for the 30 days in April yields a value of 12 inches over the drainage basin, an exceptionally large value, but 3 inches less than rainfall over the watershed for the month (Figure 14). These computations suggest that roughly 80% of the April rainfall over the White River basin made it through the river system as runoff to the basin outlet, with the remaining 20% divided between infiltration into the subsurface and evaporation back to the atmosphere.

Rainfall was extreme for the month of April, but it was most exceptional during the 4-day period from October 12 - 16 (Figure 16). And within that period it was the Good Friday storm of April 14 (Figure 17) that was most directly responsible for setting in motion the events that resulted in the Mounds Landing crevasse on April 21. The White River peak on April 16 (Figure 15) includes the cumulative effects of rainfall from 12 -16 April, but especially the contributions from the Good Friday storm. Rainfall analyses for the 4-day period show peak accumulations of more than 12 inches in northern Louisiana, Arkansas and southern Missouri.

Rainfall comes in two principal types - convective and stratiform; the 1927 Mississippi flood was dominated by convective rain (Figure 17). Convective precipitation is associated with strong vertical motions like those found in thunderstorms and can produce large rainfall rates; stratiform precipitation is associated with weaker vertical motion and modest rainfall rates. Analyses of the Good Friday storm in Figure 17 are reconstructions of radar reflectivity, which can be used to distinguish between convective precipitation (reflectivity greater than 45 dBZ) and stratiform precipitation (reflectivity less than 45 dBZ). The Good Friday storm was organized along a contiguous line of heavy rainfall extending from south Texas to central Illinois on April 14, with the largest area of heavy rainfall extending through central Arkansas (Figure 17). The area of convective rainfall on April 14 exceeded 7,500 km^2.

Extratropical cyclones were responsible for extreme rainfall during the 1927 Mississippi River flood and the most powerful produced the Good Friday storm (Figure 18). An extratropical cyclone is characterized by a region of low pressure, with frontal boundaries organized around the center of low pressure near the surface. Cold fronts, in which cold air displaces warm air and warm fronts along which warm air glides over retreating cold air, impose structure on rainfall. Heavy rainfall from the Good Friday storm was organized ahead and along the cold front and moved eastward in tandem with the frontal boundary,

The Mississippi River flowing south in flood is paired with a river of water vapor flowing north from the Gulf of Mexico. The two are offset in time, with water vapor flux from the Gulf of Mexico preceding flooding in the lower Mississippi. Water vapor flux on April 14 (Figure 19) exceeded 500 $kg\ s^{-1}\ m^{-1}$ over a large area extending from the Gulf of Mexico into southern Missouri (arrows for direction; color scale for magnitude of flux). A value of 500 $kg\ s^{-1}\ m^{-1}$ means that the transport of water vapor in the atmospheric column above the point is 500 $kg\ s^{-1}$ for every meter of distance perpendicular to the direction of flow. Northward flux from the Gulf of Mexico exceeding 500 $kg\ s^{-1}\ m^{-1}$ covered an east-west distance of approximately 300 km. Converting mass to volume of water (using the density of liquid water, 1000 $kg\ m^{-3}$) and accumulating volume of water over the 300,000 meter east - to - west distance yields a northward flux of more than 5,000,000 cfs. The flow of water vapor from the Gulf of Mexico into the Mississippi River basin was greater than two 1927 flood peaks!

The Good Friday storm was a lynchpin in the 1927 flood, but a single storm does not produce a major flood in the lower Mississippi River; the 1927 flood built over weeks and months. Rainfall during March of 1927 (Figure 20) was almost as extreme as April rainfall and followed months of above average rainfall ([14] and [31]). The most extreme rainfall extended in an arc from southern Arkansas, through northern Mississippi and into the Ohio Valley. An excerpt from John Waring Bell's diary ([1]) highlights features of the 1927 storms prior to April 14, from his location in Greenville, Mississippi: March 8 "pouring rain almost constantly for 24 hours"; March 12, "after a very stormy day yesterday it began to pour torrents about sunset, and rained very hearty until 10... At daylight, a steady unrelenting flood came down for four hours. I don't believe I ever saw so much rain"; March 18, "a tremendous storm of rain, thunder and lightning last night"; March 21, "Torrent of rain last night"; April 1, "Violent storm all night. Torrential rains, thunder, lightning, high winds";

April 5, “much rain tonight”; April 6, “rain last night of course”; April 8,“at 12 it commenced to rain hard. I have seldom seen a more incessant and heavy downpour until the present moment”.

Bell’s diary observations point to the frequent occurrence of lightning - many of the storm periods combined severe thunderstorms with heavy rain. Tornadoes resulted in more than 70 fatalities in Texas on April 12. From April 12 to April 15, tornadoes were reported in Texas, Louisiana and Arkansas, along with large hail and damaging winds (Monthly Weather Review, Severe Local Storms of April 1927). The 1927 flood in the lower Mississippi was not due to sustained, moderate rain over long durations or snowmelt, but to extreme rainfall from large systems of thunderstorms that repeatedly passed over the region during March and April.

The 1927 flood resulted from a succession of powerful extratropical systems that developed over the lower Mississippi valley during the months of March and April. Reconstructions of rainfall and reflectivity (as in Figure 17), show that the 1927 flood was associated with development of large areas of convective rainfall, principally organized along frontal boundaries (Figure 21). The March 12 storm produced a contiguous line of convective rainfall over an area of more than 12,000 km^2, extending from the Gulf of Mexico to Ohio. The 7-8 March, 17-18 March, 20-21 March, 5-6 April and 7-8 April storms all produced convective rain areas exceeding 7,500 km^2 (Figure 21). Large areas of convective rainfall extended throughout the entire period from April 12 through April 16. (Figure 21). Attempts to quantify design storms for the Mississippi have wrestled as much with how you can string sequences of storms together, as with the question of how hard it can rain in an individual storm, like the Good Friday storm.

The Atlantic and Pacific Oceans acted in concert to create an environment conducive to an extreme flood in 1927. From the Atlantic side, it was the extreme western position of the Bermuda High, the large high-pressure region typically centered in April over the middle of the sub-tropical Atlantic Ocean, that contributed to extreme rainfall. Clockwise rotation of winds around the Bermuda High contributed to strong water vapor flux from the Gulf of Mexico during the month of April 1927 (Figure 22). The storm environment for April 1927 is represented by the mean 850 hPa height field, i.e. the elevation in the atmosphere at which the pressure is 850 hPa. The height fields in the Gulf of Mexico in April 1927 were more than 2 standard deviations above their mean values. During April of 1927 the East Pacific High contributed to transport of cold air from the north to the central US, supporting an environment for development of extratropical cyclones (Figure 22). Positive anomalies in the 850 hPa height field in the Gulf of Mexico during April1927 are paired with negative anomalies over the central US. Low pressure dominated the region, reflecting the repeated development and passage of extratropical cyclones through the Mississippi Valley.

Assessments of flood magnitudes for the 1927 flood assumed prominence in determining how to protect the region from subsequent floods. Reported values of flood peaks for the Arkansas City gage location flood range from 2,400,000 cfs (15) to 3,000,000 cfs (1), with the official USGS peak of 2,472,000 cfs containing no documentation of its source (5). Barry [1] presents a discharge estimate of 3,000,000 cfs based on multiple sources that were reported during the time of peak flooding in 1927, but there is no information on how the values were determined (5). The 3,000,000 cfs peak was contested by the Corps of Engineers (5), largely because of the implications for the current flood control system, which is designed to deliver 3,000,000 cfs to the Gulf of Mexico. A flow of 3,000,000 cfs upstream of the confluence with the Red River would exceed the design capacity of the flood control system and significantly exceeds the discharge from the "largest, probable flood", as determined by the COE (4).

The Corps of Engineers made direct discharge measurements during the flood period at multiple locations along the Mississippi River and on the White River and Arkansas River. A direct discharge measurement entails current meter measurements of flow velocity, providing a mean velocity for the cross-sectional flow area. The geometry of the channel is determined (prior to the flood) by surveying and depth sounding at the site, providing the ability to compute cross-sectional flow area knowing the level of the river. Discharge is then computed as the product of velocity and area.

Corps of Engineers measurements of discharge at a location described as Chicot, Arkansas extended from April 2 to April 20 of 1927. The Chicot gaging location was later adopted as the USGS Arkansas City gage site (5). COE discharge measurements at the Chicot site increased from 1,483,000 cfs on April 11 to the final value of 1,712,000 cfs on April 20 (11). From these measurements, we know that peak discharge at Arkansas City was greater than 1,712,000 cfs. The Corps of Engineers made a series of discharge masurements on the Mississippi River upstream at Helena, Arkansas; the location is upstream of the confluences with the White River and Arkansas River. The peak discharge was 1,756,000 cfs. Direct discharge measurements were also made on the the Arkansas River at Little Rock (Figure 11) with a peak of 813,290 on and on the White River at Clarendon, Arkansas, with a peak value of 439,648 cfs (11)

Simple computations highlight the range of discharge estimates for the Mississippi River at Arkansas City. Adding the peaks from the Mississippi River at Helena, the Arkansas River at Little Rock and the White River at Clarendon, approximately 1,750,000 + 810,000 + 440,000, results in the 3,000,000 cfs value that was reported by Barry [1]. The lower bound is the 1,750,000 upstream peak at Helena. Values closer to 2,400,000 cfs arise as the middle ground between no synchronous contribution of the Arkansas and White River peaks to the Helena peak and perfect synchronous contribution. The range from 1,750,000 cfs to 3,000,000 cfs reflects the contributions of the White River and the Arkansas River to the Lower Mississippi River flood peak. The interplay of drainage network structure and rainfall distribution, relative to the drainage network, is central to understanding important features of the 1927 flood, including those associated with uncertainties in flood peak magnitudes.

The symbolic ending of the *levees only* period of flood control on the lower Mississippi River occurred on April 29,1927, when the levee at Caernarvon, Louisiana, was dynamited (Figure 23). More than 10,000 people in Plaquemines and St. Bernard's parishes were displaced and never compensated for their damages. The dynamiting of the levee at Caernarvon was not a clandestine action, but part of a plan developed by the State of Louisiana to protect New Orleans and its commercial interests ([1]).

3,000,000 cfs: Controlling the Mississippi River

COE and Federal policy shifted abruptly after the 1927 flood as the fatal weaknesses of the levees-only approach became readily apparent. The Flood Control Act of 1928 authorized the *Mississippi River and Tributaries Project* with the objective of developing a comprehensive flood control system for the lower Mississippi River and protecting the Mississippi River channel for navigation (4). Levees remained a major element of the flood control system, but *outlets* were added to levees as flood protection for the lower Mississippi River. The system also included dams and reservoirs in tributary basins, some of which were designed specifically for flood control purposes, notably in the Arkansas and White River basins, and some of which were designed principally for other purposes but served to reduce flood hazards in the lower Mississippi River.

Barry's assertion that the 1927 flood peak at Arkansas City reached 3,000,000 cfs struck a nerve with the COE because the flood control system is designed to deliver 3,000,000 cfs to the Gulf of Mexico, 1,250,000 cfs through the main channel of the Mississippi, 1,500,000 cfs through the Atchafalaya and 250,000 cfs through Lake Pontchartrain (Figure 24). Design of the system assumes a peak of 2,250,000 cfs from the Ohio River, 240,000 cfs from the upper Mississippi, 540,000 cfs from the Arkansas River and 350,000 cfs from the Red River. A flow of 3,000,000 cfs upstream of the confluence with the Red River would exceed the design capacity of the flood control system and significantly exceeds the discharge from the *largest, probable flood*, as determined by the COE.

The flood hazard in the lower Mississippi River is weighted towards the Ohio River, as illustrated in the current design flood and the engineering control system in Figure 24, with the Mississippi River above the confluence with the Ohio River playing a secondary role. The rationale is that the meteorology of flood-producing storms is characterized by a seasonally varying distribution of storms with peak flooding in the Ohio and lower Mississippi occurring during late winter and spring and peak flooding in the upper Mississippi and Missouri shifting to late spring and summer.

The most striking change to the Mississippi River flood control system following the 1927 flood was the inclusion of outlets (Figure 24). An outlet provides a *floodway* for removing water from the river, either bypassing a critical section of river before returning to the river or for transport to the Gulf of Mexico. The floodways that were constructed are the *Birds Point - New Madrid* floodway at the confluence of the Ohio and Mississippi and three floodways in the lower reaches of the Mississippi at and below the Red River junction. The *West Atchafalaya* floodway and the *Morganza* floodway divert flow through the Atchafalaya to the Gulf (Figure 25); the *Bonnet Carre* floodway diverts water from the Mississippi River immediately upstream of New Orleans to the Gulf of Mexico by way of Lake Pontchartrain.

The Birds Point - New Madrid outlet was one of the most controversial elements of the flood control system. The outlet is designed to reduce flood stages in Cairo, Illinois, but its activation, achieved by dynamiting a *fuse plug* levee, inundates communities and agricultural land in the floodway. Flow of the Mississippi River downstream of the confluence with the Ohio River is diverted to the floodway at Birds Point above Cairo and returns to the Mississippi River at New Madrid (Figure 24). The first operation of the floodway occurred on January 25, 1937 as the Ohio River approached its record flood peak of 1,850,000 cfs. Inundation of the floodway devastated the homes and livelihoods of more than 3,000 inhabitants; the National Guard provided protection from armed protesters for crews working the levees ([4]). More than 70 years would pass before dynamite was again used at Birds Point.

The three remaining outlets (Figure 24) are in the section of the river below Vicksburg. The West Atchafalaya and Morganza floodways combine (Figure 25) to form the Atchafalaya floodway. The Morganza floodway has a controlled release structure (Figure 26) that is operated when Mississippi River flow at Red River Landing exceeds a trigger level of 1.5 million cfs and the river is still rising. The West Atchafalaya floodway is the last element of the flood control system to be put into play; it is operated by dynamiting a *fuse plug* levee at the northern end of the floodway (Figure 25). The Morganza floodway was used once from its completion in 1954 until 2011. In 1973 the floodway was operated to protect the Old River Control Structure from failing ([22]). The West Atchafalaya floodway has never been activated. Bonnet Carre (Figure 24) is the last line of defense for New Orleans, diverting up to 250,000 cfs to Lake Pontchartrain. The floodway has been activated 12 times since its completion in 1931, with 4 of the events occurring between 2008 and 2018.

Control and management of the Mississippi River has often involved engineering interventions to meander bends with goals ranging from shortening the travel distance to the more complex objective of changing the distribution of sediment in the channel. Twain commented on the efforts of the Corps of Engineers to alter Mississippi River meander bends: “In the space of one hundred and seventy-six years the Lower Mississippi has shortened itself two hundred and forty-two miles. That is an average of a trifle over one mile and a third per year... Any person can see that seven hundred and forty-two years from now the Lower Mississippi will be only a mile and three quarters long, and Cairo and New Orleans will have joined their streets together, and be plodding comfortably along under a single mayor and a mutual board of aldermen.”

Cutoffs reemerged as a tool for flood control after the 1927 flood. The section of the Mississippi River from the Birds Point - New Madrid floodway near the confluence with the Ohio River down to the Red River is a critical reach in which proposed outlets were never authorized. The design discharge reaches 2,890,000 cfs below the confluence of the Arkansas River with the Mississippi. Reducing stage associated with a given peak discharge emerged as the only means of containing the river within the levees. The old strategy of eliminating meander bends with cutoffs was pursued with the objective of increasing slope and erosion of sediment from the channel and banks, thereby creating additional transport capacity during extreme floods. Adding cutoffs was combined with engineering works that stabilized channel banks in critical reaches of the river. By 1937, removing meander bends had shortened the river and markedly increased the channel capacity.

