BED DEGRADATION OF THE LOWER MISSOURI RIVER

A THESIS IN
Civil Engineering

Presented to the Faculty of the University
of Missouri-Kansas City in partial fulfillment of
the requirements for the degree

MASTER OF SCIENCE

by
JACOB ALAN MORGAN

B.S., Tennessee Technological University, 2011

Kansas City, Missouri
2013

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Jacob Alan Morgan, Candidate for the Master of Science Degree

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ABSTRACT

The phenomenon of bed degradation can be due to a multiplicity of causes, but ultimately reflects a change in either the sediment input or sediment transport capacity of a system. Causes for the accelerated rate of degradation of the lower Missouri River Bed, particularly in Kansas City are explored as well as potential countermeasures to arrest the incision. Main-stem rivers and their tributaries constitute a complex, interrelated system and consequently the Platte and Kansas Rivers are briefly discussed as well.

Although the lower Missouri River Valley has been inhabited for over two hundred years, significant changes on the scale required to disrupt sediment transport patterns has only occurred within the last century or so. Major channelization efforts orchestrated by the federal government began around the turn of the nineteenth century. These operations coupled with a series of main-stem dams built between the 1930s and 1960s served to provide a navigation channel for commercial barge traffic as well as provide flood protection.

It appears that clear water releases from upstream reservoirs and effects of the Platte River contribute little to nothing as far as degradation processes at Kansas City are

concerned. Channelization works probably play a minor role, as well as land-use changes, such as deforestation and urbanization. Significant causes to the recent increase in degradation rate are major flood events and commercial dredging. The river often degrades several feet during a single flood event and although some recovery occurs, the river's bed never reaches its previous elevation. Commercial dredging has significantly increased in the Missouri River in the same time frame that degradation has accelerated, occurring in the same areas as well.

A few European rivers that also experience bed degradation were evaluated along with countermeasures applied to them. Unfortunately, the use of the European rivers lent itself to methods to arrest degradation that are unreasonable for use on the Missouri River. In light of the probable causes for degradation, the most effective countermeasure is likely a change in dredging regulations. Further study is required, though, to more satisfactorily determine the cause(s) of degradation as well as possible countermeasures.

APPROVAL PAGE

The faculty listed below, appointed by the Dean of the School of Computing and Engineering and the Dean of the College of Arts and Sciences, have examined a thesis titled "Bed Degradation of the Lower Missouri River," presented by Jacob A. Morgan, candidate for the Master of Science degree, and certify that in their opinion it is worthy of acceptance.

Supervisory Committee

Jerry R. Richardson, Ph.D., Committee Chair

Civil and Mechanical Engineering (CME) Department

ZhiQiang Chen, Ph.D.

Civil and Mechanical Engineering (CME) Department

Jejung Lee, Ph.D.

Department of Geosciences

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ACKNOWLEDGEMENTS

Foremost appreciation is extended toward Dr. Jerry R. Richardson for his guidance and direction throughout the duration of the thesis process.

Gratitude is also given to Dr. John Shelley, of the Army Corps of Engineers, for his additional assistance in regards to Corps of Engineer work related to degradation.

The Olathe Geotechnical Engineering Team with Olsson Associates is to be thanked for the provision of employment in spite of the time commitment required by thesis research. Their understanding and support has not gone unnoticed or unappreciated.

Numerous other acknowledgements could additionally be made, but it will suffice to mention my family, especially my wife, who patiently endured many early mornings coupled with late nights as I researched and wrote at home before and after work.

Most of all, thanks be to God for His limitless grace displayed toward me in my opportunities both in employment and academia.

CHAPTER 1

INTRODUCTION

> The river is like an organism; it is internally self-adjusting. It is also resilient and can absorb changes imposed upon it, but not without limit. The limit beyond which a river cannot adjust is well illustrated by some of the effects of our national program of channelization, in which we have already dredged, straightened, channelled, revetted, trained, and "improved" more than 16,500 miles of river channels in the United States, quite apart from the thousands of reservoirs already built.
>
> - Luna Leopold, "A Reverence for Rivers" (1977)

Dynamic Stability and Degradation

Dynamic equilibrium, as used in fluvial geomorphology, and sedimentology in particular, is the term used to describe the state of a system in which the amount of sediment entering is equal to the amount of sediment leaving. Although the incoming and outgoing sediment amounts may change, the amount of material in the system itself remains constant, thus the system is at equilibrium. Dynamic equilibrium is a form of stability, although, as Schumm (1985) points out, "Because alluvial channels are composed of sediment transported by the stream, the bed and banks are erodible; therefore, no alluvial channel is actually stable in the sense that no change occurs."

Thorne, Allen, and Simon (1996) state that unstable channels "are likely to show evidence of serious, sustained aggradation, degradation, width adjustment or planform change." If the net sediment in the system is increasing, the reach experiences aggradation. The additional sediments entering the system are deposited in the reach. If the net sediment in the system is decreasing, the reach experiences degradation. Sediments are taken up by the flowing water and carried out of the reach, deepening the channel bed. Or, as Simon and Rinaldi (2006) write, degradation "is a common response of alluvial channels that have been disturbed such that they contain excess amounts of flow energy or stream power relative to the sediment load."

Degradation, then, is essentially a disagreement between the sediment that a stream actually carries and its sediment transport capacity, or the potential sediment the river is able to carry given a certain slope and velocity. Hales, Shindala, and Denson (1970) write that:

> The amount of sediment which a particular stream is capable of carrying depends upon a number of variables: The quantity of water being discharged, the slope of the stream, the cross-sectional area of the channel, the cohesiveness of the stream bed, and the particle size which composes the bed material.

Bed degradation has become somewhat of an epidemic among rivers throughout the world, especially in the United States where very few rivers are untouched by development. Simon and Rinaldi (2006) cite several examples in the United States where degradation rates have been quit excessive. From the early 1970s to 1987, the Obion-Forked Deer Basin in West Tennessee experienced erosion at rates of 1.7 million tonnes per year which are "1-2 orders of magnitude greater than those reported… for stable systems in the region."

While degradation is a natural phenomenon and is a part of the morphological evolution of the fluvial system, the impacts of humans has the effect to, as Simon and Rinaldi (2006) say, "Greatly compress time scales." Anthropogenic causes for incision have similar effects to large scale, or catastrophic, natural events. Simon and Rinaldi

(2006) write, “Because an incised channel can contain larger peak flows and often cannot dissipate flow energy across the former floodplain, these channels are particularly dynamic.” Denudation processes that generally occur over the natural development of a system on a geological time scale of hundreds or even thousands of years are reduced to very short period of time, often within a single generation.

Sayre and Kennedy (1978) write, “Benefits resulting from river modification and management programs undertaken on behalf of a given set of objectives, usually exact a price in the form of adverse impacts on other purposes served by the river.” Likewise, Winkley (1994) states:

> All alluvial rivers must be allowed to develop a plan and profile geometry that will balance their energies, accommodate all magnitudes of flow with least amount of maintenance, and adequately manage sediment activity… Bank stabilization, flood control, and navigation and irrigation construction projects have been built on many rivers without adequate consideration of the geologic history of the drainage basin and its effect on channel characteristics.

Such is the case with the Missouri River, as will be demonstrated.

The purpose of this document is threefold in nature: (1) to examine the possible causes for bed instability on the Missouri River, (2) to review possible mitigation techniques to curb degradation effects, and (3) to provide recommendations concerning the direction of additional actions.

The Missouri River

With a catchment area over 529,000 mi^2, roughly one-sixth of the continental United States, the Missouri River is the largest tributary to the Mississippi River system. Previous to the middle of the twentieth century the Missouri flowed rather freely, drifting back and forth within the floodplain, shallow and even braided in some reaches. The

Missouri flows over 2,400 miles from its headwaters at Three Forks, Montana to its confluence with the Mississippi near St. Louis, Missouri. The Missouri River provides hydroelectricity, recreation, drinking water, and navigation.

Colloquially, it has become known by names such as, the Big Muddy, the Mighty Mo, the Wide Missouri, and Old Misery. Schneiders (1999) explains these designations as describing different qualities of the river such as its high suspended sediment content, immense power, expansive width, and the suffering it has caused.

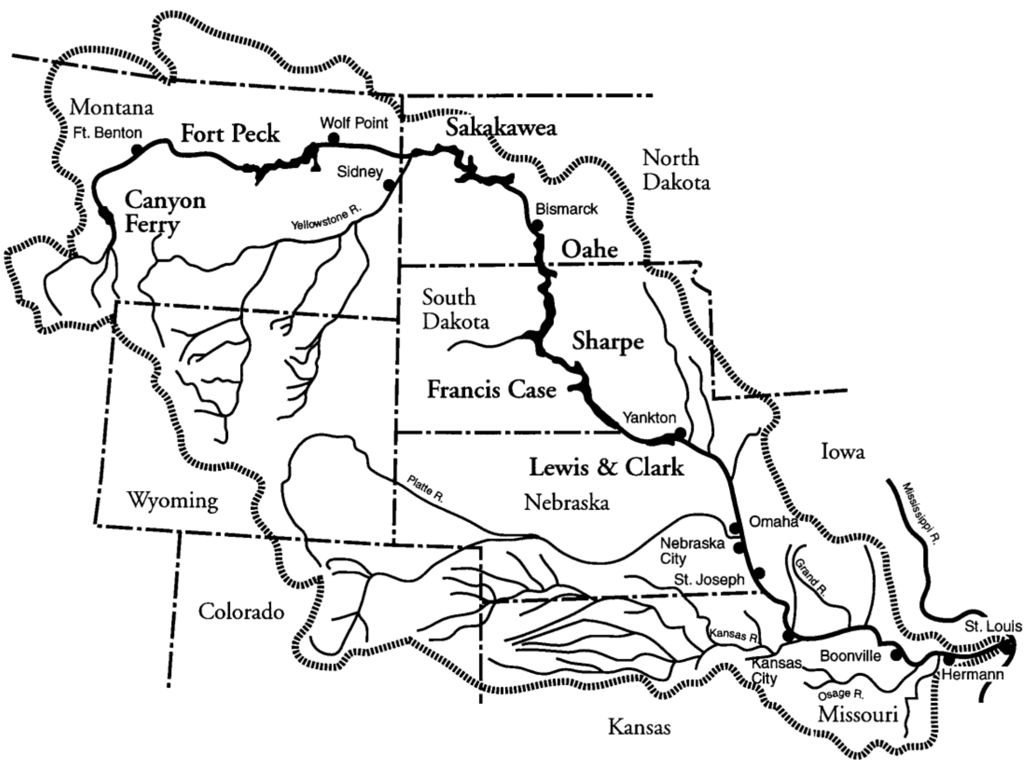


Figure 1 - Missouri River Catchment Area (Galat and Lipkin 1999)

Significant development of Missouri River through human intervention in the channel has been a relatively recent occurrence. While some Native American populations did redirect a portion of the flow for agricultural purposes, these small irrigation diversions had no significant effect on the morphology of the channel.

Following settlement, especially in the lower Missouri River valley, the river became the subject of many endeavors to "improve" the channel for navigation and flood control.

The Missouri River is a well-documented stream system. Histories recording significant events in the development of the Missouri are contained in both detailed and general works such as Terral's *The Missouri Valley: Land of Drouth, Flood, and Promise* (1947), Hart's *The Dark Missouri* (1957), Richardson and Christian's *Channel Improvements on the Missouri River* (1976), Lawson's *Dammed Indians: The Pick-Sloan Plan and the Missouri River Sioux, 1944-1980* (1994), Vestal's *The Missouri* (1996), Schneiders' *Unruly River: Two Centuries of Change Along the Missouri* (1999), Billington, Jackson, and Melosi's *The History of Large Federal Dams: Planning, Design, and Construction in the Era of Big Dams* (2005), and many Corps of Engineers publications including *The Development and Control of the Missouri River* (1947), *The Federal Engineer, Damsites to Missile Sites: A History of the Omaha District, US Army Corps of Engineers* (1985), Branyan's *Taming the Mighty Missouri: A History of the Kansas City District Corps of Engineers 1907-1971* (1974), Ferrell's *Heartland Engineers: A History* (1992), *Big Dam Era – A Legislative and Institutional History of the Pick-Sloan Missouri River Basin Program* (1993) and *Soundings – 100 Years of the Missouri River Navigation Project* (1995), and numerous others as well.

Predevelopment

In the early nineteenth century, some time prior to human intervention, the length of the Missouri River was 150 to 200 miles longer than it currently is. Freely eroding its banks, the channel constantly shifted between either side of the valley walls. The lower Missouri River flowed with great sinuousity as the valley widens dramatically past

Yankton, South Dakota. The Valley reaches its widest point in northern Monona County, Iowa with a width of 18 miles. Schneiders (1999) reports the documentation of an especially sinuous reach from Yankton, South Dakota to the Platte River. The Lewis and Clark expedition measured one bend over 18 miles long with only 974 yards across the neck.

The sinuous pattern of the channel was encouraged not only by the breadth of space allowed by its valley walls but also by climatic forces. With variations in precipitation levels and other climatic factors the river adjusts and shifts accordingly. The Missouri River basin suffered from drought conditions in the first part of the nineteenth century. The low precipitation resulted in low flow levels. Without the volume or force of flow necessary to travel directly, the channel moved from side to side, creating bends and meanders. Beginning in the mid-1800s, with increased precipitation, the river again adjusted according to its new conditions. In order to balance the increased volume and subsequent velocity, the river straightened, widened, and cut off bends. During the next several decades, Schneiders (1999) writes, "the river naturally changed from a meandering stream to a semibraided stream."

A major flood in 1844, "the greatest European-American-recorded flood to that time," contributed as it flowed through the system cutting off a number of bends. Heavy winter precipitation in the form of snow occurred in the 1856-1857 winter season, and upon melting, continued the river's straightening trend. This process was furthered by significant floods in 1881, 1903, 1908, and 1915. Schneiders (1999) notes that, "the river was first shortened by changes in the climatic cycle and only later through human action."

Historically, the Missouri River underwent biannual significant rising of the water level. The annual spring rise occurred in April, with the summer rise in June. The spring rise was a result of ice breakup in the river, melting snow from the plains, and thunderstorms. It was generally quick and violent. Confined to relatively small areas, it generally lasted a couple weeks or less. The summer rise originated from an influx of flow from melting snow in the mountains as well as extended precipitation in the catchment area. It generally affected a larger area and was more prolonged in duration. While the magnitude and time extent of these rises depended largely on the runoff amounts, these rises occurred with relative annual predictability. The figure below show s a natural hydrograph of the Missouri River displaying the spring and summer rises.

The variability in flow morphology made the undeveloped Missouri River conducive to just as diverse wildlife. With spring and summer rises constantly shifting the position of the river, habitats were simultaneously destroyed and created. As Schneiders points out:

> As the sandbars that served as nesting sites for shorebirds disappeared beneath the rising river, fish habitat increased proportionally; or when the river quit inundating a sand flat, willows and cottonwoods took root and provided cover for birds and mammals.

This dynamic equilibrium forced wildlife to migrate, finding joining additional habitats. When floods felled forest cover, for example, the animals dependent on that shelter were forced to find new shelter. This new habitat, likely already having its own inhabitants, increased in competition, causing its the growth and strengthening.

The Missouri was historically home to a wide assortment aquatic life. Rich communities of blue, channel, and flathead catfish, paddlefish, largemouth, smallmouth, and white bass, black and white crappie, blue sucker, goldeye, walleye, northern pike, shovelnose and pallid sturgeon, bigmouth and smallmouth buffalo, white sucker, and carp existed throughout the river's main channel and connected side channels and oxbow lakes. These organisms fed on the likes of plankton, insects, larvae, crustaceans, and reptiles also abundant in the ecosystem.

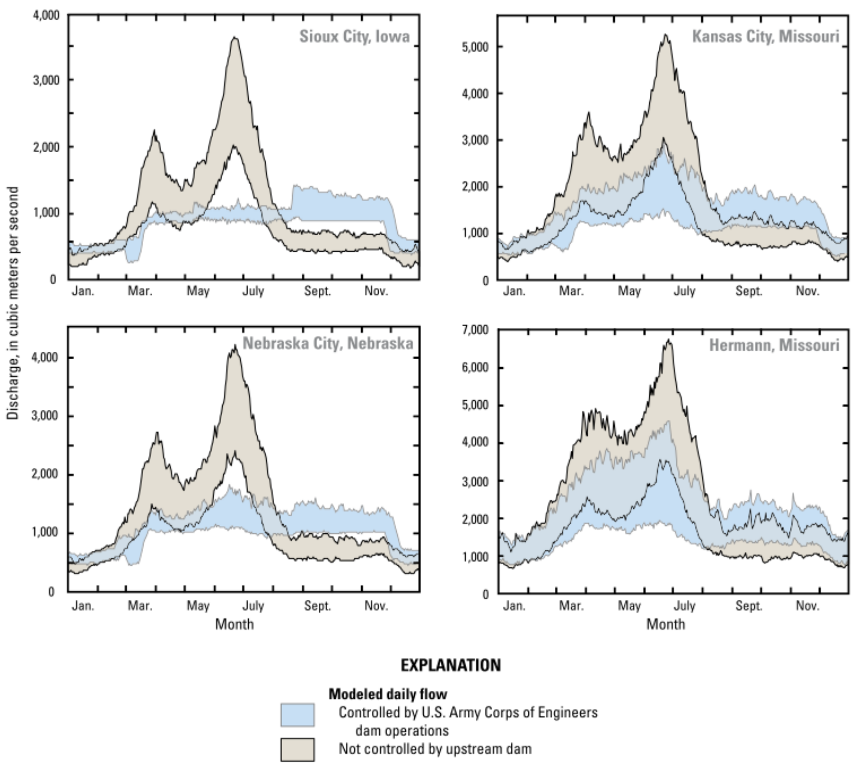


Figure 2 - Modeled Daily Flow with and without Flow Control through Dam Operation (Alexander, Wilson and Green 2012). Note the spring and summer rises in the uncontrolled flow.

Terrestrial organisms thrived as well, on the Missouri's sand and gravel bars, islands, and sand flats and dunes. Reptiles and amphibians like turtles, frogs, and snakes made use of the shallow water and bars to maintain body temperatures. Bars furthermore provided nesting and feeding grounds for Canada, lesser snow, and blue geese, ducks, piping plovers, and least terns, as they fed on the insects, snails, seeds, and berries also found there. Groves of trees such as willows, cottonwoods, elm, ash, and bur oaks, provided homes for wood ducks, woodpeckers, and eagles, as well as cover for coyotes, red foxes, gray and fox squirrels, cottontail rabbits, raccoons, opossums, beavers, weasels, muskrats, skunks, badgers, bobcats, and mink.

Early Settlement along the Missouri

With all the necessary conditions to facilitate the frontier life, during the nineteenth century the Missouri Valley became inhabited by the American military, fur traders, and farmers. The valley provided fertile soil on flat lands for agriculture, numerous wild game animals, accessible water for drinking and transportation, and abundant timber for materials. Due to the plentiful resources and economic potential the valley was populated with a heavy reliance on the river. The Missouri was especially important for transportation purposes as Schneiders (1999) notes, commenting that the pioneers needed it "to maintain a communications link with the outside world, supply them with manufactured goods, and carry their agricultural commodities downstream." This dependence led to the earliest forms of human intervention in the river system through a snag removal program. Westward expansion proceeded though, and brought with it the railroad. By the latter part of the nineteenth century the railroad had a monopolistic grasp on transportation and valley inhabitants looked again to the river for commerce. Schneiders (1999) comments on the renewed interest in transportation on the river stating, "But instead of advocating snag removal and the reestablishment of steamboat traffic, the public wanted nothing less than the complete remaking of the stream to facilitate barge traffic."

In 1804, as the Lewis and Clark began their ascension of the Missouri River they documented that the farthest upstream settlement of Europeans was just over 40 miles from confluence with the Mississippi River at the Osage Woman River. Past this settlement there also existed some French trappers as well as a small number of American farmers. Just two years later, in 1806, as the expedition descended the Missouri the explorers reported established farmers ninety miles from the confluence with the Mississippi, at the Gasconade River. By 1816 census the number of whites along the river upstream from mouth was estimated to be 500. This number increased to 17,629 by 1820. By 1830 numerous settlements existed in the valley up to 350 miles upstream from the mouth. These included Osage, Jefferson City, Rocheport, Boonville, Arrow Rock, Glasgow, and Independence (Schneiders, Unruly River: Two Centuries of Change Along the Missouri 1999).

Settlement on the river continued to grow, with an 1850 census estimating 225,000 Americans in or adjacent to the valley in the state of Missouri. By 1855 settlers were inhabiting the valley and creating communities as far as west-central Iowa, with Sioux City being established in 1856. The population followed north-northwest along the river. Schneiders (1999) adds, “Settlement in the Missouri Valley occurred before the occupation of all the lands east of the river. The valley served as both a magnet and conduit for American entrepreneurs and settlers.”

The river valley was rich with resources useful to its inhabitants. The Missouri River provided early settlers with palatable drinking water, despite its silt content. The lowlands in the valley likewise had water readily accessible, as the river’s level kept the water table relatively close to the ground surface so water wells did not require deep digging. The valley additionally provided its occupants with an abundance of timber to be used for fuel in steamboat engines as well as building materials. Generally the establishment of a new river town began with the construction of a saw mill. Valley inhabitants were amply supplied numerous types of lumber including maple, walnut, oak, and especially cottonwood, due to its abundance.

Due to its diversity of wildlife the region supplied a number of different organisms, both in the form of wild game animals and vegetation, for human consumption. The valley habitat fostered deer, elk, and buffalo as well as turkey, prairie chickens, and different types of water fowl to be procured for meat. The Missouri and its tributaries also teemed with a variety of fish that provided food for the valley inhabitants. The diverse vegetation in the valley gave settlers consumable plants such as wild grapes, buffaloberries, strawberries, currants, gooseberries, and plums as well as mouse beans, wild peas, and assorted tubers. In addition, saw grass near the river provided nutrition to cattle and other livestock raised by valley farmers. Furthermore, the flat alluvial plain between the valley walls offered farming settlers with nutritious soil, nourished during the river's annual floods. The river valley was also an easier land to cultivate than the nearby hilly lands (Schneiders, Unruly River: Two Centuries of Change Along the Missouri 1999).

Early Transportation on the Missouri

The first major mode of transportation on the Missouri was the keelboat. The figure below shows what a typical keelboat on the Missouri would have looked like. In the early 1800s these boat were primarily made in either Pittsburg, Pennsylvania or Louisville, Kentucky and were designed specifically for navigation on the Missouri.

Keelboats had four main modes of locomotion. These were movement under sail and by cordelling, oaring, or poling. Due to winding nature of the river the employment of sails was not often useful, although under favorable conditions a keelboat could travel upstream 20-25 miles per day. The other three methods of movement required laborious manpower. In 1804 the Lewis and Clark expedition averaged about nine and a half miles per day upstream with a keelboat. Seven years later Henry Brackenridge and John Bradbury made the same course with the former averaging 18 miles per day and the latter 14. Travelling downstream, on the other hand, a boat could easily make 60 to 100 miles in a day. Although burdensome, keelboats were a more desirable mode than or bulk transportation than overland wagons, as Schneiders (1999) observes: "A wagon pulled by a team of oxen or horses over poor, or nonexistent, roads carried less freight, traveled slower, and cost more."

Figure 3 - A Missouri River Keelboat (Chittenden 1903)

In the 1820s, steamboat navigation was increasingly common on the lower river, between St. Louis and Kansas City. Because steamboats were built and intended for rivers with a deeper channel, their use had been confined to the lower Missouri, especially during the spring and summer rises. By the early 1830s steamboat navigation of the upper river began with the *Yellowstone* by the American Fur Company. Schneiders (1999) documents the escalating use of the steamboat on the Missouri, stating that it reached its height in the 1850s. He continues:

> Only one steamer piled the Missouri River above the mouth of the Platte in 1832; by 1857 the port of Sioux City had twenty-eight steamboat arrivals. In 1858 fifty-nine steamboats operated on the river below the Platte, and twenty-three boats serviced the river north of Sioux City. In that same year, the port of Leavenworth logged 306 steamboat arrivals during the eight-month-long navigation season, and in 1859 Omaha recorded 174 arrivals. The statistics reveal that the bulk of the steamboat traffic moved on the Missouri River from Omaha to the south.

As steamboats continued to coarse upstream the river, the technology advanced as well and more money was invested in boats that were designed and built specifically for navigation on the Missouri. Perhaps, the greatest example of which was the *Chippewa* of Pierre Chouteau Jr. and Company. Schneiders (1999) mentions that, “The *Chippewa* represented the best in steamboat technology, materials, and construction, but it still failed to reach Fort Benton in 1859.” He continues, “It had to stop twelve miles below the fort and unload its cargo. The river was simply too low to support the mountain boat.”

The low depth of the river was not steamboat pilots’ only obstacle. As the channel shifted, eroding its bankline, trees and other riparian vegetation were uprooted and thrust into the channel. Trees’ trunk and roots would become lodged in the sediment on the bed of the river. Schneiders (1999) documents the hazards associated with snags. Trees felled by the river would fall into the current. Bark and small branches would be broken off while the heavier parts of the tree like the roots and trunk would sink to the bottom of the channel. Because of the current the remaining branches and trunk pointed downstream.

Oftentimes it was difficult to discern the location of snags, especially during periods of high flow. Darkness and fog additionally made identification of the hazards difficult.

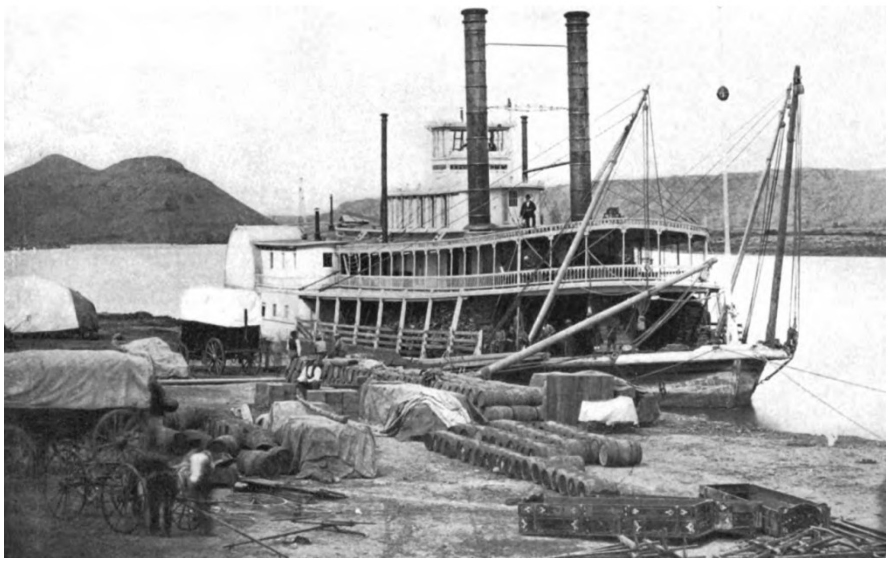


Figure 4 - A Missouri River Steamboat at Fort Benton (Chittenden 1903)

Snags did not prove to be a formidable hindrance for keelboats, as they generally moved slowly, decreasing the potential damage. In contrast, steamboats, moving two to three times as fast, were quite vulnerable. This led to the first efforts of the federal government to maintain a navigable river. Schneiders (1999) writes that for almost 40 years from the late 1830s to 1870s the government orchestrated the removal of snags and trees that could inhibit transportation.

Because of the dense traffic it experienced, the Corps focused its labors on the lower Missouri between Kansas City and the mouth. Over 17,500 snags were removed by snagboat crews in just one 13 year period. Snag removal efforts, though, were found to be somewhat ineffective for at least two reasons. One reason was that the river was continuously eroding its banks and restocking the channel with snags. The other reason was that the snagboats generally operated during times of low flow, just after the spring and summer rises. Unfortunately the high-traffic season for steamboat navigation was at times of high flows, during the annual rises. So the danger from snags was not alleviated until after the peak season had passed.

Figure 5 - Snags in the Missour River (Chittenden 1903)

It is estimated that during the nineteenth century nearly 1,000 steamboats, ferries, and snagboats were claimed by the river. Hiram Chittenden, a Corps of Engineers officer during that time, estimated that snags were the cause of around 70 percent of boat wrecks. Because of the low depth of the river, when a steamer sank it very rarely vanished beneath the water. Rather, once the boat rested on the bottom the smokestacks, upper deck, and pilot house usually stuck out above the water surface. Drowning during these occurrences was uncommon; oftentimes the crew was able to gather their personal belongings before exiting the craft and wading to the shore. If the boat or cargo was salvageable the crew might make an attempt at recovery, else the steamer was abandoned and left to be shred and consumed by the river over time.

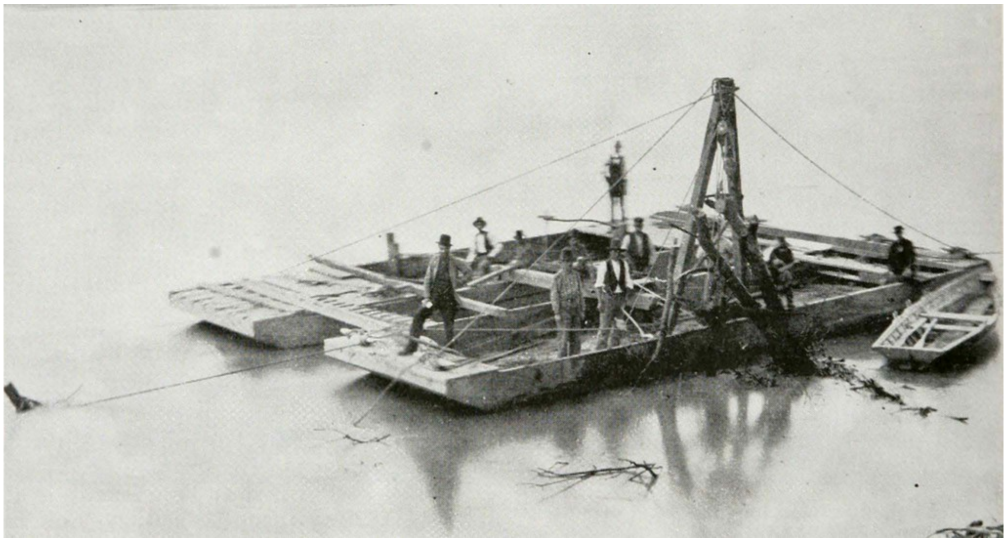


Figure 6 - Typical Snag Removal Outfit (Branyan 1974)

In the latter half of the 1800s the railroad made its way to river. It was welcomed as a replacement for the steamboat by those who inhabited the river valley. As Schneiders (1999) records, it “offered cheaper passenger fares, lower cargo rates, greater efficiency and reliability, and far more comfort than the steamboats.” Additionally, trains provided more direct routes to destinations receiving farmers’ crops. The first railroad to reach the Missouri was the Hannibal and St. Joseph line, which extended to St. Joseph, Missouri in 1859. Subsequent years saw railroad access reaching cities deep in to the Dakota Territory.