Levees remain the backbone of the Mississippi River and Tributaries flood control system, with more than 3,700 miles of levee and floodwalls along the main stem of the river. A lower Mississippi flood, like the 1927 flood, lasts for weeks and puts tremendous fluid pressure on the structure. Movement of water through the soil matrix of a levee from high pressure - the river side of the levee - to low pressure - the protected side of the levee - plays a key role in design and maintenance of levees. The Mississippi River levee system has evolved not only in response to changing perspectives of flood hazards, but also changing assessments of structural reliability of levees under the extreme loading of an extended flood fight (Figure 10). Fisk's studies of the surficial geology of the the Mississippi River floodplain (see Figure 3) were major contributions to understanding the flow environment in and around the Mississippi River levees ([9] and [10]).

If levees are the backbone of the system, the *Old River Control Structure* (Figure 27), which was completed in its original form in 1959, is the most perilous component ([22] and [27]). It is largely responsible for maintaining Congress's directive that the Mississippi and Atchafalaya partition the total flow (and sediment) in a 70 - 30 split. The central objective is to maintain the course of the main stem of the Mississippi River past Baton Rouge and New Orleans, restraining the river from changing its course to the Atchafalaya. During the flood of 1973, the battle was almost lost as the Low Sill structure (Figure 27) came close to failure from erosion of sediment around its foundation ([22]). The Auxiliary structure (Figure 28) was completed in 1986 to augment the damaged Low Sill structure. The Low Sill and Auxiliary structures are operated jointly during normal flow periods to control the partitioning of water and sediment between the Atchfalaya and Mississippi. The Overbank structure is a spillway that is operated during flood periods to control the flow of the Mississippi to the Atchafalaya and protect the Low Sill structure.

Radical changes in engineering design philosophy after 1927 produced the current flood control system for the lower Mississippi River. Prior to the 1927 flood, design of the levee system had rested on protection against the largest flood on record. For the Mississippi River and Tributaries project, the engineering philosophy was based on determining the most extreme flood that the system would be expected to withstand in the future. The design flood was termed the *maximum probable flood* by the COE. The design flood was in turn based on a *design storm*, reflecting the "primary role of meteorology in flood flow estimation" ([3]). Initial developments of a design storm and the resulting design flood were carried out separately by the U. S. Weather Bureau (renamed the National Weather Service in 1970) and the Mississippi River Commission. The two analyses involved somewhat different assumptions, the Weather Bureau referred to their design flood as the *maximum possible flood*, but both resulted in similar assessments of the flood magnitudes in the lower Mississippi

River. The resulting design flood managed a net discharge of 3,000,000 cfs to the Gulf of Mexico via the main channel of the Mississippi, the Atchafalaya and Lake Pontchartrain. The U. S. Weather Bureau carried out a series of analyses of extreme storms and floods in the Mississippi River basin (in particular [21]; see also [30]). Their fundamental idea in development of a design storm for Mississippi River flood defenses was to use observations from past storms as a basis for assessing the largest possible flood in the lower Mississippi.

The centerpiece of the design storm developed by the US Weather Bureau ([21]) is the January 1937 storm period that resulted in the record flood peak in the Ohio River and activation of the Birds Point - New Madrid outlet (Figure 29). The 1937 flood was one of the most destructive in US history ([34]), but the mainstem of the Mississippi above the Ohio River and the major tributaries to the Mississippi below the Ohio River fortunately did not add much to the flooding downstream. But the design storm did, augmenting the catastrophic Ohio River rainfall in 1937, with rainfall from a major lower Mississippi River flood event in January 1950 followed by rainfall from a major flood event in February 1938. The sequence of storm periods moves the locus of flooding progressively down the Mississippi River, with maximum rainfall exceeding 30 inches in an arc extending from the lower Ohio River through the lower White and Arkansas River basins in Arkansas (30). Each of the storm periods was separated by a 3-day period of no rainfall, reflecting the separation of major storm systems as they pass through the lower Mississippi Valley. This scenario is one of a series of hypothetical floods, creatively termed *Hypo-Floods*, that were examined.

Given a design storm it is necessary to translate the prescribed rainfall to design flood magnitudes over the drainage network (as in Figure 24). The principal steps are to convert rainfall to runoff over the drainage basin through an accounting of infiltration into the soil, conversion of runoff over a region to stream discharge from headwater basins and hydrologic or hydraulic routing of stream discharge through the river network. Each of these analysis elements received considerable attention during the phase of major river basin development in the US during the first half of the 20th century, stimulating major scientific advances in hydrologic science. Especially important for flood control were the notions of Hortonian overland flow as a runoff mechanism for flood periods and the *unit hydrograph* as a representation of streamflow response to runoff distributed uniformly over the upstream drainage area (see [28]).

Scientists and engineers involved in developing flood protection programs in the 1920s, notably Arthur Morgan (a major actor in the Miami River chapter) and Robert E. Horton (after whom Hortonian overland flow is named), were convinced that rainfall and flood magnitudes were bounded. Shortly after the 1927 flood, Horton wrote "It is not difficult to show from sound meteorological reasoning, and aside from any statistical proof, that there is a natural limitation to rain intensity for any given duration. I have long had in mind the preparation of a paper on this subject. There is a limit to the amount of moisture that can be stored and the velocity of flow of air current is fixed by barometric gradient" (Robert E. Horton letter, 18 November 1927). These ideas ground the procedures used for development of design floods, as reflected in the terms used for design floods like maximum probable flood, probable maximum flood, maximum possible flood (see [25] for a historical account).

A parallel stream of analysis for extreme floods and rainfall took place in the statistics and engineering communities, leading to a set of procedures based on *extreme value theory* for computing rainfall and flood frequency from long rainfall and streamflow records ([12]). Using these methods, it is possible to directly test whether floods are bounded or unbounded, and for the unbounded case to assess how extreme the situation is. An interesting feature of these analyses is that they often indicate that flood peaks are unbounded and suggest that the observed record of flooding in many settings provides a relatively weak foundation for assessing just how bad floods can be in the future. Both the probable maximum flood techniques and extreme value theory methods are based on heroic assumptions that preclude heroic conclusions. Between the physical arguments for bounded floods and the statistical arguments for unbounded floods, the enduring reality confronting the development of flood defenses is the difficulty of characterizing the magnitude and frequency of catastrophic floods.

The Mississippi River Flood of 2011

Faulkner's mule waiting 10 years to kick its owner was a metaphor for Mississippi River flooding (Preface); for much of the time since the 1927 flood the frequency of flooding, as represented by activation of the Bonnet Carre spillway, has been close to once per decade. The Mississippi River has become impatient in the 21st century, with floods in 2008, 2011, 2016 and 2018 requiring operation of Bonnet Carre. The most extreme flooding occurred during the Spring of 2011, with flood peaks rivaling those from 1927 (Figure 31). The peak discharge of 2,310,000 cfs on May 17, 2011 edged out the 2,278,000 cfs peak on May 1, 1927 as the record flood peak for the Mississippi River at Vicksburg.

The 2011 flood, like the design flood for the lower Mississippi River, was dominated by the Ohio River (Figure 32), which peaked at 1,260,000 cfs immediately upstream of the confluence with the Mississippi on May 5 (Figures 32 and 31). The 2011 flood peak on the Ohio River at Metropolis (Figure 31) was extreme, but the record flood on 1 February 1937 was almost 50% larger. Downstream flooding in the lower Mississippi in 1937 did not reach 2011 or 1927 levels because of the modest contributions from the upper Mississippi, less than 400,000 cfs in 1937, and other tributary streams below the Ohio - Mississippi confluence. In 2011, the peak discharge of the Mississippi River upstream of the confluence with the Ohio River, 876,000 cfs on May 2, was more than twice the 1937 peak (Figure 32; see also Figure 31).

Above the confluence with the Ohio River, the largest flood peaks on the Mississippi and lower Missouri occurred during the summer of 1993 ([19]). For the Mississippi River at Thebes (Figure 31), the 1993 flood peak of 1,000,000 cfs occurred on August 7 and is the largest during the 80 year USGS stream gaging record. Extreme flooding in the Missouri River basin, unlike flooding in the Ohio River basin, is concentrated during late spring and summer. Mississippi floods like the 1993 flood are most severe in the Missouri and main stem of the Mississippi above its confluence with the Ohio.

A sequence of storms during the week ending April 29, 2011 (Figure 33) played the role of the 12 - 16 April 1927 storms in determining peak discharge in the lower Mississippi for the 2011 flood. Rainfall was concentrated in the lower Mississippi, lower Ohio and the portion of the upper Mississippi River basin downstream of the confluence with the Missouri River. The discharge contribution from the upper Mississippi (Figure 32) was principally due to rainfall in close proximity to the Thebes gaging station. Major flooding had commenced with a series of storms during the week of April 15. The 14-16 and 25-28 April storms not only produced heavy rainfall over the lower Mississippi basin, but also tornadoes that resulted in 387 fatalities. The two month period preceding peak discharge in the Mississippi saw a procession of extratropical cyclones passing through the lower Mississippi River, producing comparably large areas of convective rainfall to the most intense storms in 1927.

As with the 1927 flood, the Atlantic and Pacific Oceans conspired to create the setting for a major flood in the lower Mississippi (Figure 22). The western margin of the Bermuda High was far west of its normal location in April of 2011, providing the environment for transport of warm, moist air masses into the Mississippi valley. The Pacific High contributed to the transport of cold air from the north into the Mississippi and the repeated development of extratropical cyclones over the central US. Similar environments mark virtually all major flood episodes in the lower Mississippi River, including the 1937 flood (Figure 22).

The first critical period of the 2011 flood fight centered on Cairo, Illinois and the confluence of the Ohio and Mississippi Rivers. By late April, hundreds of *sand boils* had developed along the Mississippi River levee system, including a massive sand boil in Cairo (Figure 34; see [26]). A sand boil occurs when fluid pressure becomes so large that groundwater flow erodes the soil that makes up the levee. The visual appearance is a boiling flow of water and sediment on the protected side of the levee. Sand boils cause internal damage to the levee and are major contributors to levee failure during a protracted flood fight. Sandbagging around the site equalizes the water surface elevation on both sides of the levee, reducing the fluid pressure in the levee and consequently the erosive flow of groundwater in the levee (Figure 34). When a levee system experiences a rapidly increasing number of sand boils and increasingly large sand boils, it is an indication that the levee is in serious danger of breaching. This was the situation in Cairo as April 2011 came to an end.

During the 6 days leading up to May 2, The Ohio River rose 6 feet reaching the critical stage of 60.5 feet at the Cairo gaging station. On May 2, the National Weather

Service forecast was for the Ohio River to crest at 63.5 feet, a stage that was beyond the design capacity of the system. Major General Michael Walsh, president of the Mississippi River Commission and Commanding General of the Corps' Mississippi Valley Division, gave the order to activate the Birds Point - New Madrid Floodway. Explosive charges were used to breach the levee at Birds Point and activate the floodway for the first time since the 1937 flood. By May 5, the Cairo stage had dropped below 60 feet and flood fight teams reported that conditions along the levee system had stabilized ([26] and [4]).

Operation of the Birds Point - New Madrid Floodway inundated approximately 130,000 acres of farmland in Missouri and was as controversial in 2011 as it was in 1937. The state of Missouri filed suit against the Corps of Engineers on April 29, 2011 to block activation of the floodway. Federal courts rejected the suit on the basis that the Corps of Engineers was acting in accord with congressionally authorized management of navigable waters.

The stretch of the Mississippi River downstream of the Birds Point - New Madrid floodway and upstream of the Old River Control structure was the setting for a protracted flood fight with the levee system providing the main line of defense. Sand boils near Greenville, Mississippi on May 12 threatened to create a levee break that would have endangered thousands and caused extensive property damage in the Yazoo River delta region. Heroic action, largely by inmate labor ([26]), prevented catastrophic failure of the levee system.

On May 9 the first bays of the Bonnet Carre spillway were opened immediately upstream of New Orleans. The trigger for operation of Bonnet Carre was a computed discharge of 1,240,000 cfs at Red River Landing. On May 14, discharge through the spillway was increased above 250,000 cfs to provide additional cushion between the river level and the tops of the levees. A peak discharge of 316,000 cfs from Bonnet Carre to Lake Pontchartrain was reached on May 17.

The discharge trigger for operation of the Morganza floodway is 1,500,000 cfs at Red River Landing and it had never been reached prior to 2011. Operation of the Morganza floodway in 1973 occurred at lower flow conditions and was carried out to keep the Old River Control structure from failing. The decision to operate the Morganza floodway in 2011 was made on May 14 by Major General Walsh (Figure 35). The predicted inundation of the Morganza floodway by the US Army COE prior to operation (Figure 36) covered an extensive area of southern Louisiana. Floodway operation directly impacted more than 20,000 people in the floodway and 11,000 homes in backwater areas ([26]). The peak flow through the Morganza floodway reached 186,000 cfs. Combined operation of the Morganza floodway and Bonnet Carre was instrumental in keeping mainline levees in the lower Mississippi River from failing. On May 19, the Mississippi River crested at Vicksburg and the most dangerous phase of the flood fight had passed.

The US Army Corps of Engineers ([26]) estimated that $234 billion in damages from the 2011 flood were prevented by the Mississippi River and Tributaries flood control system; total damages for the 2011 flood are estimated to be \$2.8 billion ([26]). Cumulative losses prevented by the Mississippi flood control system since 1928 are estimated to be \$612 billion, in comparison to a total cost of \$14 billion ([26]).

The flood control system worked as planned - major levees and outlet works along the Mississippi River did not fail. But it was a near miss! A final ill-timed extratropical cyclone in May or a less heroic flood fight along the levees could have produced a different outcome. Twain and Faulkner would wonder if the Mississippi River has more surprises in store.

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List of Figures

Figure 1: The Mississippi River basin and its principal tributaries.