Before long the steamboat had yielded its hold on transportation to railroads. Steamboats ceased operation below Yankton by 1880 and in 1887 through-steamboat navigation halted when Helena, Montana was reached by the Great Northern Railroad. The steamboat no longer provided valley residence with anything that could not be obtained by the railroad. In fact, the railroad offered even more than steamboats. It provided, Schneiders (1999) writes, “everything imaginable: prefabricated houses, farm implements, cut timber from the forests of Minnesota, furniture, toys, canned foods, and U.S. mail.” The dependence on the river was quickly substituted with a dependence on the railroad. As this transition occurred, the perception of the river changed as well. Citizens living the Missouri Valley no longer viewed the river as an artery for survival but as a flood hazard and unused potential for barge traffic.

CHAPTER 2

DEVELOPMENT AND CAUSES OF DEGRADATION

Introduction

The Kansas City reach of the Missouri River has been experiencing a downward trend in bed elevation since the 1940s. This degradation is made evident in the stage-discharge relationship. The Corps of Engineers (2012b) reports, “The Missouri River stage trend at Kansas City has been consistently downward for all discharge levels up through 100,000 cfs.” The Corps further asserts that this decrease in stage could be due to “downstream channel cutoffs… reduced Kansas River sediment loads… and gravel mining operations.” The occurrence of bed degradation is also manifested in a significant decrease in sediment carried by the river. Richardson and Christian (1976) report, “Prior to river development the average annual sediment discharge was 164 million tons at Omaha, Nebraska… After development, average annual discharge decreased to 28 million tons.”

The occurrence of channel degradation experienced in the lower Missouri River almost certainly owes, at least in part, to anthropogenic causes. Possible factors include clear water released from reservoirs upstream of the reach, land-use changes, residual sediment issues in tributaries, such as the Platte and Kansas Rivers, significant flood events, channelization of the river, and dredging activities. In reality, there is probably a combination of factors that have caused degradation to occur.

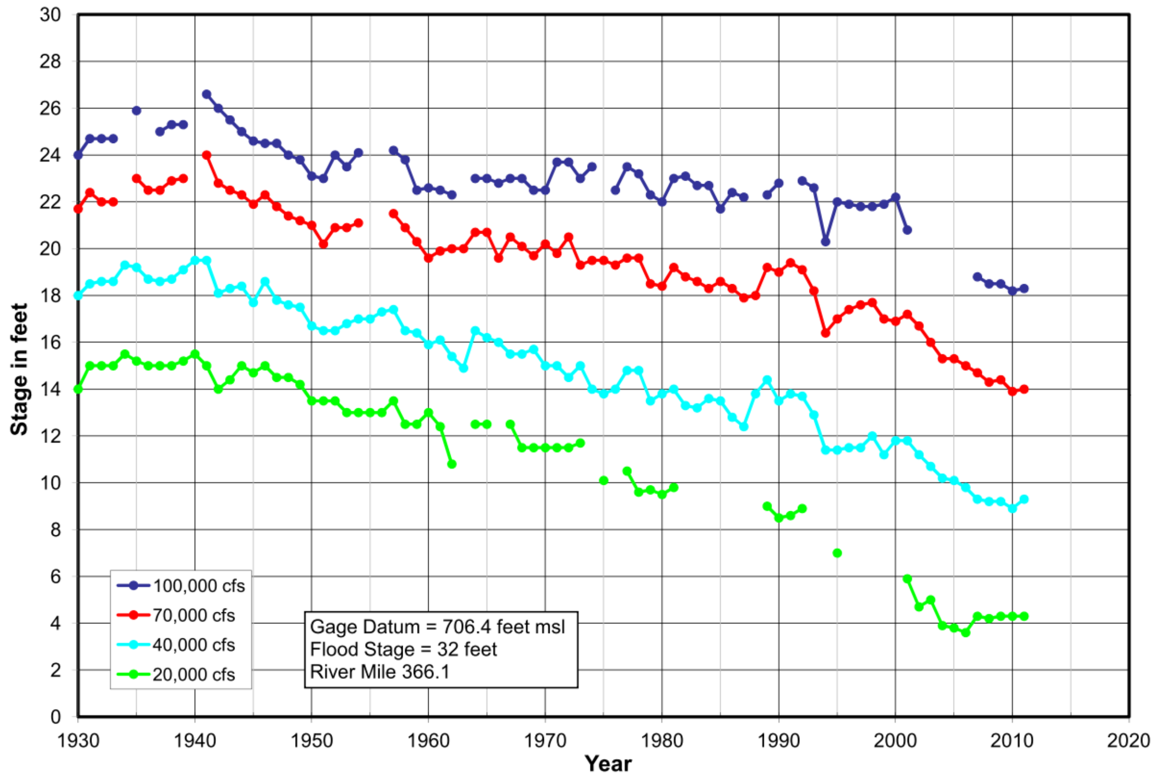


Figure 7 - Missouri River Stage Trends at Kansas City, Missouri (Corps of Engineers 2012b)

In assessment of the apparent degradation that took place, and is still taking place, at Sioux City, Iowa, Berryman, Christian, and Richardson (1976) concluded that the lowering bed elevation was due to "a reduction in suspended sediment load, a shortening of the river channel in the area, construction of river training works, and a recent (7 year) increase in the mean yearly and peak flows." The study asserts that construction of upstream dams, particularly Gavins Point, and their subsequent trapping of sediment resulted in clear water discharges which entrained sediment downstream. Dams also contributed by altering the natural discharge. They state:

> The change in the discharge hydrograph whereby large yearly peak flows no longer occur, high flows are sustained for a longer time during the summer navigation season, low flows are larger during the winter period , and sediment

inflow from the tributaries is small, helps contribute to the degradation of the channel.

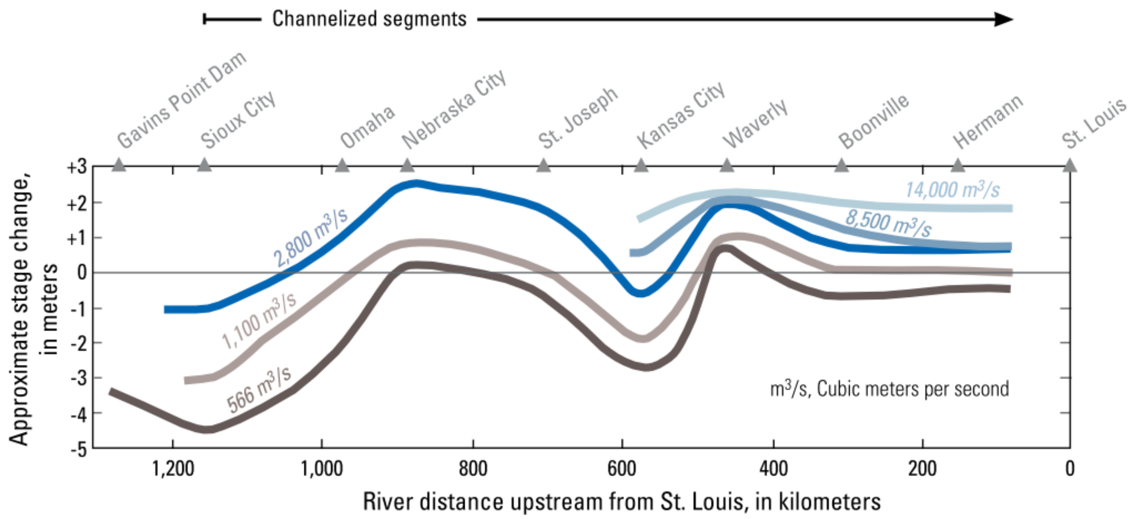


Figure 8 - Changes in Stage Discharge from 1950s to 1990s (Alexander, Wilson and Green 2012)

The report additionally assigns causality to channelization efforts. The modifications that led the reach from a braided channel to a meandering channel contributed to degradation in three ways. “One reason is that confining of the flow increases the depth and velocity, thus increasing transport capacity.” During the years 1930-1941 and 1952-1975 major realignment and training structures were constructed in the river. Another effect that channelization had to cause degradation was “the stabilizing of the banks which removes them as a source of sediment.” Without being able to erode the banks to reach its transport capacity, the river began taking up soils from its bed. “[A]nd a third reason is the increase in slope.”

The instigation of bed degradation in the lower Missouri River is probably similar; almost certainly anthropogenic, although some effect is likely due to natural causes. All accounts indicate that although it was highly variable in morphology, the predeveloped Missouri possessed dynamic equilibrium, as far as sediment transport is concerned. Only after impacts imposed on the river from human development did the Missouri become unstable. Schumm (1999) separates human effects into four groups: decreased sediment loads, increased annual and peak discharge, flow concentration, and increased channel gradient. All of these effects have been wrought on the Missouri through human development over the last century and a half. These four categories should be clearly seen in the discussion of effects that follow.

Main-Stem Dams

The fact that dams disrupt the natural processes of flow and channel evolution is one of the reasons they are built. The disruption that dams provide of the discharge in the stream, as mentioned before, is desirable for flood control and navigation purposes. This disturbance though, as well as other interruptions to natural processes, has additional consequences that are undesirable and even detrimental.

Of the 780 miles of river valley between the mouth of the Yellowstone River and Yankton, South Dakota, 650 is inundated (Schneiders, Unruly River: Two Centuries of Change Along the Missouri 1999). Although a flood control of a significant degree has been obtained, at least for the upper part of the Missouri Valley, the main-stem dams have resulted in unintended consequences. Billington et al. (2005) write, “[T]he main-stem Missouri River dams have… dramatically affected sedimentation patters within the basin, significantly altered flora and fauna growth, and affected water quality along the length of the stream.”

Figure 9 - Main-stem Missouri dams and reservoirs (USGS 1998)

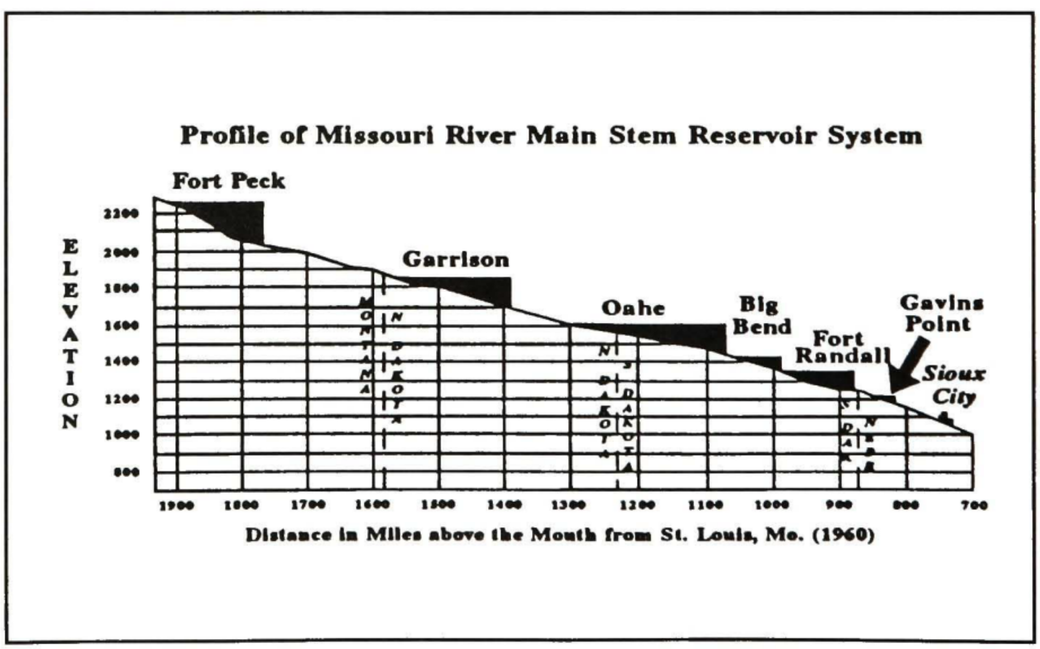


Figure 10 - Missouri River Main-Stem Reservoirs Profile (Ferrell 1993)

Fort Peck

During the early stages of channelization the Corps had calculated that in order to sustain a 6-foot navigation channel the Missouri needed to maintain a discharge around 20,000 cfs. For over half of all days during the navigation seasons of 1929, 1930, and 1931 though, the river below Sioux City did not carry this minimum discharge. The river's flow hit a low in September 1931 with a discharge of only 10,700 cfs. With the realization that the Missouri could not consistently deliver the flow that was required to maintain a depth of 6-feet, especially during times of drought, the Corps began considering construction of a reservoir, either on the Missouri itself or one of its major tributaries.

The two possible dam placements were a main stem reservoir in Montana located at Fort Peck and on the Kaw River near Topeka, Kansas. Captain Theodore Wyman Jr., the district engineer in Kansas City, examined four different dam combinations. The first consideration involved no dams. The second option consisted of building a low dam at Fort Peck with a capacity of 4M acre-feet (MAF) as well as a dam near Topeka. Along with this option was the consideration of a possible 9-foot channel downstream of Kansas City. The third alternative entailed a higher dam at Fort Peck (6 MAF of storage) in addition to the dam at Topeka. This option provided further security during times of extreme drought. The last option consisted of the largest possible dam at Fort Peck, with a storage capacity of 17 MAF, and no dame at Topeka. Under this option the reservoir at Fort Peck would be able to supply enough flow to maintain a 9-foot navigation channel from Sioux City to the mouth.

In late March 1933, less than a month after Roosevelt took office, his administration brought an abrupt stop to all new work on rivers throughout the nation, in order to determine whether or not the projects justified federal funding. Furthermore, with the Great Depression well under way, the administration was planning a relief program to address the soaring unemployment rate and select river projects were to be included in that program. In June the National Industrial Recovery Act (NIRA) was passed, which established the Public Works Administration (PWA) and appropriated to it $3.3B. According to the NIRA the PWA was able to disperse funds allocated to it independent of Congress, thereby expediting any projects that might instigate recovery for the economy.