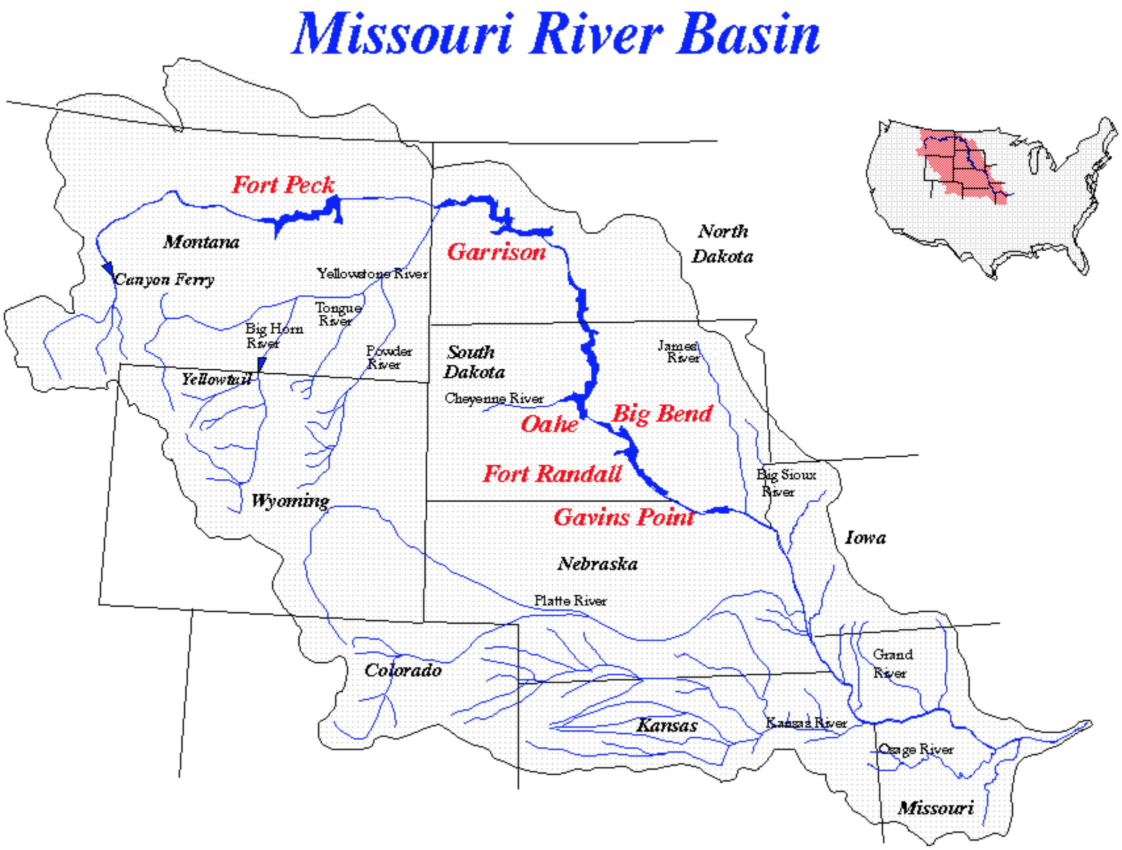

Figure 2: The Missouri River River basin, including locations of the major dams - Fort Peck, Garrison, Oahe, Big Bend, Fort Randall and Gavins Point.

Figure 3: Map of the Mississippi River meanders near the confluence with the Arkansas River from Harold Fisk ([9]).

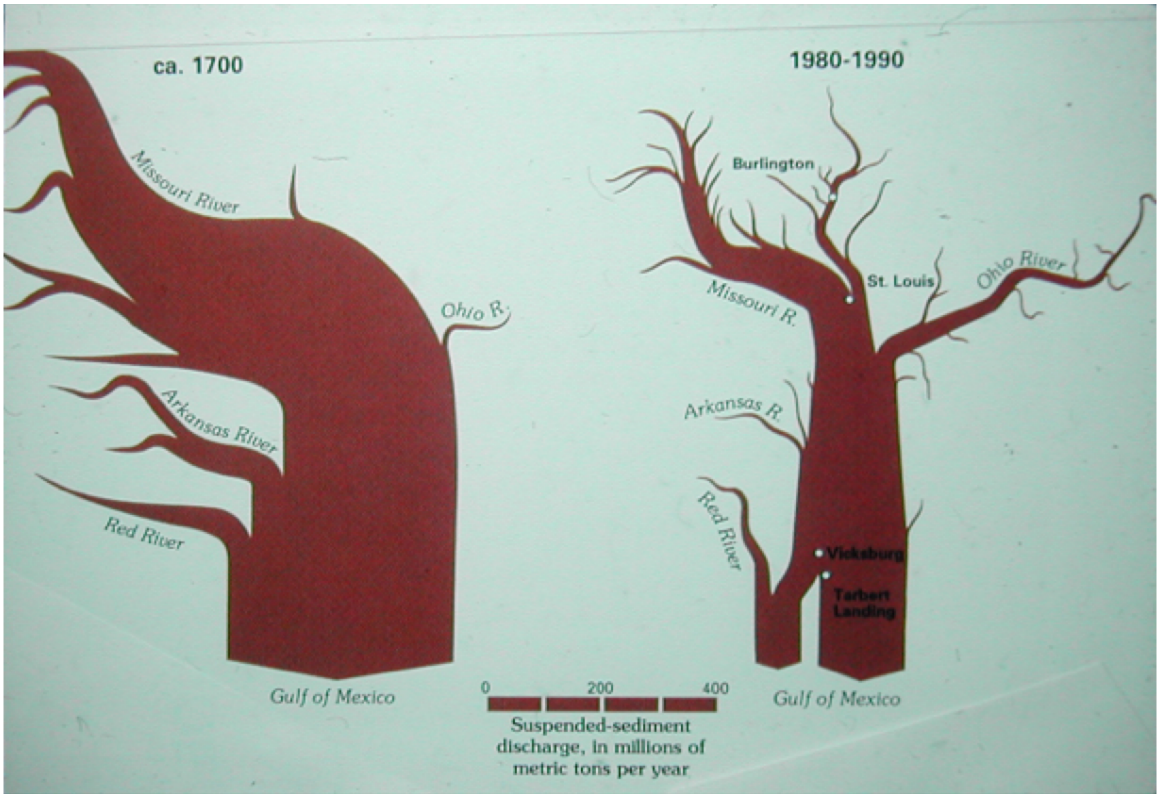

Figure 4: Sediment Transport in the Mississippi River and its tributaries prior to European colonization (left) and during the late 20th century (right; [24]).

Figure 5: Space Shuttle photograph of the Lower Mississippi Delta, including the navigation outlet at Southwest Pass (from LaCoast.gov).

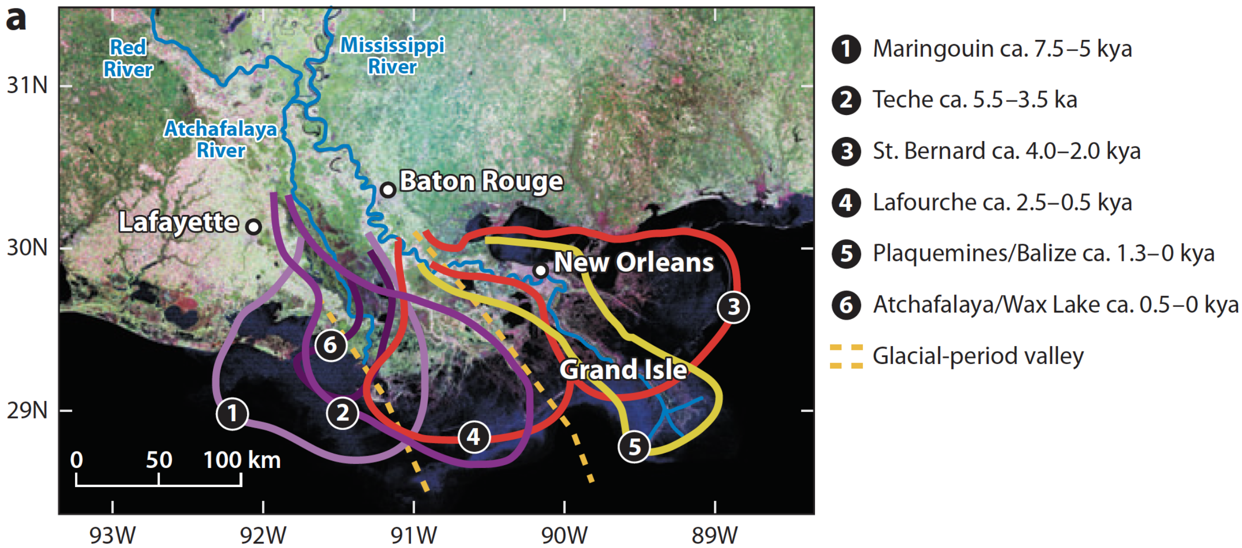

Figure 6: Changing course of the lower Mississippi River; delta lobes from 7,500 years ago to the present (from Blum and Roberts, 2012).

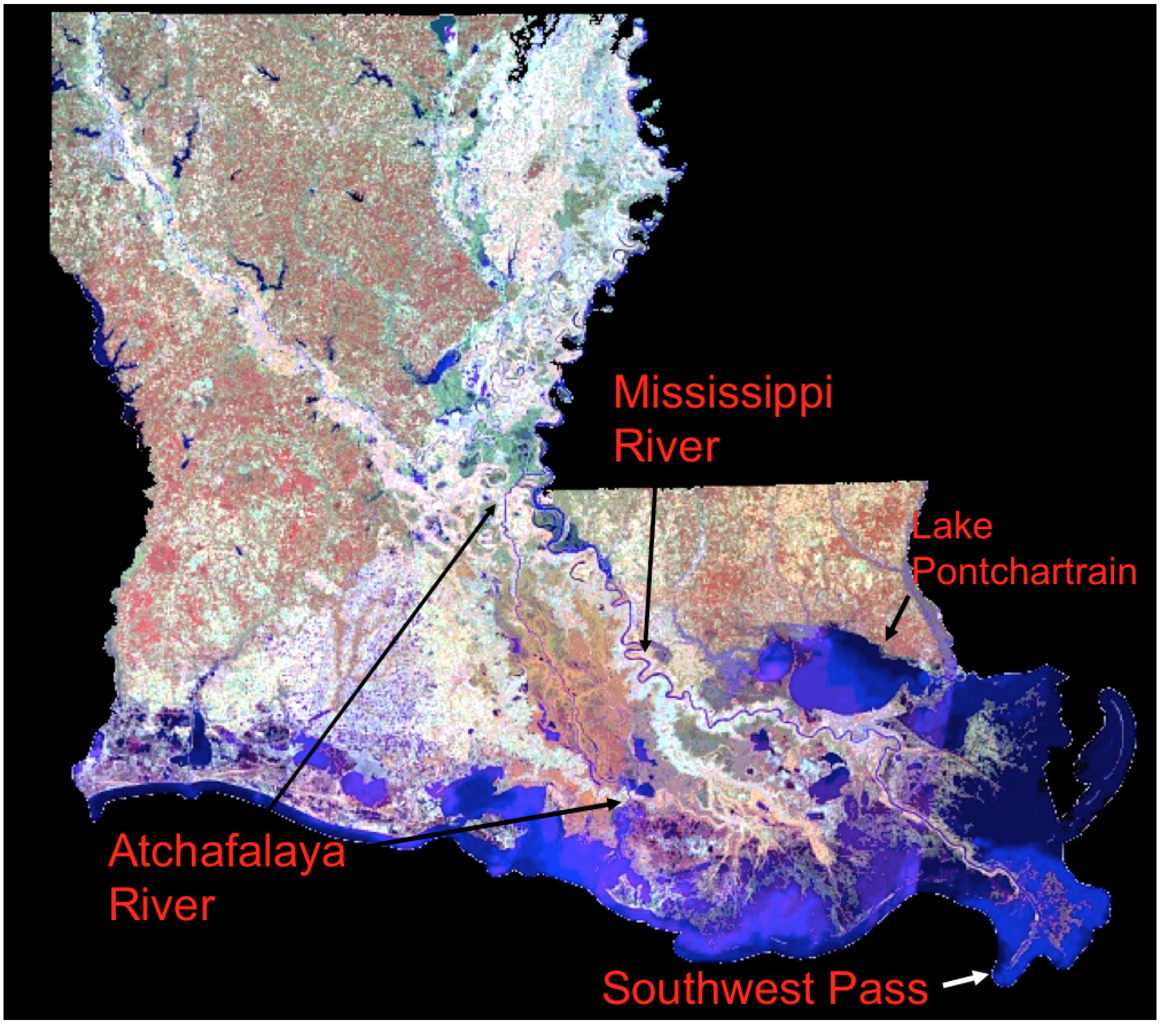

Figure 7: Satellite imagery of the lower Mississippi in Louisiana showing the Mississippi River, Atchafalaya River, Lake Pontchartrain and the exit of the Mississippi River at Southwest Pass, (from LaCoast.gov)

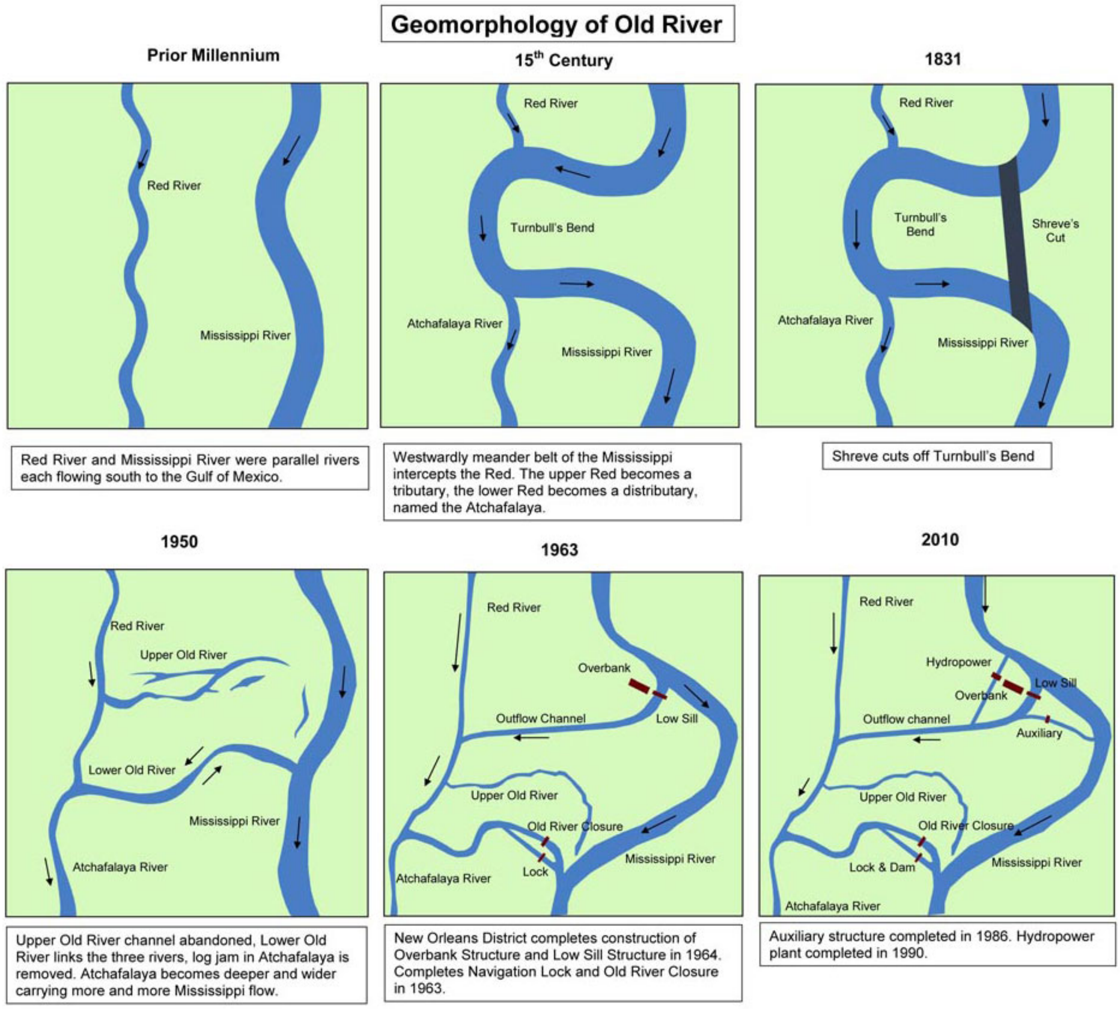

Figure 8: Geomorphology of Old River and development of the Old River control structures.

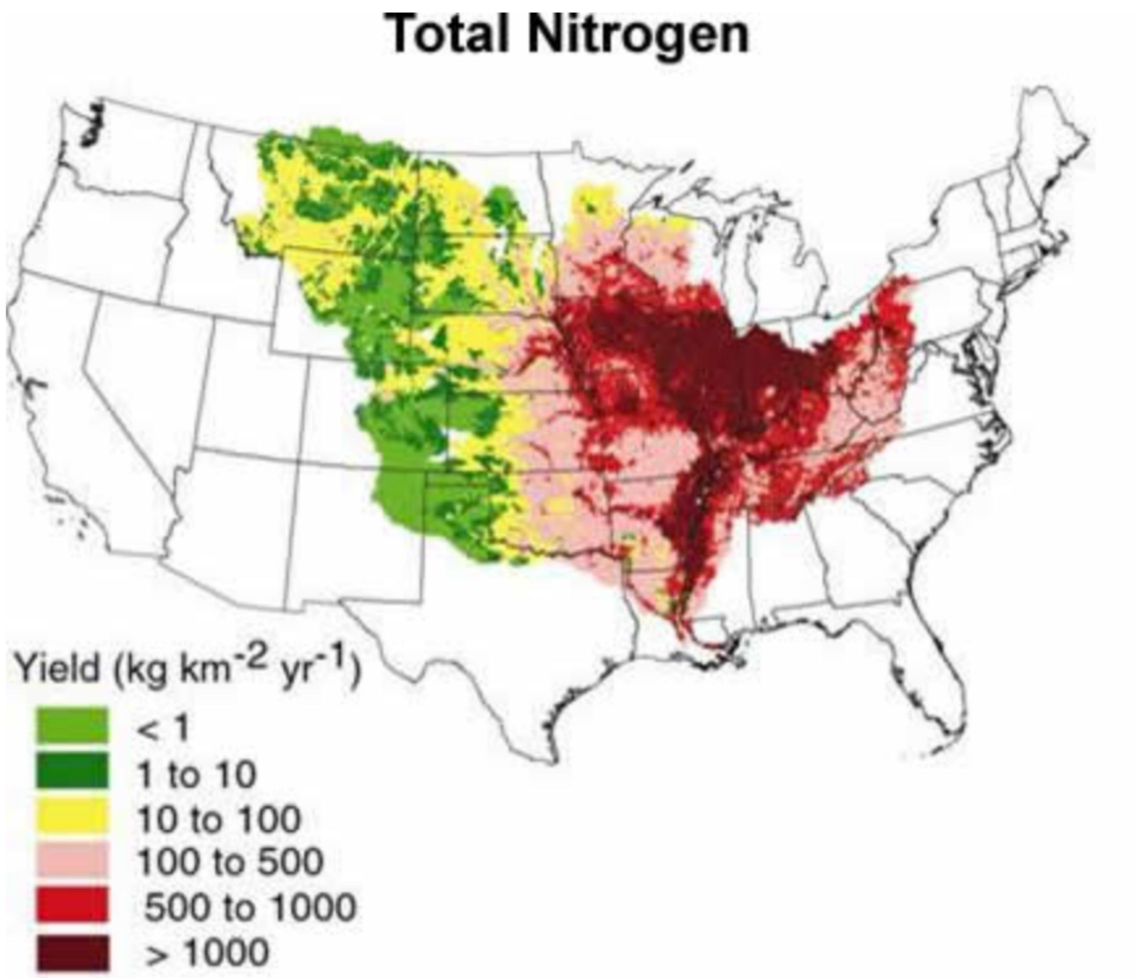

Figure 9: Distribution of nitrogen sources delivered to the Gulf of Mexico (source: USGS).

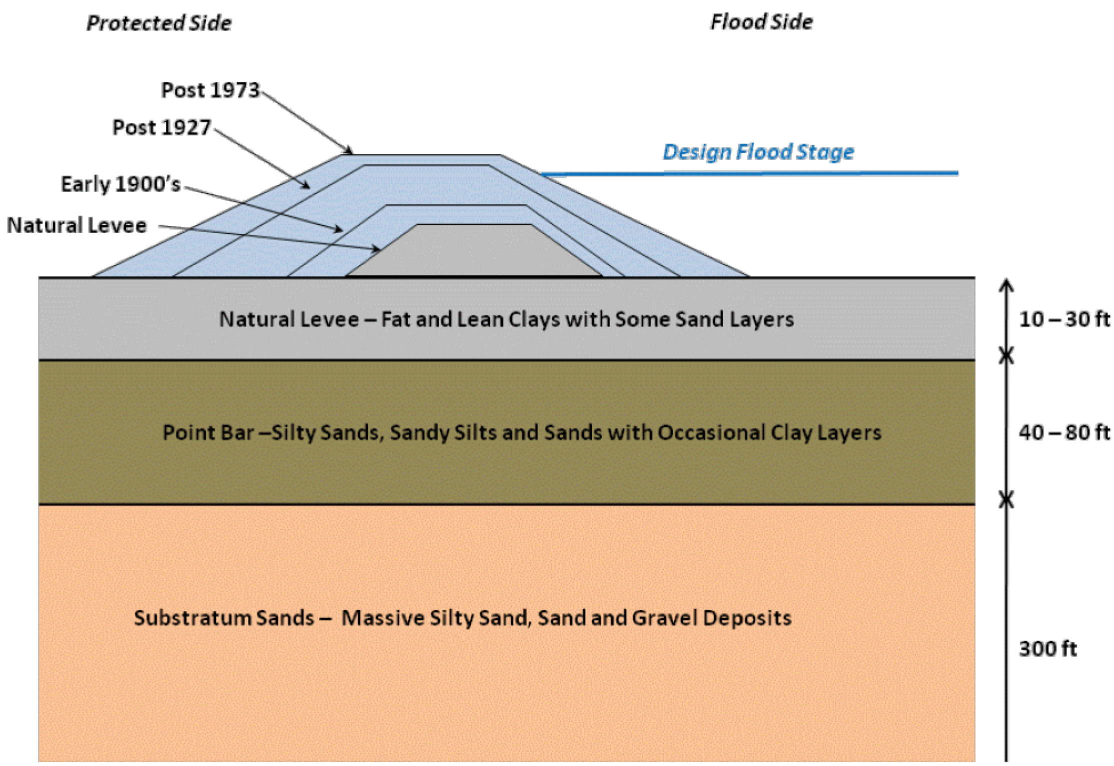

Figure 10: Idealized representation of levee sections (over time) along the lower Mississippi River.

Figure 11: Flood map of the 1927 flood in the Lower Mississippi. Inundated areas are shown in light green and dark green shading. Arrows indicate locations of major crevasses.

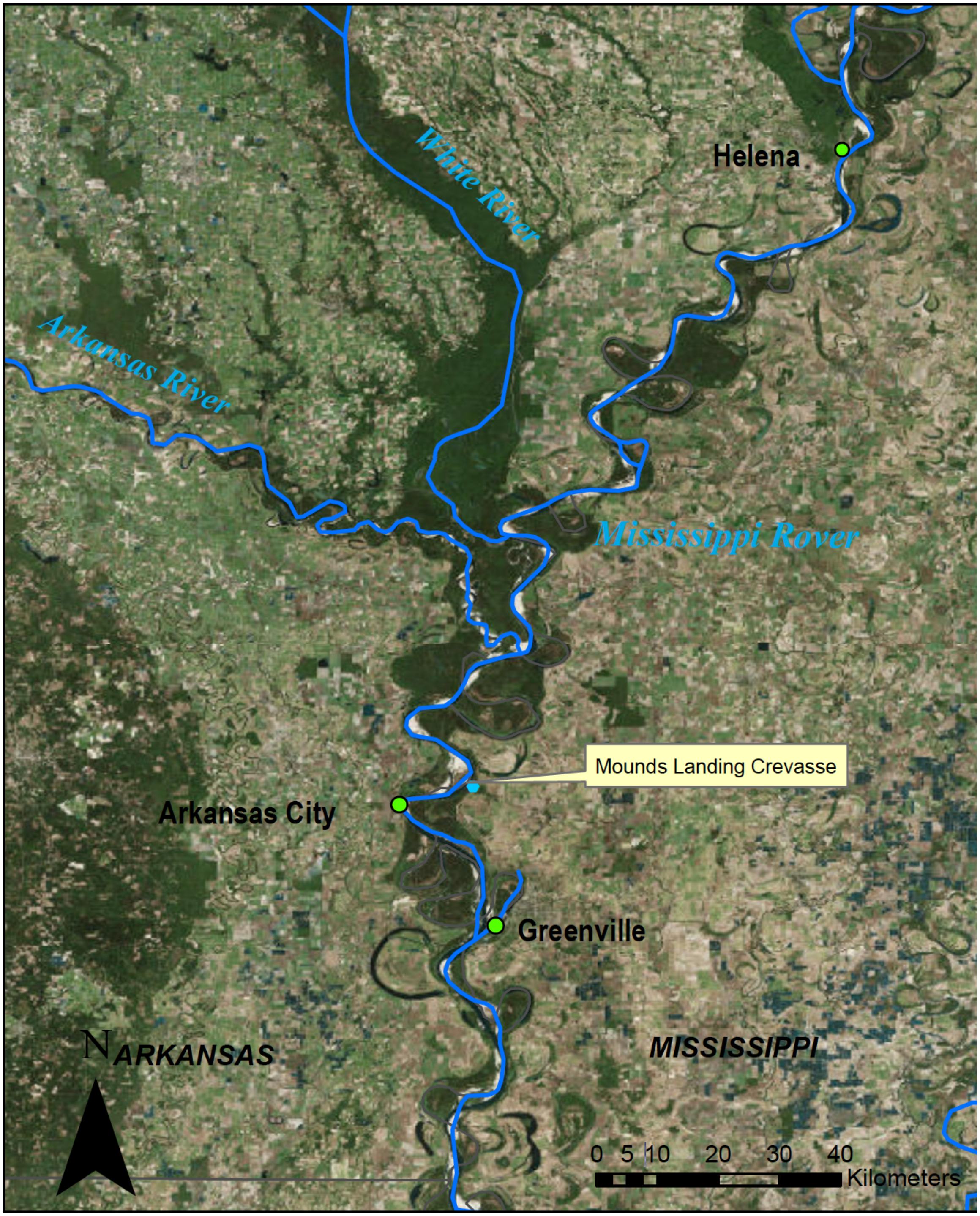

Figure 12: Mounts Landing Crevasse on 21 April 1927.