One of the first items on the agenda was series of hearings regarding funding for the Missouri River from the PWA. The Corps of Engineers put out two proposals, one by Captain Theodore Wyman of Kansas City recommending that the 6-foot channel from Kansas City to the mouth be finished and that construction for the Fort Peck Dam commence immediately. The other proposal was written by division engineer George Spalding of St. Louis. Spalding asserted that neither the Fort Peck nor Topeka dams should be constructed. Additionally, he argued that St. Joseph should be the northern limit of the six-foot channel. He reasoned that development of the upper river should only progress once the lower part had proven that the navigation channel would be used by barge operators.

A group of prominent men from the Missouri Valley made their way to Washington to ensure that Wyman's proposal was chosen over Spalding's. A week and half later the PWA received a request from the War Department for a$17.6M allocation to be used for channelization of the Missouri. The Corps' plan was to use $3.5M to continue the last of the channelization works downstream of Kansas City and the other $14.1M to be spent on the Upper River Project. The PWA, before allocating any funds, sent board member Secretary of War George Dern to the Missouri Valley. Dern spent time in Omaha and Kansas City and in August 1933 PWA chief Harold Ickes appropriated $14.1 for work between Sioux City and Kansas City.

The next month the Corps made known their intentions of pursuing a dam at Fort Peck. The project, estimated at $145M, would include the construction of a 17-19.5 MAF reservoir as well a six-foot navigation channel downstream of Sioux City. Due to apparent reservations of Ickes and the Public Works Board, in early October, members of the Missouri River Navigation Association as well as congressional representatives took the proposal straight to President Roosevelt, who responded favorably. Senator Bennett C. Clark of Missouri, one of the representatives, additionally was able to secure the $3.5M appropriation from Ickes for the completion of the barge channel downstream of Kansas City. On 15 October 1933 Ickes released an additional $15.5M for the initiation of construction of the dam at Fort Peck. The financing of a dam at Fort Peck practically insured that there would be additional federal funds for deepening any navigation channel to a depth of 9 feet.

Less than a week and a half after receiving funds, District Engineer Theodore Wyman had established a Corps office seventeen miles north of the dam site at Glasgow, Montana and had men performing clearing operations at the dam site. In order to facilitate construction activities, in February 1934 construction began on a railroad-highway bridge just downstream of the dam site. Furthermore, building of a power line stretching 287 miles, from the generating station at Rainbow Dam, was begun in May to power the construction activities at Fort Peck. In June commencement began of the four 24-foot-diameter tunnels that would funnel the Missouri through the adjacent shale bluffs around the future dam. Each tunnel was designed to carry 84,000 cubic feet per second, the entire flow of the river. In July the project received an additional $25M from the PWA and by August, when Roosevelt visited the site, the project was employing 7,000 men.

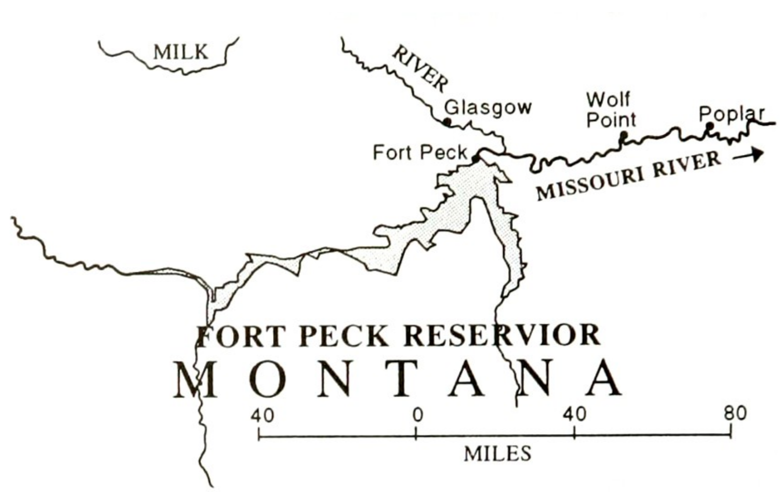


Figure 11 - Fort Peck Dam (Ferrell 1993)

By February 1935 construction of necessary infrastructure such as railroads, bridges, and barracks for housing workers had been completed and construction of the hydraulic-fill dam was ready for commencement. In spring 1935 four dredges, the *Gallatin*, *Jefferson*, *Madison*, and *Missouri* began operation in the Missouri River removing gravel, sand, silt, and clay from the river bed and sending it by pipe, sometimes two miles long, to the dam site. The coarser-grained soils settled while the water with entrained fines sifted to the core of the structure. The water was then drained back to the river, sometimes carrying rogue sediment with it. Billington et al. (2005) reports that, “[B]y the end of June 1936, the dam had retained slightly more than 30 million of the 37.5 million cubic yards [of solid material] pumped through the pipes.”

Figure 12 - Hydraulic Fill Being Discharged (Corps of Engineers 1985)

The Corps realized in late 1935 that hydraulic fill operations were ahead of schedule such that if original diversion tunnel designs could be modified, the dam could be closed a year ahead of schedule, in summer 1937. When the Corps decided on a single layer lining for the tunnel, rather than the original three-layer lining, a dispute occurred with the contractor regarding the corresponding price change. When a settlement was not reached the government assumed the contract and increased the labor force on the tunnel from 1,000 to 3,500 men. The tunnels were completed in June 1937 and two weeks later the Missouri flowed wholly through the cavities in its shale bluffs. By summer 1938, the end was in sight, as it was likely that fill could be completed by November.

Construction was not without problems though. On the morning of 22 September 1938 a survey crew chief reported to Jerold Van Faasen, the supervisor in the Soil Engineering and Fill Control Section, that the upstream embankment was only higher than the core pool's water by one foot, normally four to five feet. As Billington et al. (2005) notice, "The water level of the core pool had not risen or dropped and the downstream freeboard remained safely where it had been the day before. The upstream embankment was moving down." Survey parties were ordered to resurvey the site. Having tremendous trouble performing his task one of the surveyors later recalled how he noticed underneath him a small crack that quickly grew into a large crack until suddenly the embankment slid down devouring his fellow surveyors below. 34 men were consumed by the sliding mass; 26 came up alive, while 6 lives were claimed.

The Corps of Engineers brought together a Board of Consultants comprised of 9 experts who, over the next several months, examine the cause of the slide and how the dam might be rebuilt. In March 1939 the Report of the Board of Consultants was complted and in July it was published. The Board, with some internal disagreements, concluded that the dam foundation was subjected to shear forces that the weathered shale and bentonite seams could not resist. Billington et al. (2005) record that the Board further more "recommended that the dam section be increased such that the upstream slope be flattened from the average of one in four (a slope angle of 14°) to an average of one in eight (an angle of about 7°)." Additionally they "recommended that the shell could be completed up to within about twenty-five feet of the crest by [hydraulic fill], but above that only by dumped fill compacted by rollers." One of the dissenters to the report conclusions, Warren J. Mead, professor of geology at MIT, argued that no cost-benefit analysis could justify construction of such a dam.

Disagreements over the cause of failure continued into the subsequent years, particularly between Karl von Terzaghi, an Austrian civil engineer, and Thomas Middlebrooks, an expert on soil mechanics with the Corps. Both claimed that the failure was triggered by a weak foundation, but Terzaghi asserted that the failure was ultimately due to liquefaction of the hydraulic fill. Middlebrooks, on the other hand, maintained that the failure was entirely foundational and in no way a flow failure due to liquefaction. Ultimately the specific mode of failure, whatever it was, was exacerbated by the steep upstream slope and as Billington et al. (2005) assert, "the speed of construction contributed to the flow, and the redirected river-partly undermining the region beyond the tow-helped to extend the slide."

The dam's four diversion tunnels, each having a diameter of 24 feet and stretching over a mile in length, were sawn and blasted out of the adjacent bearpaw shale. Each tunnel has the capacity to carry the normal river flow. The spillway structure, with a width of 800 feet, has 16 gates measuring 25 feet by 40 feet. The dam was finally closed in mid-1937 and was completed in 1940. Located over 1,800 miles above the mouth of the Missouri River, the reservoir impounded behind Fort Peck Dam drains over 57,000 square miles. With an immediate purpose of job creation in the midst of economic depression, the dam additionally was intended to provide minimum depths required for the navigation channel. (Corps of Engineers 1947)

Pick-Sloan Plan

The effect of the Pick-Sloan Plan can scarcely be overstated, as Martin Reuss (2005) notes, "[The Pick-Sloan Plan] shaped the development of the entire Missouri River Valley and literally transformed the landscape of America's heartland." Although the idea and preparatory planning of additional dams on the Missouri main-stem were being carried out some years prior, the immediate development of the Pick-Sloan Plan for main-stem reservoirs on the Missouri River was a direct result of the flood of 1943, or rather, the floods of 1943.

Three floods occurred during the spring and summer of 1943; in March, May, and June. The first gave rise due to rapidly increased temperatures melting the winter's snowpack in the upper Midwest. The hardest hit section was along the Nebraska-Iowa border. The second flood can be traced to high precipitation events occurring in the basins of some of the Missouri River's tributaries in the state of Missouri. The lower 140 miles were the only section of the river affected, but the effect was significant. The third and final flood, occurring in June, originated as the Mountain snow began to melt and drain into the Missouri's tributaries, particularly the Yellowstone River. With the Yellowstone's mouth downstream of Fort Peck, the dam proved ineffective in preventing flooding. Furthermore, as the swollen river made its way downstream the states of Kansas and Missouri experienced unusually significant precipitation events.

In May 1943, just after the second flood had subsided, the governors of Iowa, Missouri, and Kansas joined the Missouri River States Committee (MRSC) in order to expedite flood protection measures. The MRSC, previously only made up of states in the upper basin, promoted the development of the basin in the form of a dam-building program. The dam at Fort Peck illustrated the inability of dams too far upstream to cause a significant difference on flow in the lower part of the valley. For this reason and because it had the most agreeable geological conditions, South Dakota was the most favorable state for dam building.

That same May Congress, due to the efforts of lower valley lobbyists, directed the Corps of Engineers' chief of engineers to conduct a study on the feasibility on dams aimed at flood control. Colonel Lewis Pick was the head of the Missouri River Division at that time and he was directed by the chief of engineers to perform the survey and provide recommendations.

In summer 1943 Merrill Q Sharpe, governor of South Dakota, was elected MRSC's chairman. Upon taking his position he instituted a large campaigning effort throughout the Missouri Valley, consisting of meetings in major cities. These meetings were attended by Corps engineers and Bureau of Reclamation (USBR) field agents who presented the audiences with information regarding river development. Following them the audience was presented with speeches given by local commercial club members and political representatives outlining the economic benefits of basin development. There was basin-wide support for river development. The specificities of the plans, however, were not unanimously agreed upon. Upper basin residents wanted reservoir waters to be used for hydroelectricity and irrigation, while lower residents viewed the reservoirs as flood control and an opportunity to guarantee a flow depth required for navigation.

In August 1943 Pick had completed his study, in just 90 days, and submitted it to congress. The Pick Plan was only thirteen pages long but intended to achieve flood protection downstream of Yankton, protect the constructed navigation channel, and provide sufficient flow to maintain traffic in the channelized portions. The plan consisted of levees, reservoirs on Missouri River tributaries, and four earthen-filled dams on the main-stem Missouri: Garrison in North Dakota, and Oahe, Fort Randall, and Gavins Point in South Dakota. The plan additionally called for lower, auxiliary dams below Garrison, Oahe, and Fort Randall to re-regulate the flow when there were large releases. The main objective of the reservoir system would be flood protection and navigation. The reservoirs would fill with water collected from the Missouri's annual rises and the dams would release at uniform rates able to sustain a navigation dept of nine-feet below Sioux City. Any ability to provide water for irrigation or hydroelectricity would be secondary. Consequently, lower basin states fully approved of the Pick Plan.

Table 1 - Projects proposed by Pick (Corps of Engineers 1985)

Area	Project	Approximate Gross Storage Capacity (acre-feet)	Estimated Construction Cost (millions)
Missouri River Main Stem: Fort Peck to Sioux City	Garrison, ND	17,000,000	$130 1/
	Oak Creek, SD	6,000,000	60
	Oahe, SD	6,000,000	50
	Fort Randall, SD	6,000,000	75
	Gavins Point, SD	200,000	15
Yellowstone River Watershed	Lower Canyon, MT	2,250,000	35
	Boysen, WY	3,500,000	20
Republican River Watershed	Medicine Creek	(not given)	2.4
	Hale	''	7.2
	Red Willow	''	2.1
	Enders	''	6.7
	Beecher Island	''	6.6
Levee System			80

1/ Includes diversion into the Dakotas.

Although the Pick Plan did not prioritize water distribution the way he would have liked Sharpe, both governor of South Dakota and MRSC Chairman, endorsed the program believing that there would be sufficient water retained to satisfy both the upper and lower basin states' interests. He was not joined by the remaining upper basin states.

When the Corps submitted the Pick Plan to Congress in late 1943 the conflict between the upper and lower basin states heightened.

When the Pick Plan was introduced into the House of Representatives in March 1944 the upper basin states, led by Senator Joseph C. O'Mahoney of Wyoming, increased their efforts in the Senate. In May 1944, in response to the Corps' Pick Plan which favored the interests of the lower states, the Bureau of Reclamation released its own study along with recommendations for a main-stem reservoir system. The plan, authored by Bureau of Reclamation field agent William Glenn Sloan, of Billings, Montana, gave priority to the upper basin states' interests of hydroelectric power and irrigation.

The Sloan Plan, similar to the Pick Plan, recommended dams at Oahe and Fort Randall, but unlike the plan put forward by the Corps, the Sloan Plan had only one dam in addition to these; at Beg Bend, South Dakota. The three main-stem dams in Sloan's plan would provide hydroelectricity required to pump the stored water to irrigation fields in eastern South Dakota. Any excess of power would be sold to public or private utilities. With the submittal of the Sloan Plan the conflict between the two geographical regions of the basin further increased.

In August 1944 at a MRSC meeting, Sharpe, realizing that these major disagreements would prevent any dam-building project from being accomplished, convinced the MRSC that any plan needed to be unanimously supported by both the upper and lower basin states. The MRSC called for a unified approach and petitioned an authorization for a coordinated plan from both the Corps and Bureau of Reclamation.

Table 2 - Projects proposed by Sloan (Corps of Engineers 1985)

Area and Project	Approximate Gross Storage Capacity (acre-feet)	Estimated Construction Cost (millions)
Missouri River Main Stem: Fort Peck to Sioux City		
Oahe	19,600,000	$ 72.8
Fort Randall	5,100,000	55.7
Big Bend	250,000	26.0
Smaller projects	—	239.1
Yellowstone River Watershed		
27 reservoirs and irrigation distribution	4,285,200	177.6
Niobrara, Platte, and Kansas Rivers		
22 reservoirs and irrigation distribution	5,650,400	273.0
Upper Missouri Basin		
19 reservoirs and irrigation distribution	3,359,950	103.6
Minor Western Tributaries		
15 reservoirs and irrigation distribution	1,237,000	35.0
Lower Missouri Basin		
Pick plan approved	—	195.8
Fort Peck		
Power system	—	11.0
Transmission grid	—	68.0
Total		$1,257.6

A water conservation conference, held in Chicago in September 1944, which was well attended by upper basin representatives, produced amendments to the Pick and Sloan plans which were being considered by the Senate Commerce Committee. These amendments included acts such as state reviews of federal river development plans, priority of irrigation and other upper basin water uses over downstream navigation, and the creation of a Missouri Valley Authority (MVA), similar to the Tennessee Valley Authority (TVA), which had been created in 1933. While there were many supporters of the MVA bill, states ultimately were uninterested, wanting to rather work with established federal organizations like the Corps of Engineers and the Bureau of Reclamation.

In October 1944, in Omaha, Nebraska, an interagency group met to compromise the two plans. The effort was headed by Sloan, representing the Bureau of Reclamation and R.C. Crawford, representing the Corps of Engineers, in place of Pick who was overseeing Corps work in Burma. The resultant Pick-Sloan Plan, somewhat of a combination of the two previous plans, called for five dams on the Missouri main-stem: Garrison in North Dakota and Oahe, Big Bend, Fort Randall, and Gavins Point in South Dakota. A Corps of Engineers (1947) publication stated, “The Garrison, Oahe and Fort Randall dams will be high head structures, with maximum heights of 210 ft., 227ft., and 160 ft., respectively… The Gavins Point and Big Bend Dams… will be comparatively low head structures.” The purposed main function of the dams would be to provide flood protection and provide navigable flows, but hydroelectricity and irrigation would also be supported through the stored water.

The combined plan was authorized by Congress in the Flood Control Act of 1944 and on 22 December 1944, President Franklin D. Roosevelt signed the Pick-Sloan Plan into law. The MVA bill, though, had been left on the cutting-room floor of the subcommittee considering the flood control and rivers and harbors bills. Lower basin interests received favor when the Corps was chosen as the body to have jurisdiction over the dams. Furthermore, in March 1945 after inclusion in the Rivers and Harbors Act, construction of a nine-foot navigation channel from the mouth to Sioux City was authorized by Congress. In 1946, immediately following the close of World War II, the Corps began construction on two of the main-stem dams, Fort Randall and Garrison.

Garrison

Garrison Dam, with a reservoir capacity of 24.5 MAF, is the third largest in the United States, surpassed only by Hoover Dam's Lake Mead and Glen Canyon Dam's Lake Powell. In June 1946 the Corps of Engineers began construction of Riverdale, North Dakota. A new town designed to house dam workers and their families throughout the construction of Garrison Dam. Design and construction of the dam though was put on hold due to opposition from leaders of the Fort Berthold Indian Reservation, a large portion of which to be inundated by the forthcoming dam. Billington et al. (2005) note that an amendment to the bill allocating funds for the dam, added by Senator O'Mahoney, provided bargaining power to the Indians by "[stipulating] that no money would go for the dam until the government and the Indian Tribes reached an agreement." General Pick warned in early 1947 that if such an amendment were included in future appropriation bills work on the dam would be discontinued. Future appropriations did not contain similar amendments but opposition to the dam continued.

Coincidentally, the Garrison Dam project gained momentum in just the same way as Pick-Sloan Plan, after a major flood. The Missouri River States Committee, local Missouri River basin newspapers, and President Truman called for immediate funding for flood control projects. In late July 1947 $20M was allocated to Garrison Dam, with $5.1M set aside for Indian tribes who were being forced to relocate almost 80% of their membership. The Manda, Arikara, and Hidatsa tribes requested almost $22M, though, and in 1949 Congress assigned an additional $7.5M to the tribes. Realizing the inevitability of construction, though, a contract was with the federal government.

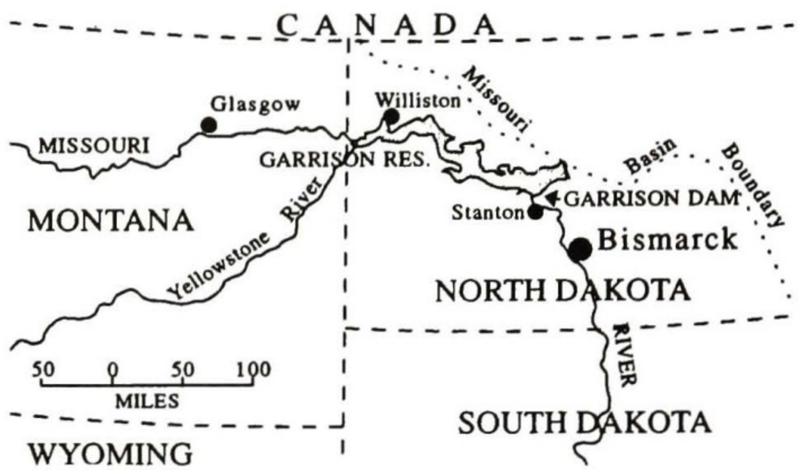


Figure 13 - Garrison Dam (Ferrell 1993)

Design of Garrison Dam was heavily influenced by Fort Peck Dam. Garrison was to have a slope of one to eight on a majority of upstream and downstream sections. The 12,000-foot-long structure, though, would be constructed using rolled earthfill instead of hydraulic fill. Additionally, the design included a 1,250-foot impervious blanket that stretched from the upstream toe to the reservoir, to prevent failures such as the one at Fort Peck Dam during its construction. Excavation for the intake, powerhouse, outlet, and spillway commenced in February 1948. The removed material was to comprise the embankment structures.

Controversy continued to cloud Garrison Dam though, and in spring 1939 development plan co-contributors, Lewis A. Pick, who had just become Chief of Engineers, and William Sloan, newly elected chairman of the Missouri Basin Interagency Committee, both addressed the House of Public Works Committee. The disagreement occurred over the planned height of the structure. Sloan, supporting the Bureau of Reclamation, insisted that the planned pool elevation had always been 1830 feet above mean sea level, while Pick argued that the pool elevation collectively agreed upon was

1850 feet above mean sea level. For the Corps of Engineers the 20 feet of extra height would provide additional water for power and navigation and space for flood control. The additional height meant inundation, though, for irrigation districts and the town of Williston, important to Reclamation interests. In August the House sided with Pick and the Corps of Engineers to set the pool elevation at 1850 feet.

Spring and summer 1951 saw construction of the intake and powerhouse structures as well as continued earthwork. The flood of 1951 bolstered interest in Missouri Valley development. By the end of the year, as Billington et al. (2005) note, “the intake structure was more than half done and the powerhouse foundations prepared.” Floods in 1952 aroused interest even more, as Lieutenant Colonel R.J.B. Page, the Corps’ Garrison District Engineer, claimed that dams on the Missouri main-stem were the only actions that could have prevented the flooding that had occurred that year. By the end of the year the Missouri was ready for redirection from its natural channel to the tunnels constructed on the west bank of the embankment. To assist in the river’s realignment, the contractor constructed lumber mattresses over rock dikes across the old channel.

Spring of 1953 came without significant flood events, making the closing of Garrison Dam in April a smoother endeavor than had been anticipated. After two days of dumping rocks into the opening between the two embankment arms the river coursed entirely through the dredged channel to the intake tunnels. President Eisenhower visited Garrison Dam in June to participate in the formal dam closing ceremonies, where he was presented with a gift by the affiliated Indian tribes. The dam was finally completed in 1955 and was dedicated by the Corps in 1956.

Oahe

Oahe Dam, the third Pick-Sloan dam to obstruct the flow of the Missouri River, is, like its predecessors, a rolled earthfill structure. In fact, as the Corps of Engineers (1985) notes, it was, “upon its completion, the largest rolled earthfill dam in the world.” Originally planned for 20 miles upstream of the South Dakota capitol of Pierre, the dam site was modified to 6 miles above the city, due to more favorable geologic conditions. The new site would additionally allow the Corps to forgo building a community for dam workers and instead have them live in Pierre. In July 1950 excavation began.

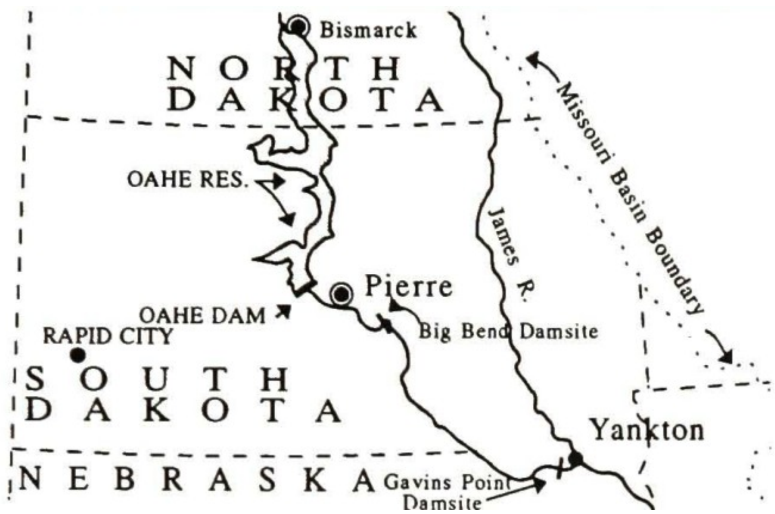


Figure 14 - Oahe Dam (Ferrell 1993)

In 1952, though, just after the Guy H. James Company had completed its contractual excavation activities on the dam’s western bluff, opposition arose. The Corps of Engineers (1985) record that “a group of 14 private power companies hired the engineering firm of Mead and Hunt of Madison, Wisconsin, to evaluate Oahe Dam and the other dams on the Missouri.” The study found that efficient storage capacity for flood control was contained in the impoundments behind Fort Peck, Garrison, and Fort Randall Dams and Oahe Dams not necessary. Oahe supporters claimed that it would be needed to provide additional storage, without which minimal hydroelectric power would be produced by Fort Randall and Garrison Dams.

Work continued, and in November 1955, during excavation of the eastern bluff by Western Contracting Corporation of Sioux City, 7M cubic yards of material slid off the bluff into the cleared area. In 1954, wells had been drilled horizontally into the shale bluffs to release excess water pressure to prevent such slides from taking place. The slide occurred anyway and Western Contracting's payment was increased to excavate the additional material and by late 1957 the embankment was ready to be closed and the river diverted.

In 1953, Mittry Constructors of Los Angeles were awarded the contract for outlet work construction. Because of fears that explosives would further deteriorate the already fractured shale, Mittry utilized a continuous mining machine, reffered to as the "Mittry Mole." The Corps of Engineers (1985) record that, "The mining machine could advance the tunnel's length more than 2 feet per hour over an extended period, doubling the previous progress record." In 1955, construction of the flood control tunnels were contracted to Foley Brothers, Inc. of St. Paul who built their own continuous mining machine and were subsequently subcontracted by Mittry to complete their tunnel work. In April 1957, Oahe Constructors, as Foley Brothers, Inc. had renamed themselves, completed the flood control tunnels.

In light of the slide that had occurred earlier in construction, the Corps modified their plans for the seven power tunnels. The new plan had the tunnels running through a lower, less fractured layer of shale. Furthermore, the Corps of Engineers (1985) write that, "The tunnels themselves were curved to travel through the most stable strata available." The final tunnel was completed in March 1961. The powerhouse, construction of which had begun in 1958, was to contain seven 89,500-kilovolt generators. In March 1962 the first General Electric generator was put online as a trial. That summer a second was added to operation and President Kennedy visited the dam to dedicate the generators. In June 1963 the seventh and final generator was operating and by 1964 the dam was virtually complete.

Big Bend

Although an original part of the Pick-Sloan Plan, by the early 1950s the Corps had become unsure about its necessity. The four other main-stem dams had purposes more clearly defined and well orchestrated with one another. The Big Bend Dam, on the other hand did not provide anything additional in the form of flow control for flood protection or navigation. Only after significant prodding by South Dakota politicians and officials, in 1954, did the Corps begin to seek funding and evaluate possible dam sites. The original site specified by the Pick-Sloan plan was replaced by a more favorable site downstream adjacent to the Fort Thompson Indian community. This site would most satisfactorily supply the dam with the geographical and geological conditions for its intended purpose, hydroelectricity.

In June 1956 an appropriation of $150,000 was secured by Senator Karl E. Mundt of South Dakota for a final site-selection study. Six sites were examined throughout 1957 and the Corps concluded that the site designated D1/D2, near the previous site examined adjacent to Fort Thompson, was most favorable for both storage and power production. Construction on the dam did not commence immediately, though, due to opposition by Senator Francis Case from South Dakota. He objected to a Preference clause in the Pick-

Sloan Plan which apportioned only a fraction of power output to South Dakota private utilities while the rest was distributed to out-of-state public utilities.

Prior to the Corps' final site decision, in summer 1957, Case presented S.R. 2822 to the Senate, proposing that South Dakota receive a federal permission to construct a dam itself at Big Bend. With Pick-Sloan dams on either side of the Big Bend Dam site, the Corps feared that if the dam was built by South Dakota it would have the potential to cause a serious disruption in the main-stem reservoir system. The Corps' management of flow and ability to maintain a navigation depth would be compromised. The lower valley states as well feared that South Dakota would have the ability to deny Missouri River water to downstream states.

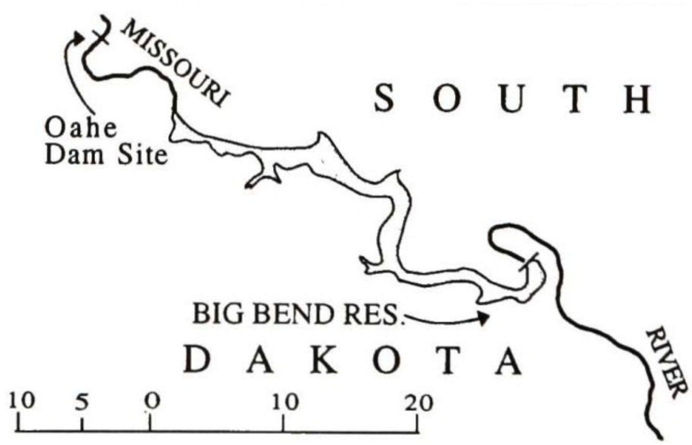


Figure 15 - Big Bend Dam (Ferrell 1993)

In March a settlement between the two parties was reached when the Preference clause was annulled and South Dakota was guaranteed 50% of the power output instead of a set number of kilowatts. Case gave approval of the Corps' proposed Site D1/D2 and a Corp proposal that the planned height be raised 8 feet, to an elevation of 1,422 feet above sea level, which was estimated to more than double power output.

The only opposition to dam construction that remained came from Lower Brule, an Indian reservation that would be inundated by the proposed reservoir, but their petitions were ignored. In 1959, after a decision had been made to lower the height 2 feet, to an elevation of 1,420 feet above sea level, in order to save Fort Pierre and Farm Island State Park, access roads were built to the dam site. Construction commenced in 1960. The dam was completed in summer 1963 and by the next year the Lower Brule and Crow Creek reservations were inundated.

Fort Randall

Work related to Fort Randall Dam began shortly before work for Garrison Dam. Prior to construction of the dam itself, the Corps prepared for its necessary workforce by building Pickstown from 1946 to 1950. Construction of the dam began in 1948 and was completed in 1956. Like Garrison Dam, Fort Randall was to be constructed with rolled earthfill. The Corps of Engineers (1985) records, “At the height of construction, almost 5,000 people worked on the dam.” Six days consisting of 10-hour shifts were accomplished by a lighting system that allowed around-the-clock work.