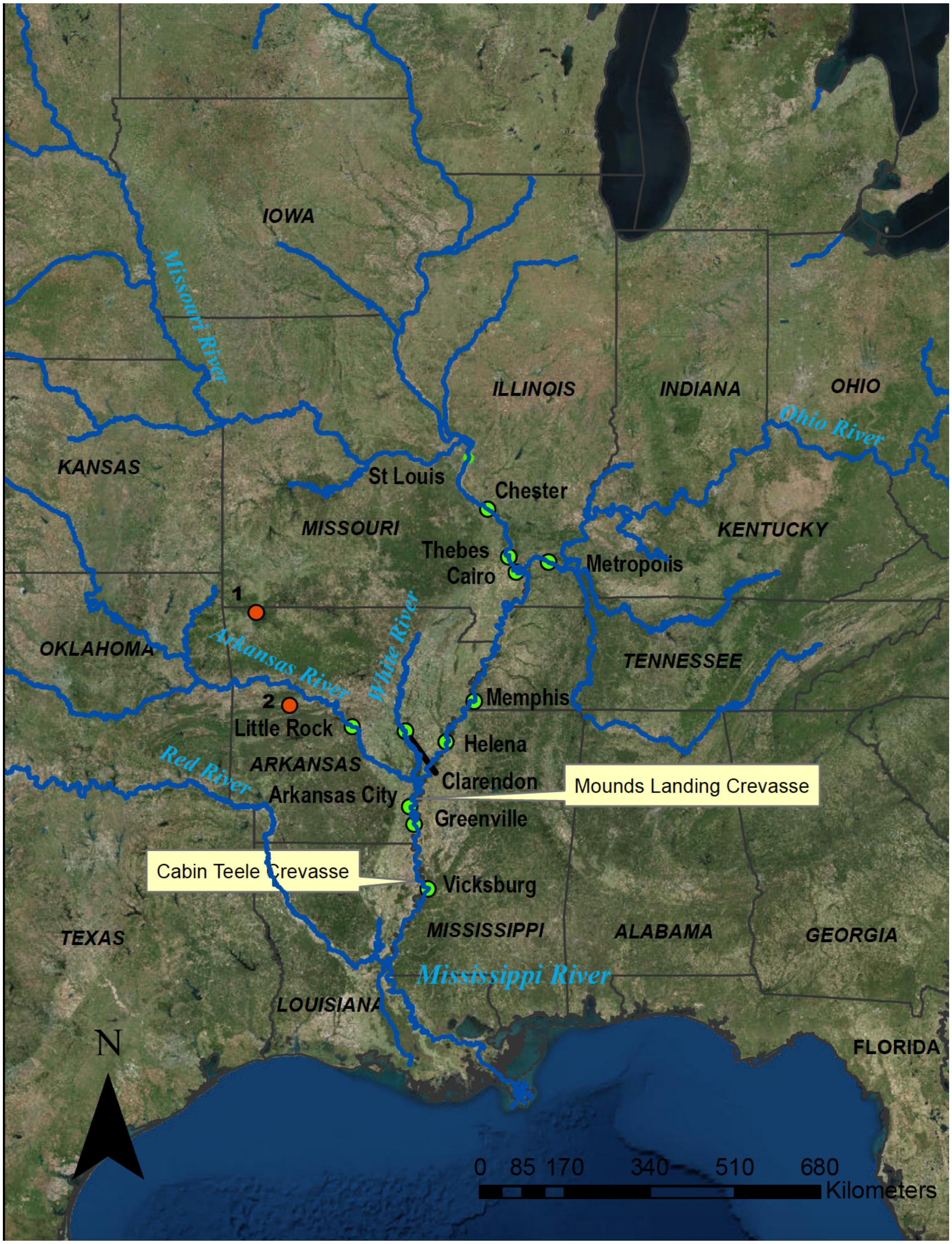

Figure 13: Mississippi 1927 flood locations

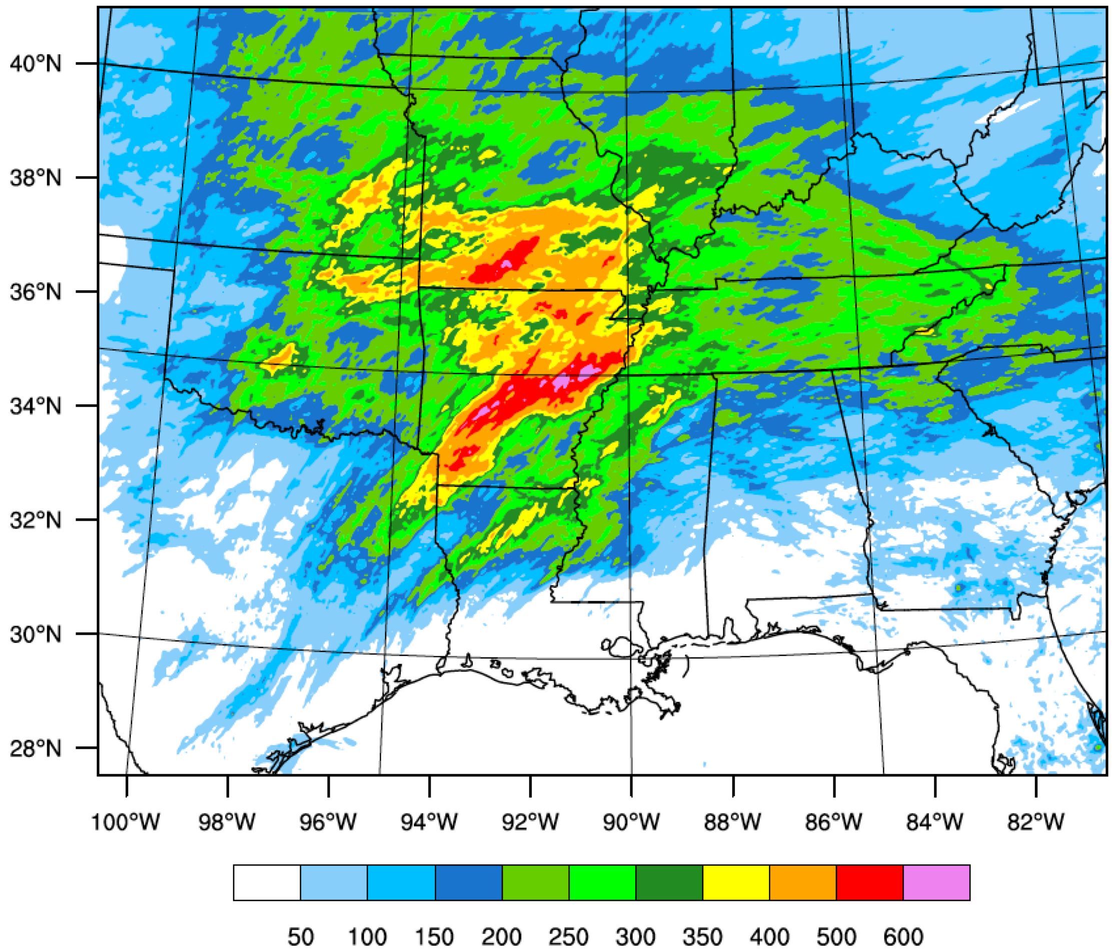

Figure 14: Monthly rainfall (in mm) for April 1927, based on regional climate model simulation (31).

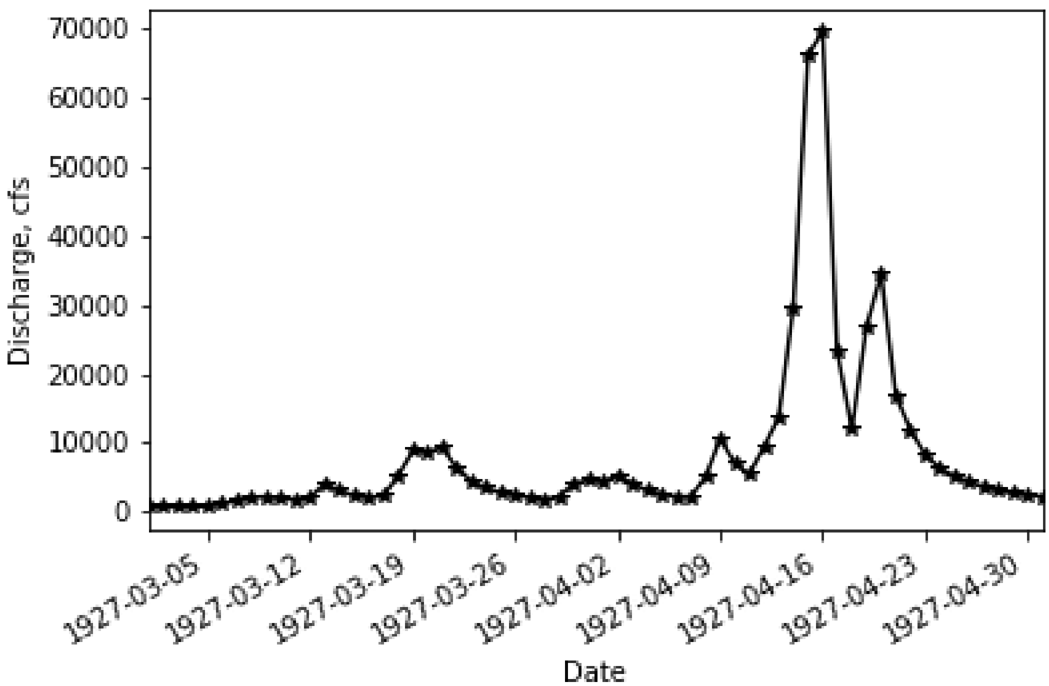

Figure 15: Daily discharge time series for the White River at Beaver, Arkansas, 1927, (source: USGS)

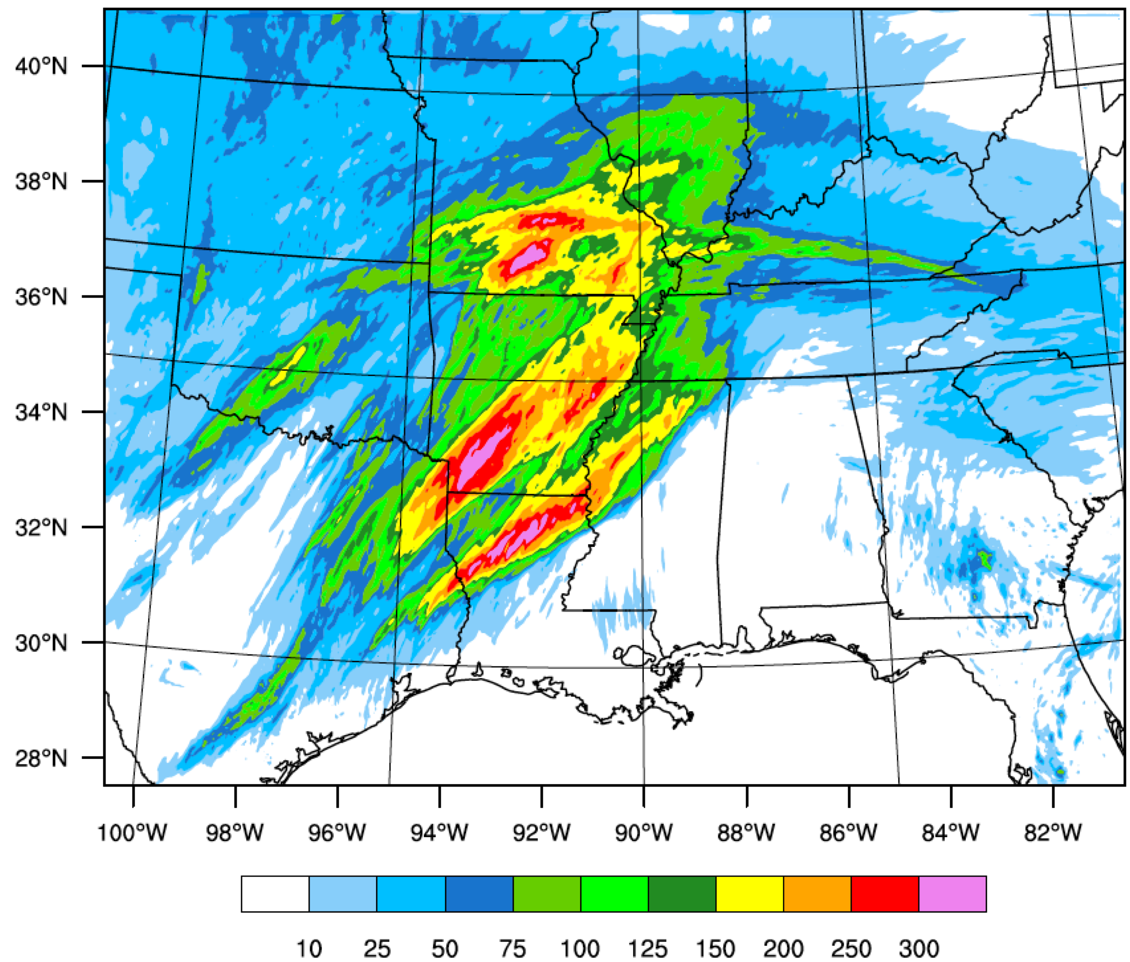

Figure 16: Storm total rainfall (in mm) for the period 12 April 12 UTC - 16 April12 UTC, 1927.

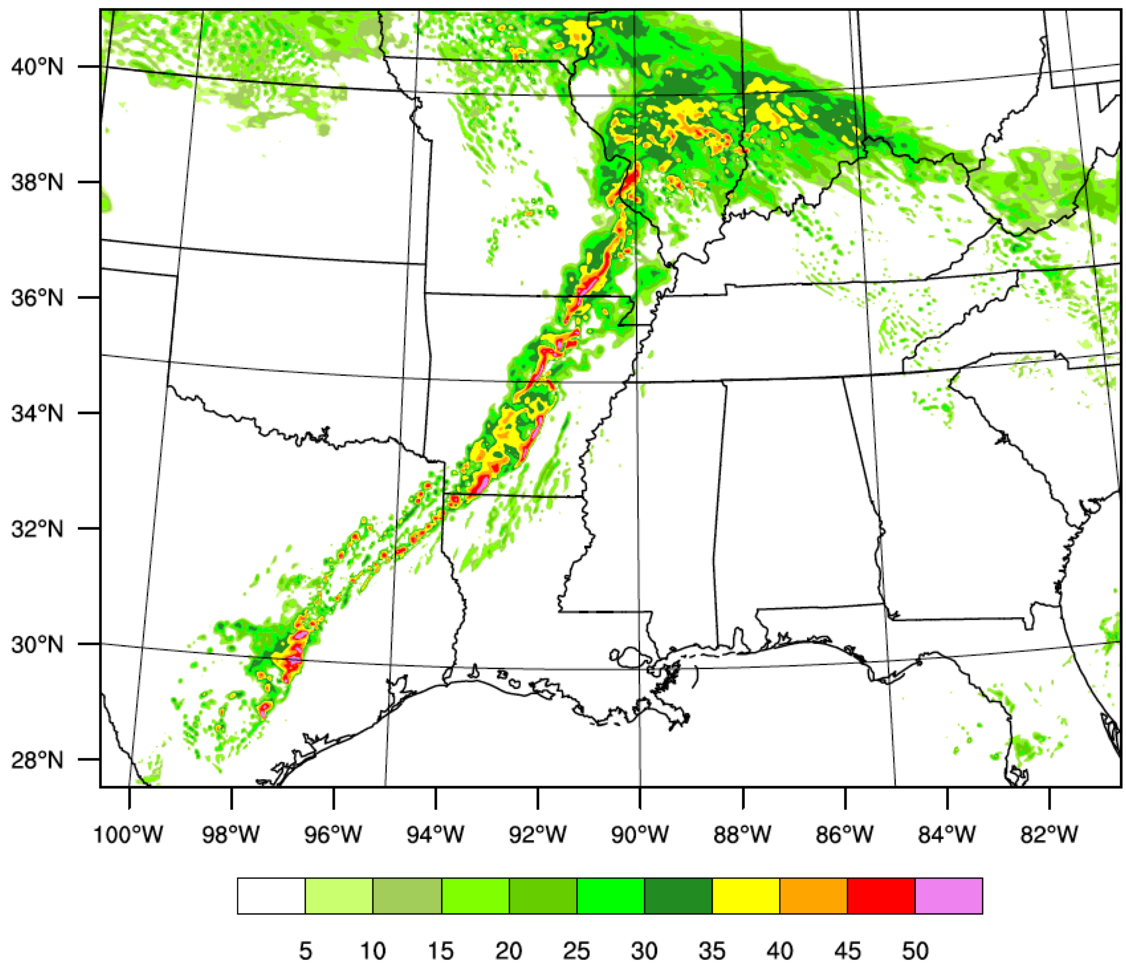

Figure 17: Reflectivity (dBZ) at 850 hPa for 12 UTC on 14 April 1927. Reflectivity values greater than 45 dBZ are associated with heavy, convective rain

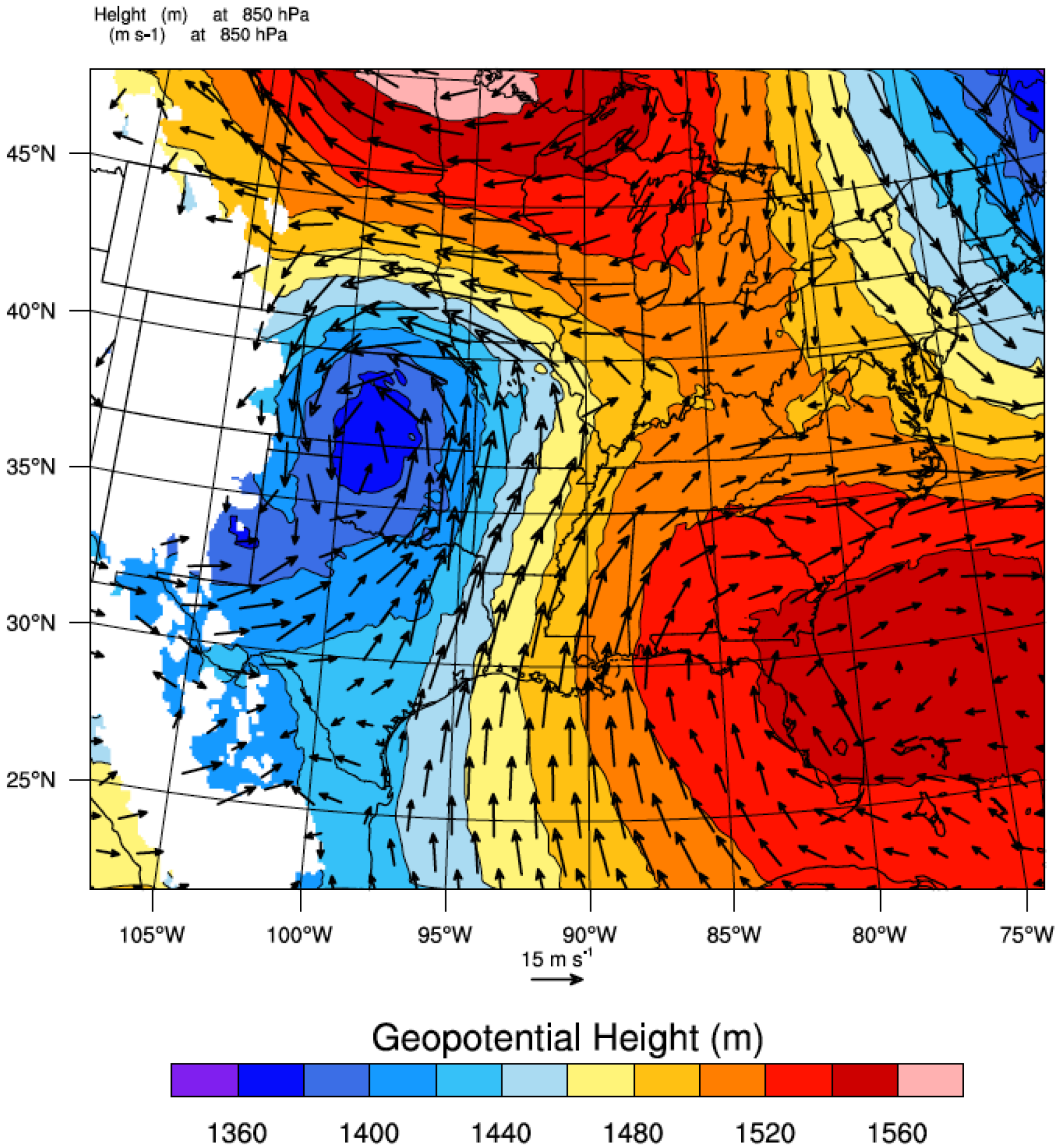

Figure 18: Geopotential height field and wind field at 850 hPa at 0000 UTC on 14 April 1927.

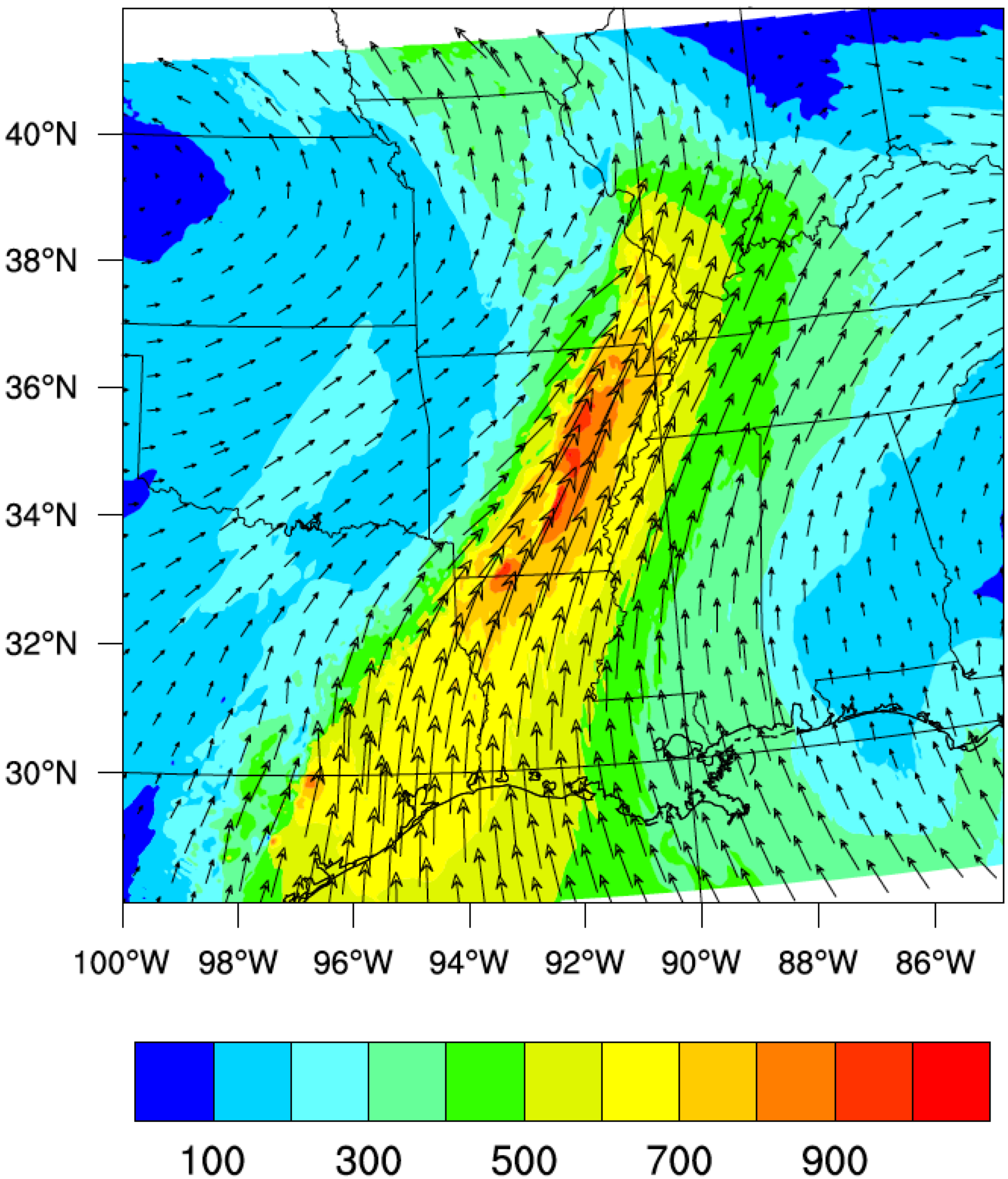

Figure 19: Integrated water vapor flux ($kg\ m^{-1}\ s^{-1}$) at 12 UTC on April 14. Color scale provides magnitude of the integrated water vapor flux vector. Arrows indicate direction and magnitude of flux (color scale can be used to relate length to flux magnitude)

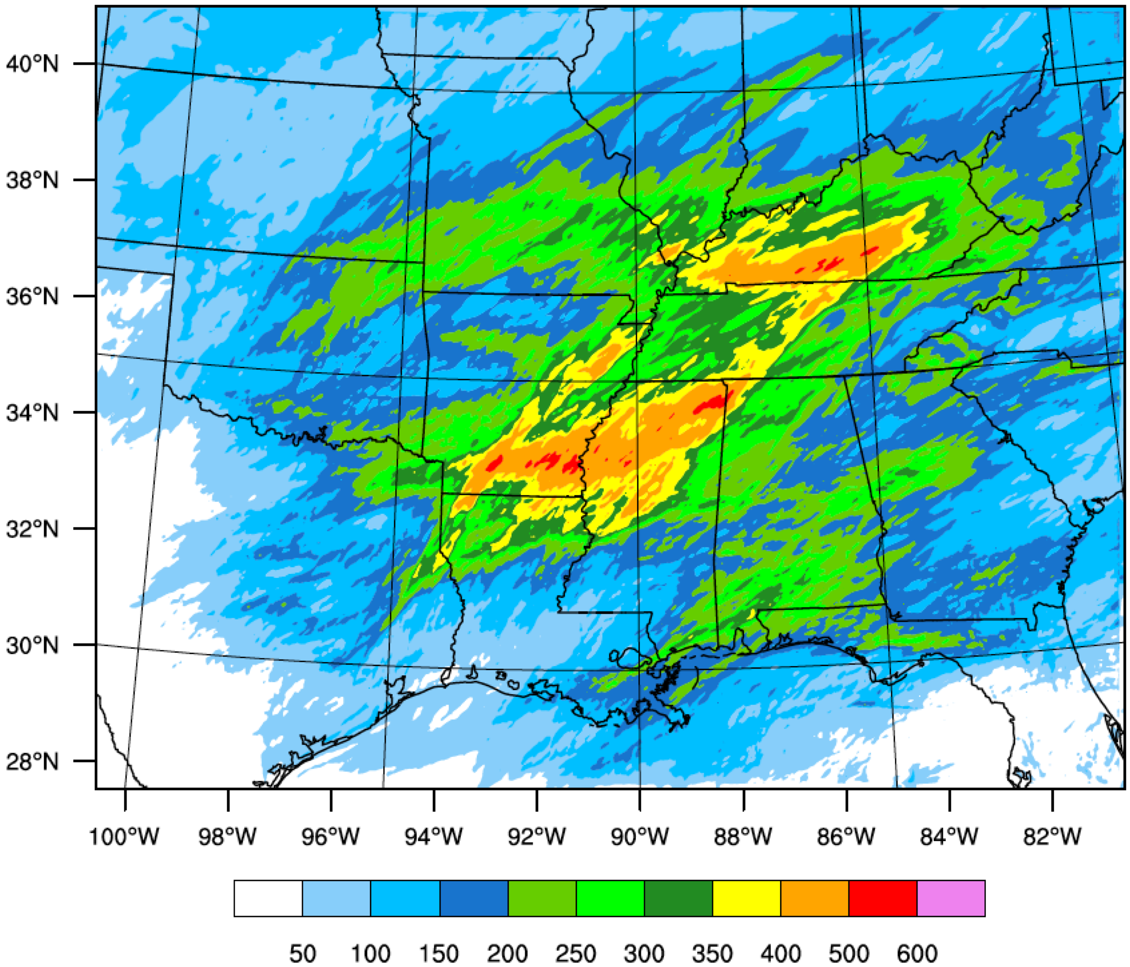

Figure 20: Month rainfall (in mm) for March 1927.

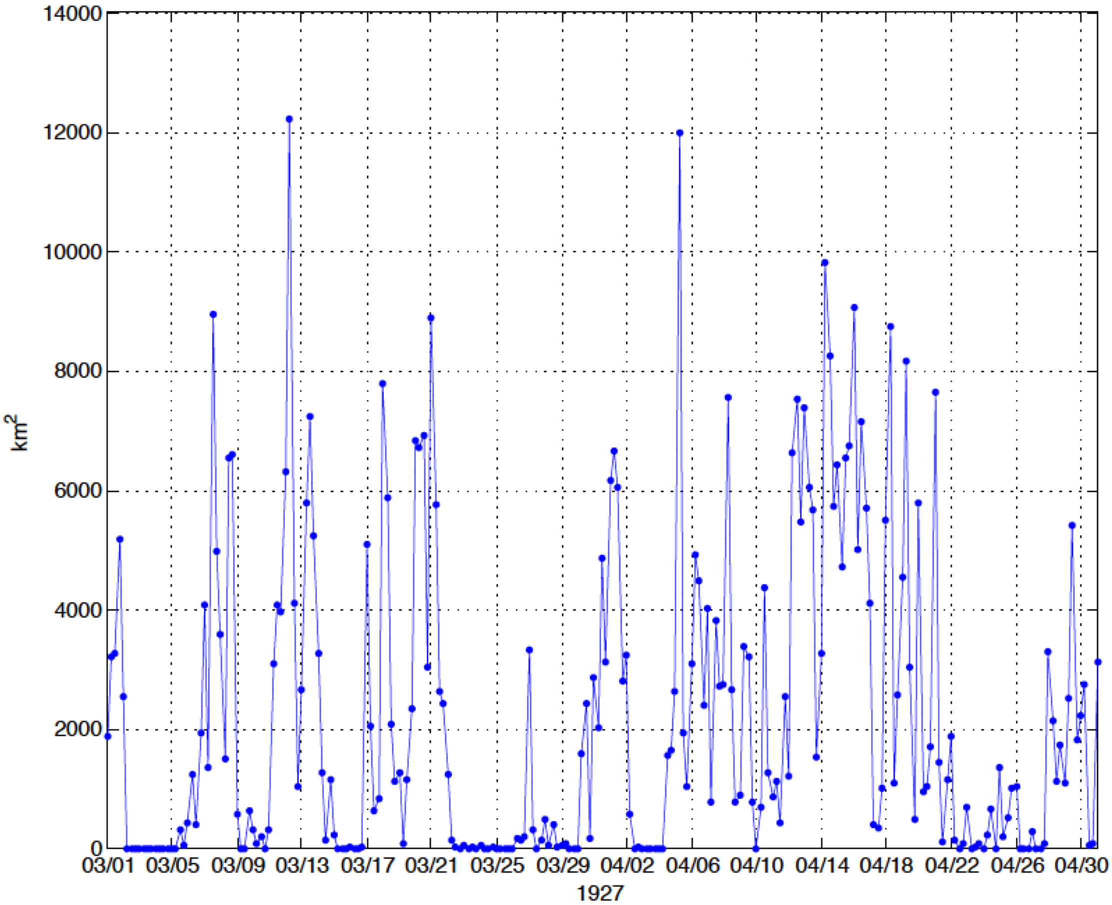

Figure 21: Time series of area for which reflectivity at 850 hPa exceeds 45 dBZ during March and April of 1927.

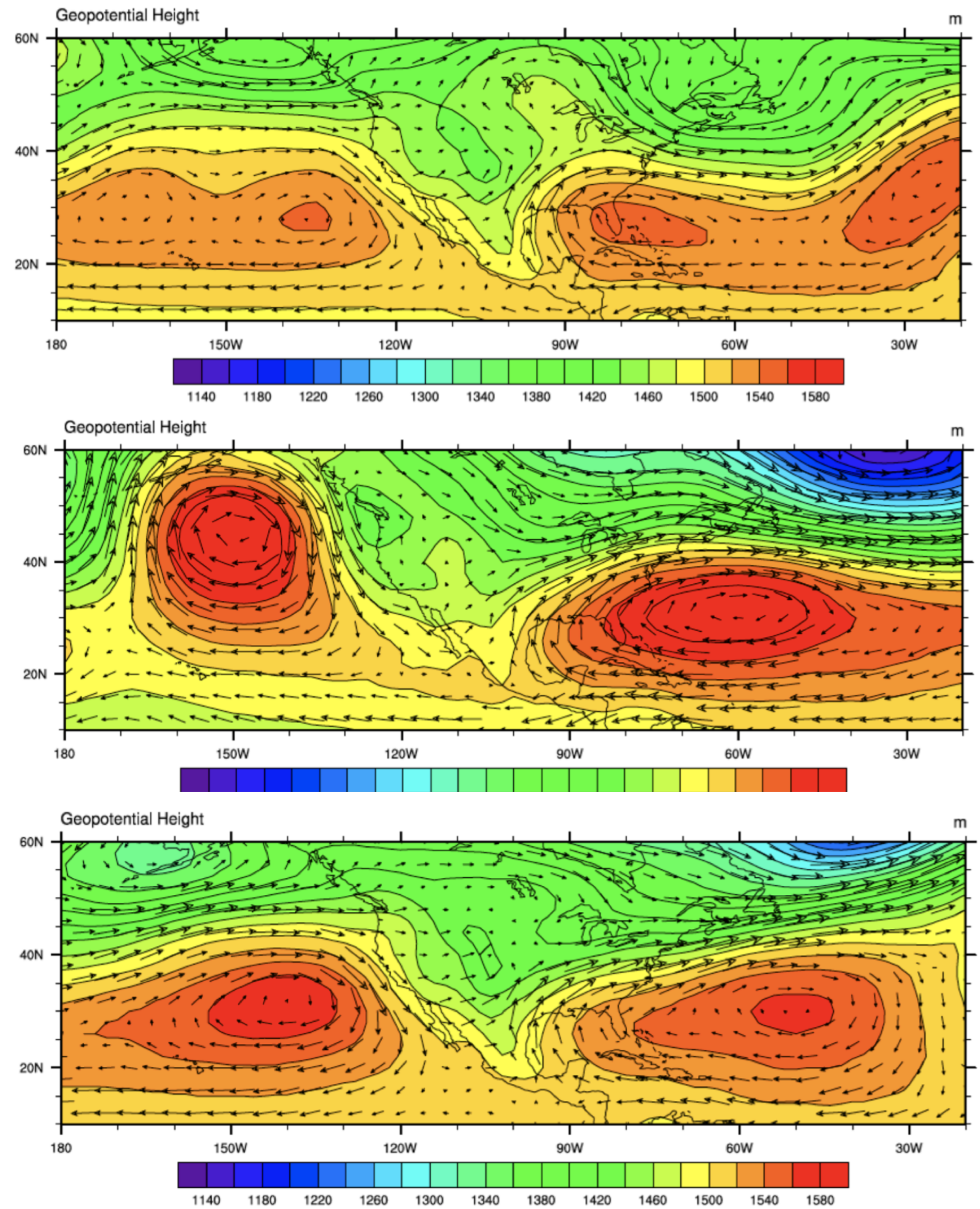

Figure 22: Mean 850 hPa height and wind field for April 1927 (top), January 1937 and April 2011, based on 20th Century Reanalysis fields.