Excavation of the powerhouse, approach channel, and outlet sites began in early 1948, mostly accomplished by Western Contracting Corporation of Sioux City. Silas Mason Company, contracted to dill the power-generating tunnels through the river’s bluffs, began their work on the 22-foot diameter cavities in May 1949. The Corps of Engineers (1985) states, “Although work had begun on both the tunnels and the intake structure in 1949, Silas Mason had virtually completed the tunnels by the end of 1951 while work on the intake structure continued.” 1951 also saw the beginning of excavation for the spillway and stilling basin. Construction of the intake structure was contracted jointly to the Al Johnson Construction Company and the Winston Brothers Company, both of Minneapolis. The intake structure was completed in July 1952.

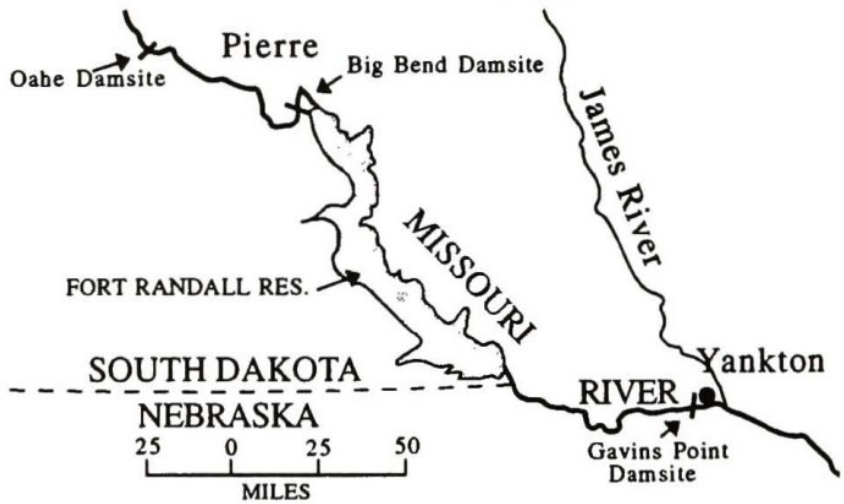


Figure 16 - Fort Randall Dam (Ferrell 1993)

The first generator to produce power at Fort Randall Dam began with a Western Union signal sent by President Eisenhower in March 1954. Less than two years later in January 1956, the eighth and final generator began providing power. By summer 1956 the dam was virtually completed, costing over $180M, over 2.5 times the estimated cost.

Gavins Point

Gavins Point Dam, the smallest of the five Corps of Engineers dams on the Missouri, was constructed from 1952 to 1957. The Corps of Engineers (1985) reports that the dam site, four miles due west of Yankton, was decided based on three criteria: "the need to keep (1) the reservoir's headwaters below Fort Randall's tailrace, (2) the dam out of Yankton proper, and (3) the spillway in a Niobrara chalk foundation." The Gavins Point Dam was the last remaining reminder of the low re-regulation dams first proposed by, then Lieutenant General, Lewis Pick. Flow at near capacity levels is required to achieve maximum efficiency of the generators possessed by the upstream, larger main-stem dams. Consequently, the Corps planned on releasing stored water in "intermittent surges. This procedure," the Corps of Engineers (1985) states, "results in optimal production of electricity, but it could wreak havoc with riverine operations downstream."

Figure 17 - Gavins Point Dam (Ferrell 1993)

In May 1952, after appropriate access roads had been constructed or improved, construction was able to begin. Experiencing significant flooding, the river, it seems, made an effort to elude its would-be captors. The Missouri had shifted its flow from the channel at the dam site to a new channel on the Nebraska side of the river. Accordingly, the Corps' earthwork contractor, the List and Clark Construction Company of Kansas City, had to first redirect the flow to its previous channel before commencing construction of the embankment. The majority of construction at the dam was contracted to Western Contracting Corporation of Sioux City, Massman Construction Company of Kansas City, and J.A. Jones Construction Company of Charlotte, North Carolina. In order to work through the bitter South Dakota/Nebraska cold of winter 1953-1954, a covering for the concrete operations was constructed out of lumber and tar paper and boilers kept the shelter at around 50°F.

By fall 1954 the contract to construct the power house had been awarded and by the following March earthmoving had progressed to the point of dam closure. Despite protests by barge owners downstream, the Corps planned on reducing flow from Fort Randall Dam and dumping material from the embankment into the remaining channel width. Closing operations began in July 1955 and lasted five days. In September 1956 the first generator began producing hydroelectricity, and by 1958 all generators were online the dam was producing 500M kilowatt-hours of electricity annually for South Dakota and Nebraska.

Degradation downstream of Gavins Point reached alarming levels throughout the 1960s and 1970s and was the subject of a workshop held in Omaha, Nebraska (Sayre and Kennedy 1978). The subject has additionally been studied in depth by the Corps of Engineers (1996). The effect of all Missouri main-stem on erosion has additionally been studied by the Corps of Engineers (1993) and Pokrefke et al. (1998).

The effect of dams on the river system must not be underestimated. These impacts have been studied in numerous publications including Williams and Wolman's *Downstream Effects of Dams on Alluvial Rivers* (1984), Shields, Simon, and Steffen's "Reservoir effects on downstream river channel migration" (2000), Graf's "Downstream hydrological and geomorphic effects of large dams on American rivers" (2006), and Grant, Schmidt, and Lewis's "A Geological Framework for Interpreting Downstream Effects of Dams on Rivers" (2003). Related to the phenomena of bed degradation, dams have two major modes of influence. The first is the clear water discharge released by dams. Sayre and Kennedy (1978) write:

> The reservoir formed behind a dam acts as a sediment trap. Therefore, the water released from the dam is practically sediment-free. Generally the flow seeks to satisfy its sediment-transport capacity by eroding material from the channel bed and banks in the river reach downstream from the dam

The second is the disruption of flow. Generally peak flows are dissipated and sometimes naturally occurring low flow levels are raised. Sayre and Kennedy (1978) write, “Dams on rivers are generally operated to regulate the release flows, in such a way that discharge and velocity variations at downstream locations are much smaller than they were naturally.” As far as sediment supply is concerned Sayre and Kennedy conclude that dams are the most important factor. Related to transport capacity, they conclude that flow regulation, as well as training structures, contribute the greatest effect. Although, aggradation trends at Rulo, Nebraska indicate that the degradation associated with Gavins Point Dam does not extend to the Lower Missouri River (Corps of Engineers 2009b).

Channelization

The first known navigation of the length of the entire Missouri River was made by the Corps of Discovery, the Lewis and Clark expedition. This was, of course, long before any type of channelization had occurred on the river. Additionally, as aforementioned, the Missouri became an artery for Midwestern settlers. Keelboats and flat bottom boats were first used on the river followed by steamboats in the latter part of the 1800s. Navigation was dangerous though. Richardson and Christian (1976) report that “more than 440 steamboats were sunk during the period prior to the railroads.”

As the railroad became the primary mode for transportation the frequency of steamboat operations dramatically declined. Waugh and Hourigan (1980) record that "traffic had dwindled from a high of 115,000 tons in 1885 to about 34,000 tons in 1906." Schneiders (1999) speaks of the shift in focus for Missouri River residents that resulted from change in transportation. Realizing that steamboat traffic could never regain its strength, Missouri Valley residents pushed for channelization of the Missouri in order to accommodate barge traffic. This, they thought, could compete with the railroads.

At the first, Congress was reluctant to finance any channelization efforts and wanted local proponents to show that such an endeavor would be a reasonable investment of federal funds. Starting in the late 1870s and going into the mid-1890s Congress was asked for appropriations from the citizens of Sioux City, Council Bluffs, Omaha, Nebraska City, St. Joseph, Leavenworth, and Kansas City. Even once construction of the barge channel had commenced, Congress did not stay committed to the task.

Federal interest in channelizing the Missouri for navigation purposes began in 1867 when Captain Charles W. Howell of the Corps of Engineers traveled from Sioux City to Fort Benton. Spending nearly three months on the *Miner*, Howell documented potential threats to navigation such as bars, snags, and rapids. The earliest real push for channelization of the Missouri happened in December 1875. It was at this time that a bill was introduced to the U.S. House by Congressman John B. Clark Jr., from Fayette, Missouri. Schneiders (1999) writes that the bill's objective was to seek funding to deepen and permanently locate the channel. Clark's bill did not pass, though, and that year's Rivers and Harbors Act appropriated a much smaller amount directed to local bank stabilization at St. Joseph and Nebraska City. A similar bill was introduced by

Congressman Clark Buckner, from St. Charles, Missouri, in January of 1877. Although this bill only requested appropriation of funds for channelization from the Congressman's hometown to the mouth, some 30-odd miles, it met the same fate as Clark's bill and never passed the House.

Just a few years following Buckner's attempt, the Corps of Engineers stepped up to the plate. Major Charles Suter of the Office of Western River Improvements in St. Louis, which oversaw Corps efforts on the Missouri, wrote a report that in February 1881 was submitted by the secretary of war to Congress. The report studied the viability of improving Missouri's channel for barge traffic. Suter estimated that the cost per mile was not likely to exceed $10,000, making the cost to improve the length from Sioux City to the mouth, 800 miles, $8,000,000. Kansas City to the mouth at this rate would cost $3,750,000. Suter's report continued to argue that, "The benefits attendant on such an improvement can hardly be overestimated." He asserted that boats and barges of the size then common on the Lower Mississippi would have no problem navigating the report's guaranteed safe and permanent channel with a depth no lower than 12 feet.

1881 saw the Missouri River Improvement Convention in St. Joseph, organized by individuals desiring to restore transportation on the river. Schneiders (1999) explains that the convention had two intentions: "to generate popular support for channelization of the river and to use any public endorsement to pressure Congress into adopting the channelization program outlined in Suter's report." In early 1882 a committee, which had been elected at the conference, petitioned Congress through a letter, claiming that the improvements could save Midwest farmers over $14 million per year by using barge rather than rail to transport agricultural products. The committee asserted that, "[T]he channel would pay for itself in saved transportation costs after only six or seven months of operation".

In August 1882 the convention's requests were granted when Congress passed the Act for the General Improvement of the Missouri River, appropriating $850,000 for channelization (roughly equal to the total money spent on the Missouri in the previous five years combined). Congress additionally called for the Corps to adopt new methods of construction. Rather than focusing their efforts on reaches near towns, a continuous, systematic approach would be implemented, to improve the entire 800-mile length to Sioux City.

The task of overseeing this barge channel construction fell on Major Charles Suter. The first $850,000 installment was used to acquire the tools necessary to complete such an endeavor. Schneiders (1999) explains how Suter bought "mattress boats, barges, snagboats, hydraulic graders, hydraulic pile drivers, quarterboats, yawls, skiffs, and a floating machine shop." Neither 1882 nor 1883 saw any actual construction of the barge channel, though. Suter had expended his entire budget on his fleet of 188 boats rather than starting partial construction.

The reasons for Suter's decisions remain somewhat unknown. It is possible that although he estimated to have been able to build half the fleet he had and still complete 40-50 miles of channelization, he believed Congress would continue to provide the necessary appropriations to complete the construction to Sioux City. Whatever the reason, in 1884 Congress established the Missouri River Commission (MoRC), a five-member group with Suter as its president. The commission was created in an effort to ensure that decisions made regarding channelization would not be politicized or influenced too greatly by local constituents. Furthermore, Congress appropriated an additional $0.5M for efforts below Sioux City.

Suter's plan was to channelize the river at Kansas City first, and then progress toward the mouth near St. Louis, but his momentum came to a halt when, in 1885 Congress ordered Suter and the commission to use their appropriated money on bank-protection efforts at Kansas City and St. Joseph, where previous revetment work was in jeopardy. Early methods of bank protection are displayed in the figure below. Additionally, that same the committee was rejected funds for channelization from Congress for the following fiscal year.

In September of 1885 a River and Harbor Convention occurred in St. Paul, Minnesota to discuss navigation issues in relation to the Mississippi River. In attendance were also around 50 individuals from the Missouri Valley who created an executive committee assigned the responsibility to see to all matters having to do with improvement of the Missouri River. Some of the men on the committee included: T. B. Bullene and H. M. Kirkpatrick of Kansas City, John H. King of Chamberlain, and Thomas C. Power of Helena. King and Power were both involved in the steamboat industry. These two men, joined a few months later by Isaac P. Baker, favored river improvement as a means to bolster their own industry which had been suffering for some time. Not only could a channelized stream be used by them for profit, but their steamboats, dry docks, and machinery could be used in the construction of improvements as well.

Just a of couple months after the River and Harbor Convention in St. Paul, in mid-November 1885, the executive committee sent invitations for another convention on Missouri River navigation to governors, senators, congressional representative, and other "distinguished citizens" from the Missouri basin. The convention was to be held in Kansas City, Missouri just six weeks later on 29 and 30 December 1885. The convention was well attended, despite the late notice. 200 individuals were present including business executives, judges, lawyers, and local government officials. The state of Missouri had the largest representation, but Dakota Territory, Iowa, Montana Territory, and Minnesota also sent delegations of two or three individuals each.

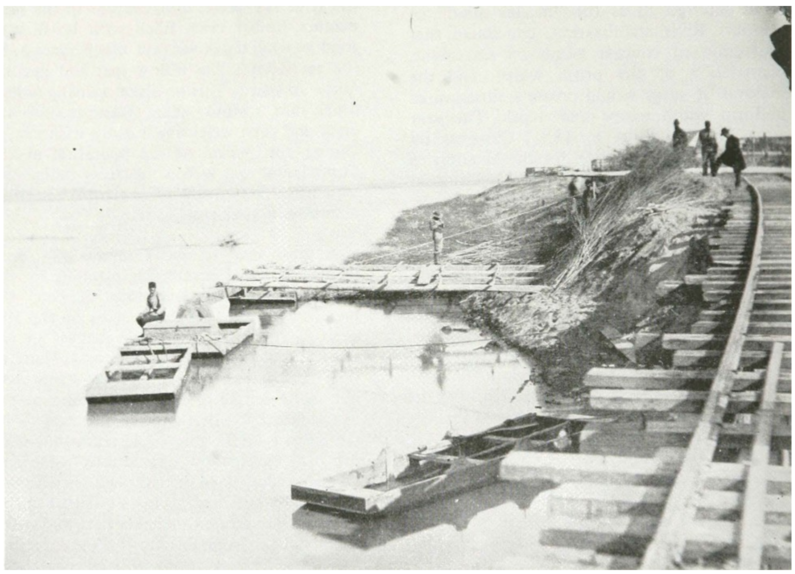


Figure 18 - Early Bank Protection Efforts (Branyan 1974)

The convention saw much discussion revolving around the federal government's responsibility to develop the nation's waterways, and to improve the Missouri specifically. The men asserted that if their current representative did finance river improvements they should be voted out of office. It was also agreed that there needed to be a unified approach with no locality seeking money on its own from Congress for things like bank-protection projects. The men resolved to hold another convention the following year in Omaha and to send lobbyists to Washington, DC. The convention's efforts were successful and in late June 1886 Congress appropriated $375,000 for improvement on the Missouri followed by $1M in 1888. These monies though were not used on channelization for navigation improvements. Instead, the Missouri River Commission, being pressured by towns in the Missouri Valley, built bank-protection structures with the federal money.