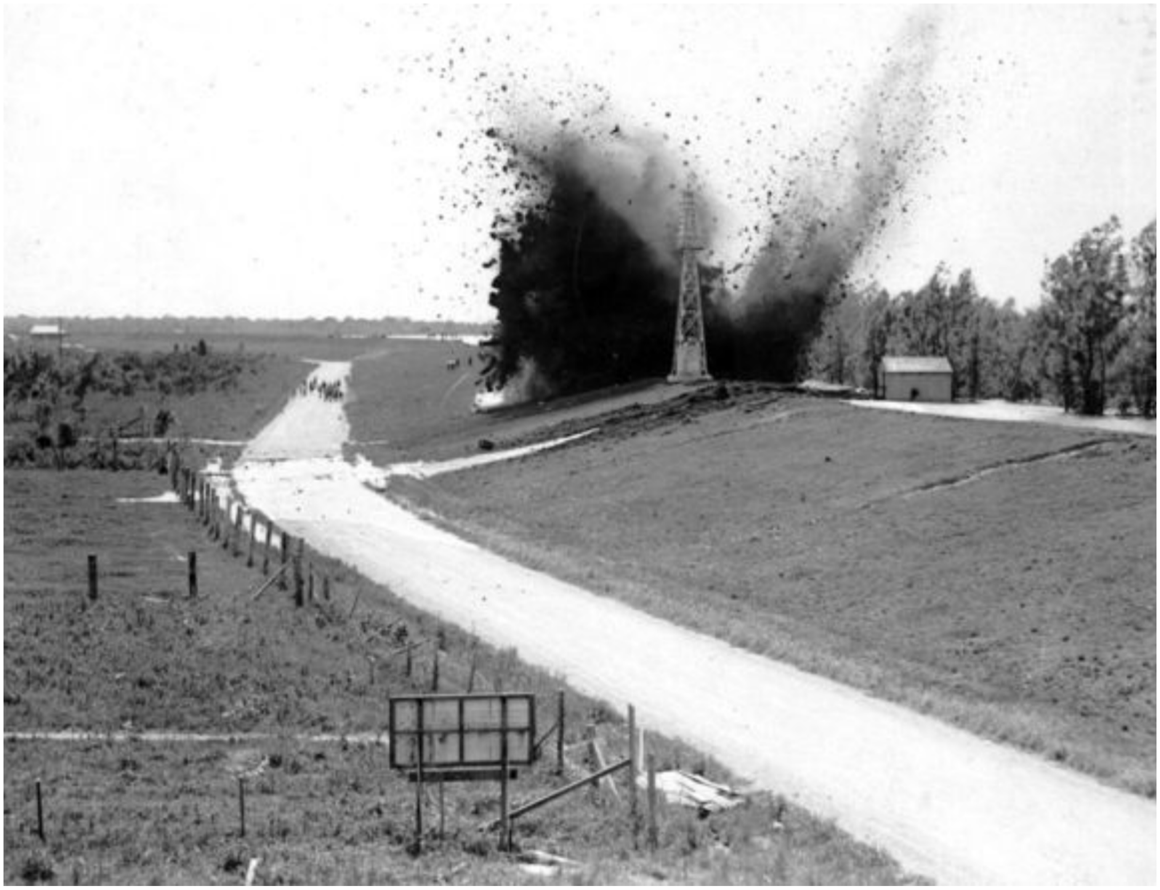

Figure 23: Dynamiting the levee at Caernarvon on 29 April 1927.

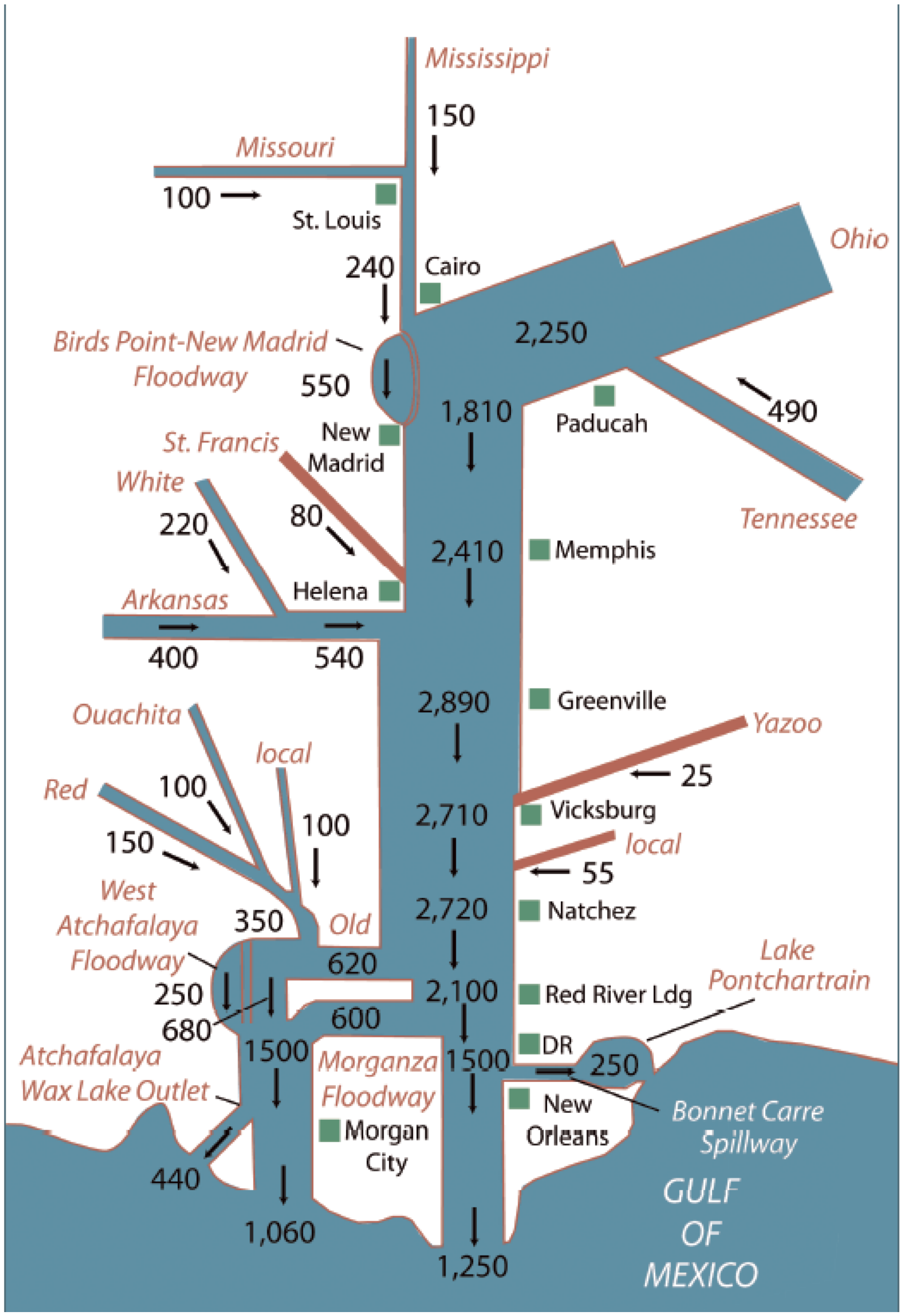

Figure 24: Design flood magnitudes (in 10^3 cfs) and outlets for the Mississippi River and Tributaries flood control project.

Figure 25: Schematic illustration of the Atchafalaya Floodway.

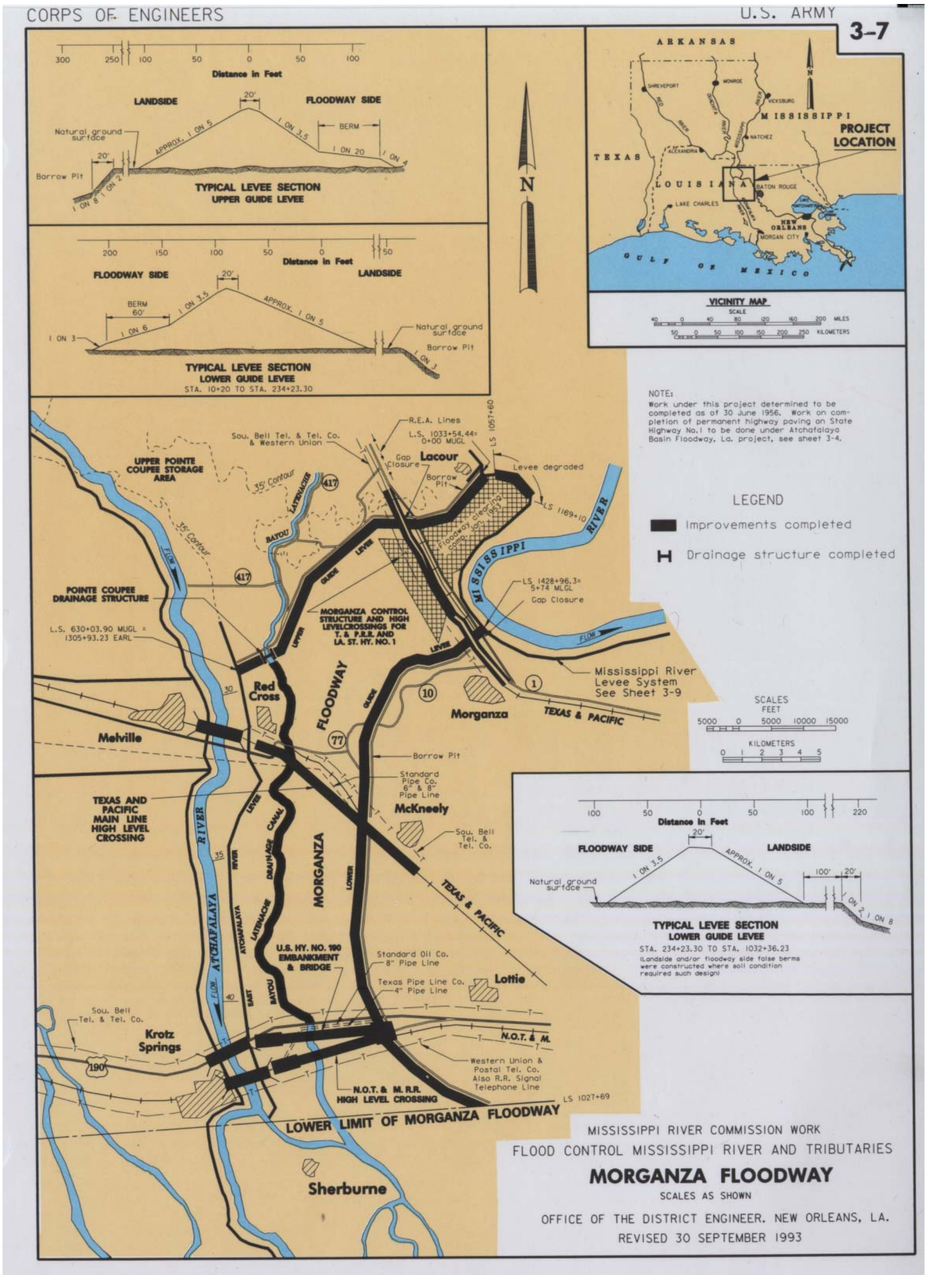

Figure 26: Schematic illustration of the Morganza Floodway. [Use scale greater than 200 for details]

Figure 27: Old River Control structure looking downstream, east-southeast along the Mississippi with the 3 dam structures feeding the Atchafalaya to the west

Figure 28: Old River Auxilary Control structure looking upstream (top; towards the Mississippi River) and downstream (bottom; towards the Atchafalaya River).

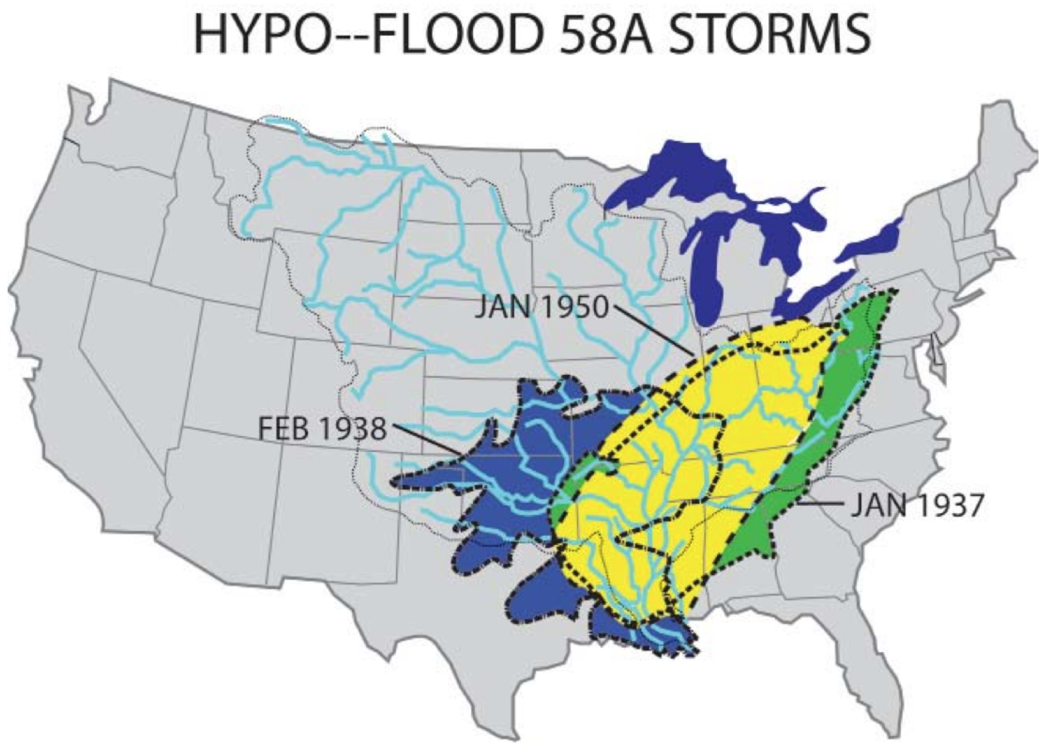

Figure 29: The design storm for the lower Mississippi River, "Hypo-Flood 58a", consisting of a sequence of storms during January 1937, February 1938 and January 1950

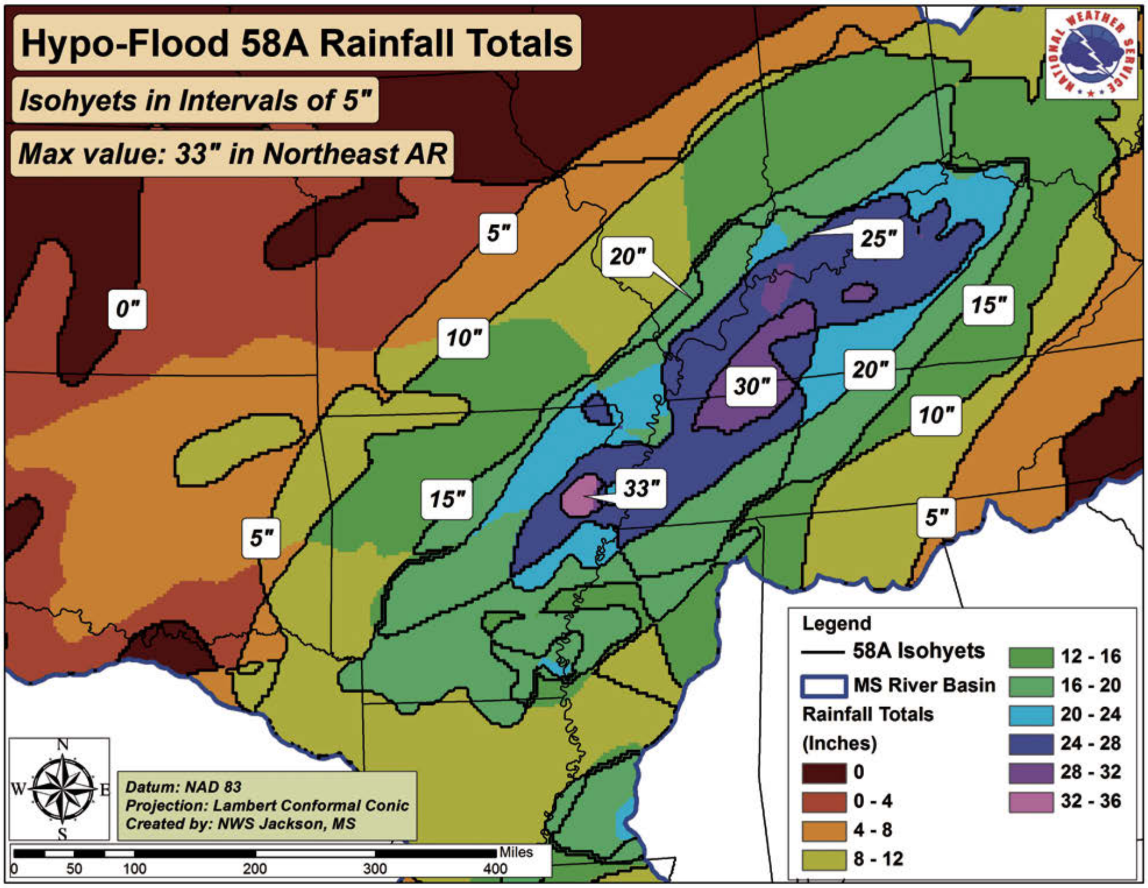

Figure 30: Total rainfall (inches) from Hypo-Flood 58a

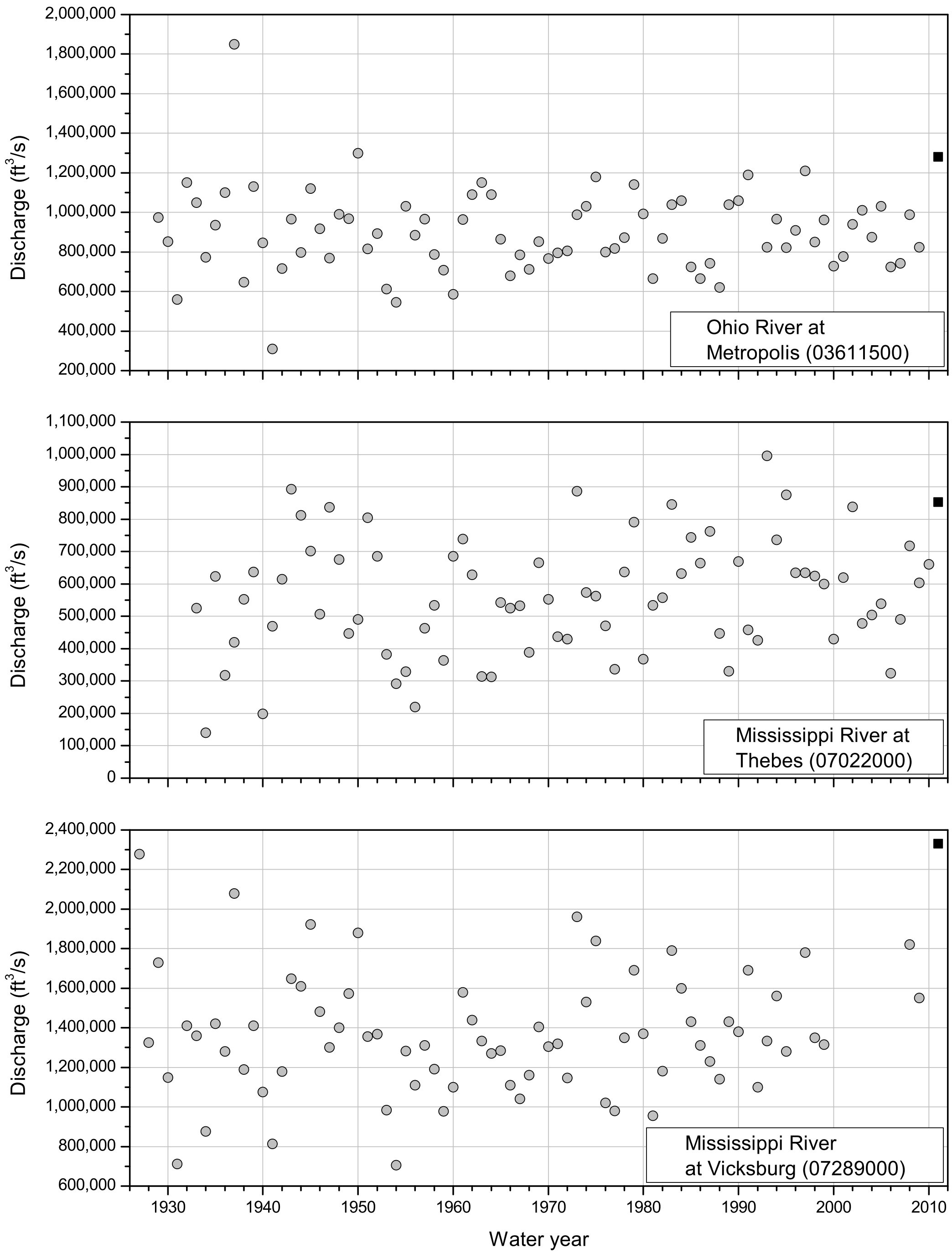

Figure 31: Annual flood peaks for the Mississippi River at Vicksburg (bottom), Mississippi River at Thebes, above the confluence with the Ohio River (middle) and the Ohio river at Metropolis (top).

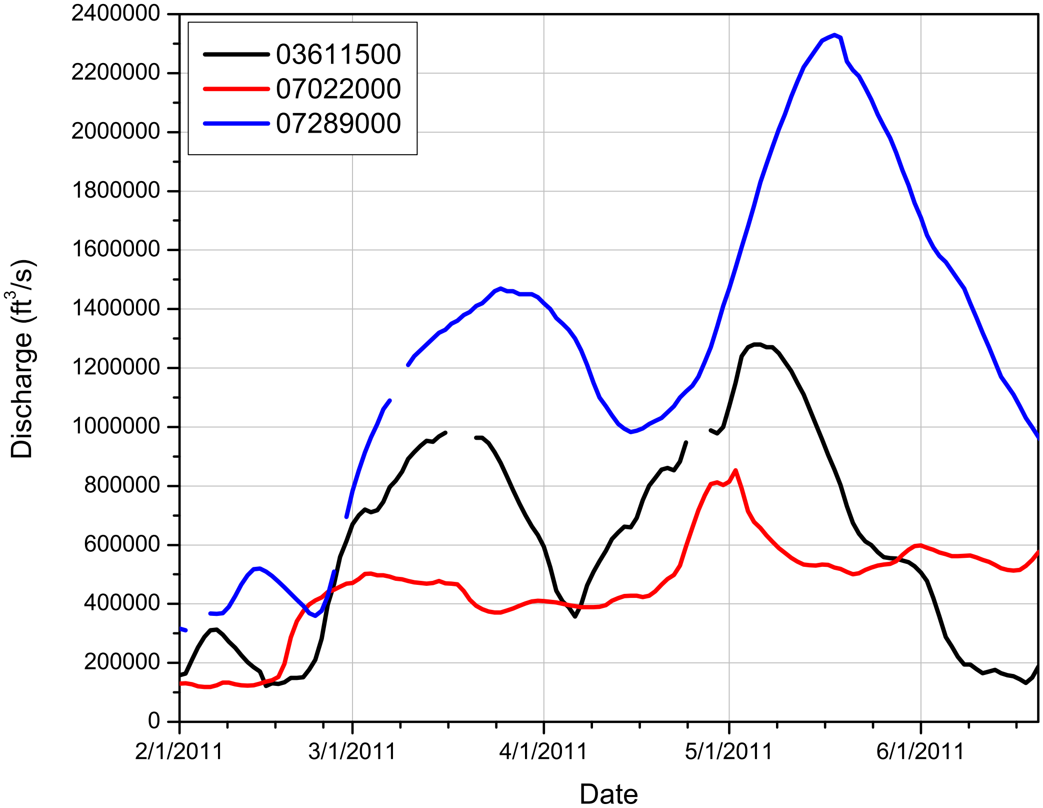

Figure 32: Discharge time series (cfs) for the 2011 Mississippi River flood at Vicksburg (blue), Ohio River at Metropolis (black) and Mississippi River at Thebes (red).

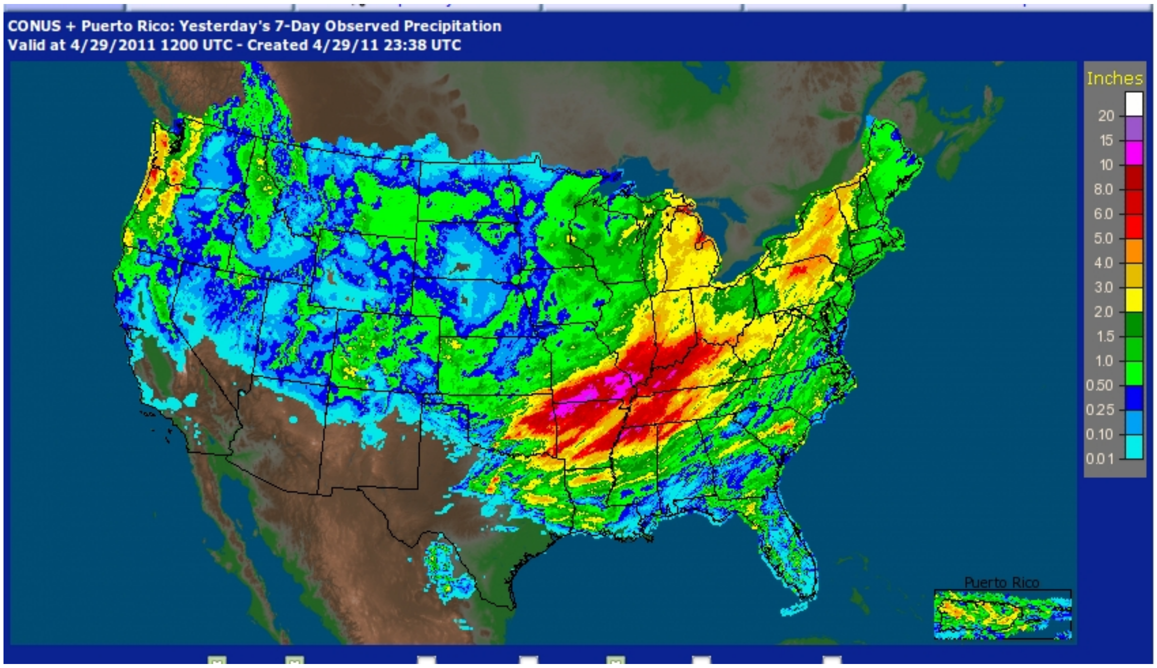

Figure 33: Mississippi River Basin rainfall (inches) for the week ending 29 April 2011 flood.

Figure 34: Massive sand boil along the levee in Cairo, Illinois in late April 2011. Sandbags are in place to raise the water surface elevation above the boil to equal the water surface elevation on the other side of the levee.

Figure 35: Opening of Morganza floodway on 15 May 2011. The view is looking southeast along the floodway. The main channel of the Mississippi is seen at the top of the image

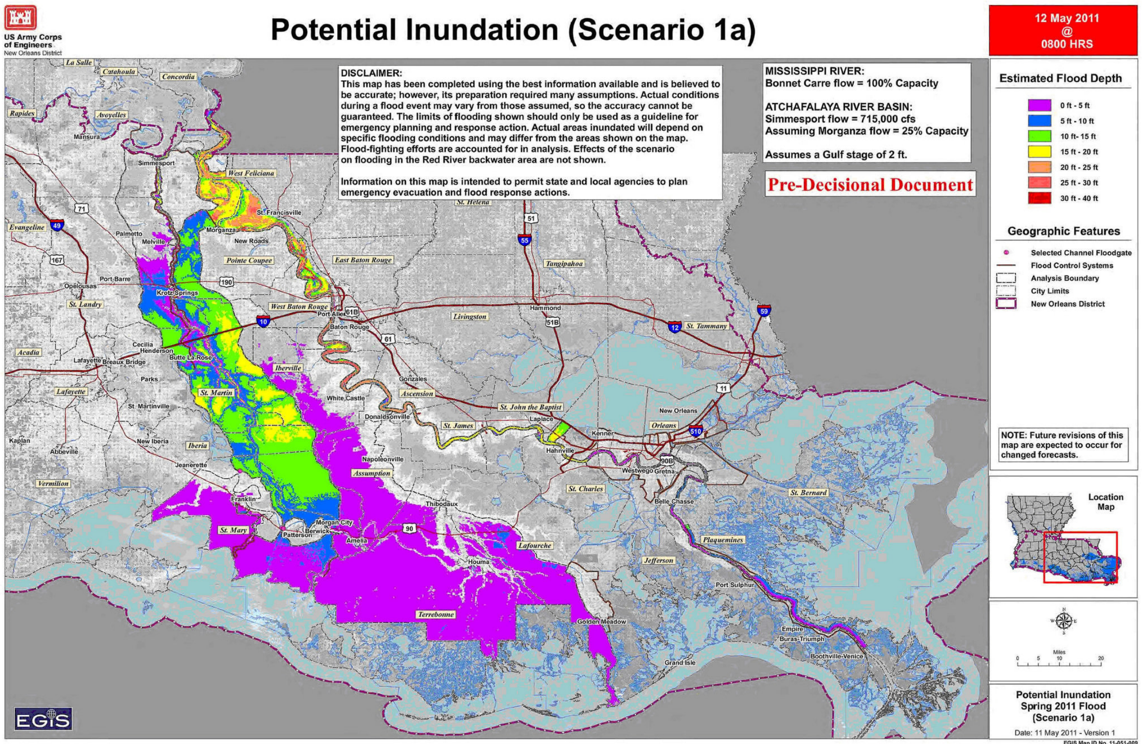

Figure 36: Army Corps of Engineers, New Orleans District Inundation forecast for the Morganza floodway on 12 May 2011.