Missouri Valley residents may have verbally supported channelization of the river to promote barge traffic, but those intentions were overridden by bank-protection efforts near communities. And although these works provided somewhat of a navigable channel though those communities the reaches of river between were still plagued with sandbars, shoals, and a shallow thalweg. Although the channelization of the river was to be overseen by the Missouri River Commission and the Corps of Engineers, Congress oftentimes bent to the demands made by town citizens, especially in St. Joseph and Kansas City. Over $2M was appropriated to the Missouri River commission between 1884 and 1890, none of which was used to fund channelization.

A more unified approach was experienced in the 1890s and exemplified in the efforts conducted between 1891 and 1896. Congress allocated $800,000 to the Missouri River Commission in September 1890 with an order for use on channelization instead of bank stabilization. The previous plan for channelization, laid out by Suter, had divided the Missouri from the mouth to Sioux City into six reaches. In 1891 as Suter and his engineers began channelization work, they altered the previous decision to work in a downstream direction. Instead, Suter began channelizing along the first reach which stretched from the mouth to the inflow of the Osage River, a total of 137 miles. The work would now progress in such a way that it would progressively open more length of the river to commerce, being connected with the Mississippi. It also meant that the newly finished channelized reaches would be exposed to the erosive strength of the wild river upstream.

In order to facilitate channelization Suter planned on the use of hydraulic pile drivers, piles, and pile dikes. The piles used were wooden, generally white oak or cypress, and varied in length from 30 to 50 feet or more. With diameters ranging from 8 to 10 inches at the head and 13-20 inches at the butt, the piles were driven into the thick clay soils underlying the bed material in the river. Oftentimes hundreds of blows from the hydraulic jack were required to achieve the depth required.

Multiple rows of piles, spaced at ten feet, became the framework for the pile dike. Once the piles were firmly anchored in the river's subsurface, laborers attached boards along the length and width of the rows. Following this a willow curtain was formed using willow saplings trimmed of their branches. The curtain ran the length of the dike. The fact that these pile dikes were permeable meant that the river's power wasn't completely forced upon them as water was still able to flow through the structure. The river's velocity through the dike was significantly lowered though, which resulted in the deposition of sediment accumulating on the downstream side of the dike.

In addition to pile dikes the commission and the Corps employed the use of revetments in the first reach. Revetments consisted of a woven willow mattress overlain with stones. Small willow trees were cut and woven into a mattress by hand. The finished mattress was then laid on the bank, which had to be graded to a 45° angle. The mattress extended several feet beyond both the low and high waterlines to prevent being eroded by the extreme flows. Because in some places the difference between the low and high water level was over 35 feet it was not uncommon for the willow mattresses to exceed 40 or 50 feet in width. Once placed, the mattress was overlain with stones to stabilize it.

An area of particular concern for Suter and his engineers was just downstream of the mouth of the Osage River. Here the river became braided with sandbars and fast currents, frustrating steamboat pilots. In order to remedy this predicament and create a deepened, narrower channel the Corps was required to limit flow to the main channel, cutting of the side channels. One side channel, the Osage Chute, was especially difficult, as 45% of the flow coursed through this chute. Modified revetment had to be employed, involving seven consecutive layers of willow mattresses and stone over the entrance. This modified structure, with a length of 1,525 feet. At only a fraction of a mile long it cost over $25,000, a steep price considering Suter's original cost estimate of $10,000 per mile. Despite the cost, once closed the revetment reduced flow through the chute to 5%.

Throughout the first years of channelization Congress's commitment remained somewhat uncertain. As a result, residents in the Missouri Valley were required to be persistent in their lobbying efforts. A number of meeting and conventions took place in 1891 including the Missouri River improvement convention on 15 and 16 December. There were over 400 in attendance representing states ranging from Tennessee, Louisiana, Mississippi, Colorado, Ohio, North and South Dakota, and Iowa. The convention produced the Missouri River Improvement Association whose purpose was to promote and seek congressional funding for channelization of the entire length of the Missouri River, as well as the lower Mississippi, as barge access to Memphis, New Orleans, and the Gulf of Mexico were necessary for channelization on the Missouri to be profitable.

Figure 19 - Upper Missouri River dike of the late 1800s and early 1900s (Thomas and Watt 1913)

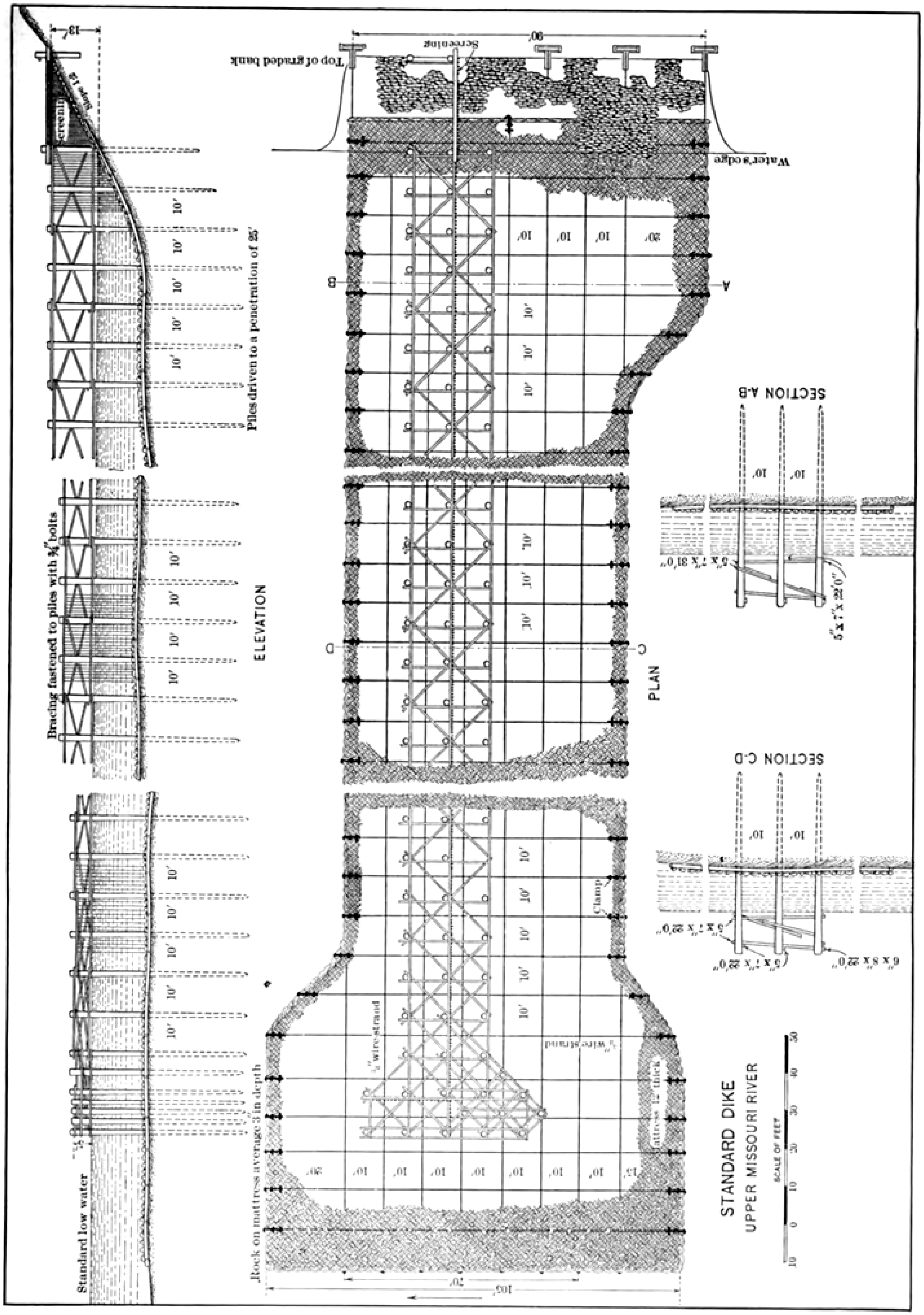
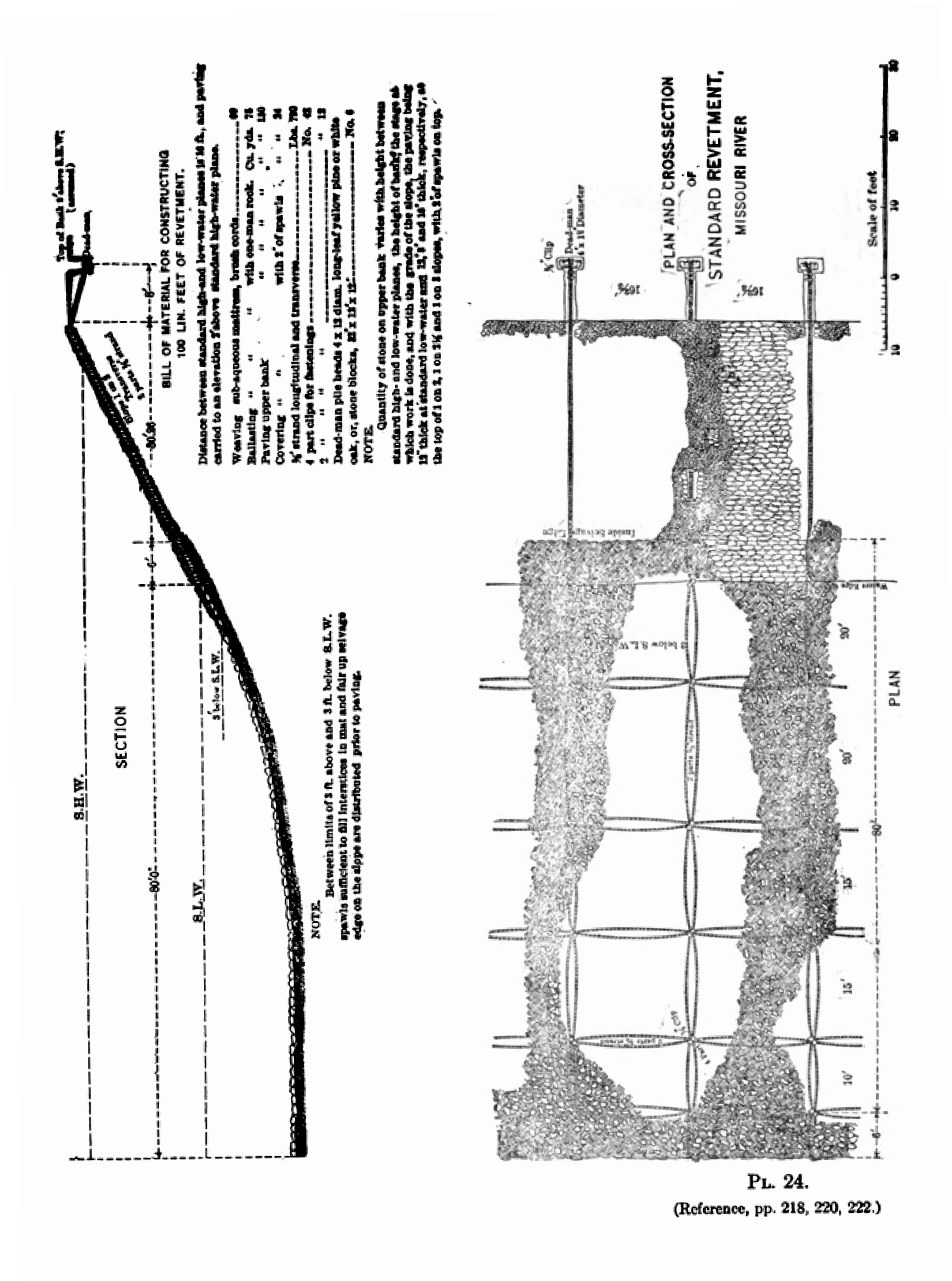


Figure 20 - Revetment used on the Missouri in late 1800s and early 1900s
(Thomas and Watt 1913)



With new found enthusiasm for improvements the efforts were granted large sums of appropriations from Congress between 1890 and 1895. The Corps of Engineers (1985) records that in 1890, “Twenty dikes and 20,724 feet of mattresses went in to protect Sioux City.” But the channelization works did not always progress as smoothly as anticipated. Only 45 miles between the mouth and Kansas City had been improved for barge traffic and that at nearly $58,000 per mile, almost five times as great as Suter’s first estimates. Additionally, Suter had originally estimated a low-flow channel depth of 12 feet but was only achieving 6 feet in the barge channel during low-flow periods. Consequently, in 1896 Congress drastically cut funding for the channelization efforts. From 1896 to 1902 the only improvements made were snag removal efforts and minimal bank-protection works, barely covered by federal funds. Schneiders (1999) notes, “In 1902 there still remained 324 miles of free-flowing river between Kansas City and the mouth. That same year, Congress passed an act abolishing the Missouri River Commission.” While some still held hope for a channelized Missouri that could foster barge traffic, Congress had all but given up on the Missouri.

According advice made by Captain Hiram Chittenden of the Corps of Engineers, Kansas City Mayor James A. Reed and the Kansas City Commercial Club organized a River Congress. Held in October 1903 the congress drew an attendance number over 200, including the Senators of Kansas and Missouri as well as Missouri Congressmen. The congress concluded that ample protection from floods could be garnered through a system of dams and reservoirs on the Kaw River, construction of levees along the Missouri and Kaw Rivers, and the channelization of both rivers. The congress additionally created a permanent river commission, made up mostly of men from Kansas City, who would lobby Congress for federal aid in these projects. However, as Schneiders (1999) points out, "the U.S. House Committee on River and Harbors rejected all the proposals for flood control, pointing out that such action was outside the jurisdiction of the federal government. The Congress and the Corps only had constitutional authority to improve the Missouri for Navigation."

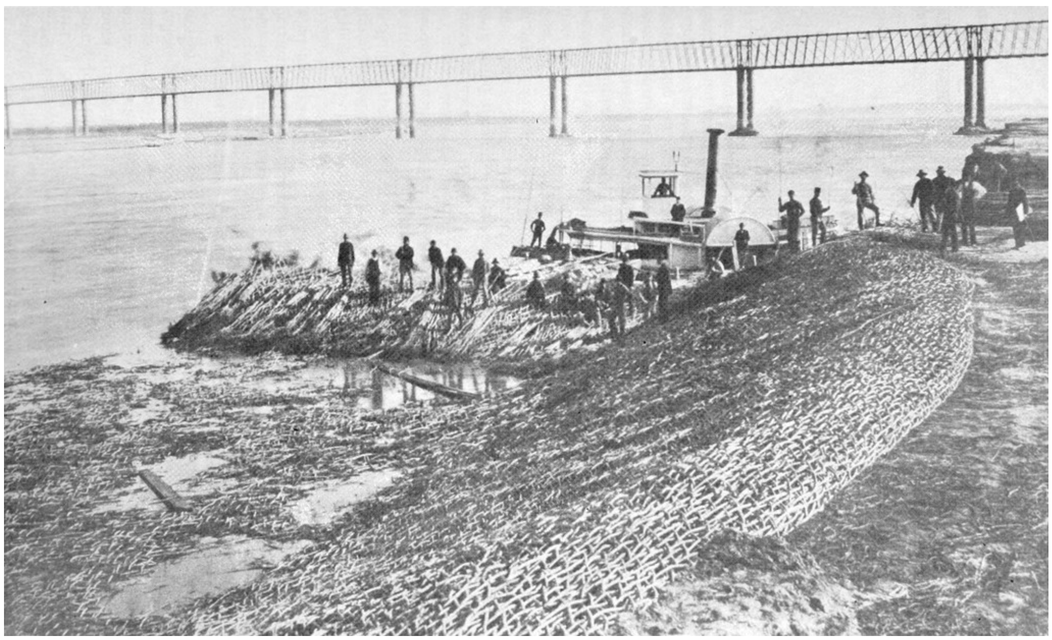


Figure 21 - Typical Woven Willow Mattress at Omaha (Branyan 1974)

The subsequent years of 1904 and 1905 saw additional flooding. This led Lawrence M. Jones, a member of the Kansas City Commercial Club, and other Kansas City businessmen, in July of 1906, to create the Missouri Valley Improvement Association. The association's purposes, as described by Jones (1908) were:

To prove the Missouri River navigable.

To have the river navigated by commercial freight carriers.

> To secure from Congress appropriation for improvement of the channel in aid of navigation.
>
> To establish and maintain a close working relationship with the National Rivers and Harbors Congress and other organizations promoting river improvement.
>
> To conduct a campaign of education intended to inform the people of the Missouri Valley and trans-Missouri region, the officials in Washington and the Congress of the United States, of the magnificent possibilities and tremendous commercial importance of Missouri River improvement.

In order to harbor support from Congress or other federal officials, Jones sought to prove that the Missouri was, in fact, navigable. After proving that the Missouri could sustain steamboat and barge traffic, Jones would convince Congress that the river ought to have federal money for improvements. Later that summer, Jones commissioned the *Lora* and *Thomas H. Benton*, both steamboats, as well as the *Louise* and *America*, both barges. They were loaded with cargo in St. Louis and made their way up the river to Kansas City, arriving in late September 1906. Apparently impressed with the voyage, appropriated a small sum of federal dollars for snag removal on the Missouri.

Throughout 1907 Jones continued in his efforts to acquire federal support of Missouri River navigation. A key event occurred in Memphis, Tennessee: The Lakes-to-the-Gulf Deep Waterways Association meeting. Attended by President Theodore Roosevelt, the meeting's goal was to promote support for a system of inland waterways including the Great Lakes and the Illinois, Mississippi, and Ohio Rivers. Through a speech made at the event, Jones put the Missouri river "on the map" by linking it to the system as a necessary component to any inland waterway system.

The attendance of hundreds, including President Roosevelt, demonstrated the magnitude of support for water way development, not only in private industry, but the federal government as well. Roosevelt had previously created the Inland Waterways Commission to, as Schneiders (1999) writes, “take an inventory of the nation’s water resources and to establish guidelines for their development.” Per a request made by Jones, members of the Inland Waterways Commission traveled to Kansas City to attend a series of Commercial Club meetings. Speaking at these meetings Jones reaffirmed the importance of channelization of the Missouri River from Kansas City to the mouth. The party traveled the river as well, aboard a snagboat, where channelization techniques and technologies were explained by Colonel E. H. Shulz of the Corps. Headway was apparently made for Missouri River improvements in 1907 when the Corps of Engineers formed the Kansas City District to manage work on the Missouri River.

With the formation of the Kansas City District channelization supporters no longer had to travel to St. Louis, where the Corps division office was located, to meet with officials. With its new, local ally, that same year the Missouri River Valley Improvement Association published *The Missouri: A Deep Waterway*, a pamphlet outlining and promoting channelization of the Missouri.

Following Kansas City’s lead, other Missouri Valley communities experienced renewed fervor for channelization. In late January 1908 the Real Estate Association of Sioux City hosted the First Annual Convention of the Missouri River Navigation Congress. 600 attendees convened from all over the Missouri Basin, making it the largest meeting addressing Missouri River improvements. Supporters and attendees included: Governor Coe I. Crawford of South Dakota; Joseph Ransdell, president of the national Rivers and Harbors Congress; Mayor Henry M. Beardsley of Kansas City, Missouri; Governor John Burke of North Dakota; Governor George L. Sheldon of Nebraska; and

Governor A. B. Cummins of Iowa. Representatives elected Edgar Ellis, a congressman from Kansas City, as the president of the Missouri River Navigation Congress and Lawrence Jones as vice-president.

Later that year the Missouri Valley River Improvement Association published *The Deep Water Project for the Missouri River*, another pamphlet concerning channelization. A twelve-foot deep channel, the pamphlet maintained, could be accomplished at a cost of $50,000 per mile, making the whole 800 mile length cost $42.5M. The pamphlet further contended that value of reclaimed bottomlands between Sioux City and the mouth alone would cover the total cost of channelization.

The spring of 1908 experienced another great flood, exceeded in level only by two previous events, the floods of 1844 and 1903. The flood waters of 1908, though, lingered in the valley longer than any previous flood, preventing farmers from planting crops. With a fresh view of the river's destructive power the motivation for channelization only grew. In July of that same year Congressman Edgar Ellis, also president of the Missouri River Navigation Congress, wrote to a lawyer and supporter of channelization, Louis Benecke, who lived in Brunswick, Missouri. Ellis urged Benecke to establish a local branch of the Navigation Congress, a plan he had for every community between Kansas City and St. Louis.

In January 1909 Ellis's efforts were rewarded when Congress allocated $655,000 for the recommencement of channelization. This represented the first congressional financial support for channelization since 1895. $450,000 of the allocated funds was reserved for efforts between Kansas City and the mouth. In the spring the Corps of

Engineers held public meetings to determine the optimum location for immediate improvement.

In pursuit of additional congressional funds, Ellis suggested the creation of a barge line by Kansas City businessmen. This line would run between Kansas City and St. Louis and it would, Ellis hoped, help those in Congress with reservations realize the potential of channelizing the Missouri. The Kansas City Missouri River Navigation Company was formed in 1909 by members of the Kansas City Commercial Club, with Walter S. Dickey as president. The company stock was sold with over 4,000 people making investments. Months later, in February 1910, Theodore Burton, the chair of the House Rivers and Harbors Committee, held a hearing to ascertain the situation. Dickey and others of the Kansas City Commercial Club traveled to Washington to be present. Apparently the newly formed company made an impression as the channelization project received an appropriation of $1M.

Owing to the continued lobbying efforts of Missouri Valley towns as well as the growing popularity of the progressive conservation movement, in early 1912the construction of a six-foot-deep channel was authorized by Congress. Although considerably less than the original 12-foot depth planned by Suter, studies conducted by the Corps revealed that the Missouri could maintain only a six-foot channel. Congress continued to provide funding, with $800,000 in July 1912 and $600,000 following a month later and $2M the following spring. According to Corps of Engineers estimations, the project could be completed in ten years with appropriations of $2M per year. Although financial support was not garnished to this degree, Congress kept the Corps funded enough to construct channelization along large stretches. At that time the methods of construction and channelization had changed very little from the first channelization efforts used by Suter in the 1890s.

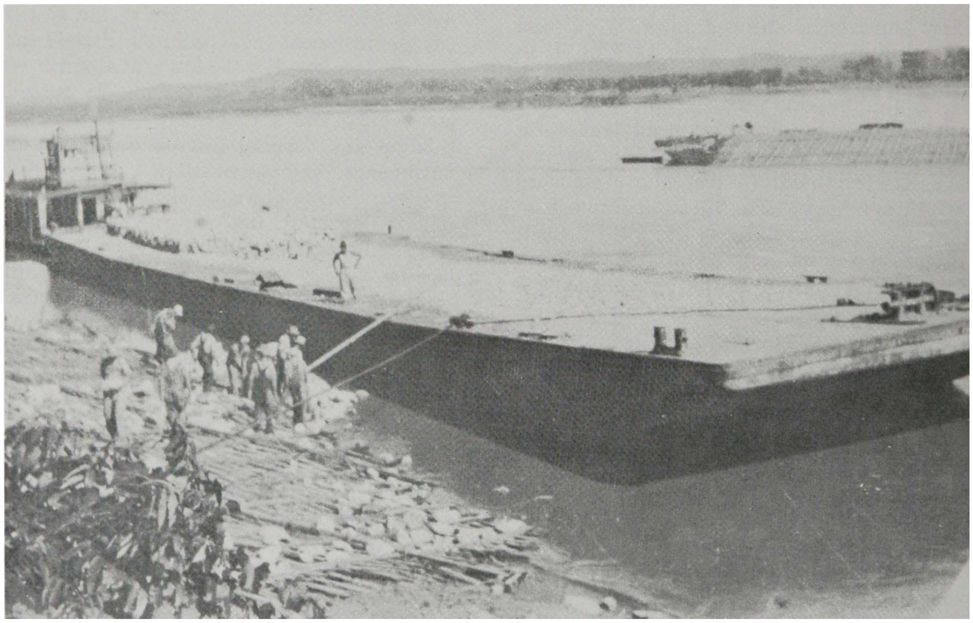


Figure 22 - Men Placing Stones on a Willow Mat (Branyan 1974)

In spring of 1915 Congress ordered a review to determine the cost-effectiveness of the Missouri River barge channel to be conducted by the Corps of Engineers' Board of Engineers, created in 1902 to examine proposed or existing federal navigation projects. Under the leadership of Lieutenant Colonel Herbert Deakyne, the report was submitted to the board in August 1915, stating that channelization of the Missouri River was not a cost-effective endeavor. Deakyne argued that the barge channel was not necessary for transportation purposes as rail lines existed paralleling both banks of the river. He further recommended that Congress cease all channelization work and limit their efforts to snag removal.

Upon receiving word of Deakyne's conclusions the residents of the Missouri Valley reacted. The Kansas City Commercial Club as well as communities all along the river from Kansas City to St. Louis wrote and pledged their support for channelization project. Due to the magnitude of the response the Board of Engineers held a hearing in October 1915. Missouri Valley business men and other working for the barge channel insisted on the complete channelization of the river. Consequently, the board discarded Deakyne's report. Schneiders (1999) writes, "In April 1916 W. M. Black, chairman of the Board of Engineers, submitted a report to his colleagues that unequivocally endorsed the future channelization of the Missouri. Black urged Congress to continue to underwrite the project."

While Missouri Valley residents were pleased with the decision, Senator Theodore Burton of Ohio and Congressman James Frear of Wisconsin were less than content, asserting that the channelization of the Missouri was, in fact, unnecessary. They called for the House of Representatives Judiciary Committee to take action by investigating the Missouri River lobby. They contended that channelization was not for navigation purposes at all, but rather for flood control and property protection. Of course the constituents of these men were also benefiting greatly from the channelization of both the Ohio and Mississippi rivers. Their assertions were answered by Congressman W. P. Borland from Kansas City who challenged the men to visit Kansas City to experience firsthand the work of the Kansas City Missouri River Navigation Company. Congress was not swayed by arguments of Burton and Frear and the channelization projects moved onward.

Work was forced to experience drastic funding cuts, though, as the world was knee-deep in the efforts of World War I and by 1916 channelization efforts had halted. Furthermore, the Kansas City Missouri Navigation Company had sold its steamboats to the federal government for use on the Mississippi in the war effort. At the close of the war work was not continued, and from 1916 to 1922 there was not enough funding to even maintain the existing structures. Only 35% of the length between Kansas City and the mouth had been channelized and having been neglected those structures were deteriorating under the power of the river.

Failure to resume work on the river concerned Kansas City Commercial Club members, who in November 1923 held a meeting where E. M. Clendening, the club’s executive secretary, declared that the federal government would not finance channelization to completion at it was left to local advocates of channelization to see it to the end. J. C. Nichols, a commercial club member and local real estate tycoon, retained belief that channelization could only be achieved through federal funding. As a result Nichols attended a Mississippi Valley Association meeting in the mid-1920s where discussion was dominated by the channelization efforts of the Mississippi and Ohio Rivers. Nichols realized the need for a new organization focusing its efforts on the navigation potential of the Missouri. He and Lawrence Jones promoted a unified organization involving the entire valley. Through discussions with commercial club members in Omaha, St. Joseph, and Sioux City it was determined that federal financing was attainable and so the newly formed Kansas City Chamber of Commerce held a conference on Missouri River navigation in October 1925.

At an attendance of nearly 750, the event was the most well attended conference on channelization that had taken place. The keynote address was delivered by Herbert Hoover, secretary of commerce, who promoted the inland system of waterways that had previously been known as the Lakes-to-the-Gulf Deep Waterway but had since been named the Cross of Commerce. Hoover asserted that as a part of this system a barge channel should be constructed in the Missouri from the mouth to Kansas City. He argued that the full benefits of such a system could not be realized until the system was completed and the waterways linked. At the close of the conference the Missouri River Navigation Association was formed with the governors of the ten states of the Missouri Basin as board members. Arthur J. Weaver, a banker from Falls City, Nebraska was elected the association's president. The association's goals were twofold: to convince Congress to complete channelization between Kansas City and the mouth and then to persuade Congress to extend the project north, farther upstream the river.

Efforts were rewarded in December 1925 when Congress appropriated an additional $10M for river and harbors, specifically the Mississippi basin. Since the Mississippi would need to be channelized before the Missouri could be effectively navigated this was viewed as a step in the right direction. That same month the Upper River Committee was formed by the Missouri River Navigation Association to investigate the possibility of extending the barge channel to Sioux City. The committee found that such an endeavor was economically feasible and submitted to Major C. C. Gee, of the Kansas City District of the Corps of Engineers, a report of their findings. Gee was convinced but officials higher in the Corps retained reservations, wanting to first see that the Kansas City-to-mouth channelization efforts were justified.

In 1926 Weaver and Nichols continued to bolster their support by traveling to towns in the Missouri Valley holding meetings. If Congress was going to continue channelization efforts there needed to be a strong public support. In late April 1926 Congress listened to the valley residents' request and of the $50M appropriation for rivers and harbors that year, $2M was earmarked for channelization work between Kansas City and the mouth. This along with vocal support provided by federal officials ranging from President Calvin Coolidge, the secretary of commerce, the secretary of war, and the chief of engineers, motivated the Kansas City Chamber of Commerce as well as the Missouri River Navigation Association to once again push for congressional authorization of a six-foot channel north to Sioux City.

The enthusiasm for channel extension north led to an introduction of an amendment to the Annual Rivers and Harbors bill on the floor of the House of Representatives. In spring 1926 Missouri channelization supporters met with federal representatives from the Missouri basin states to introduce the amendment which would authorize the Upper River Project, extending the barge channel from Kansas City to Sioux City. The bill, along with its new amendment, passed the House but was held up in the Senate Commerce Committee. In June the committee held hearings on the amendment where C. E. Childe of the Omaha Chamber of Commerce and Mayor Stewart Gilman of Sioux City testified, arguing the importance of the barge channel to the communities in the valley. Their arguments were unsatisfactory to the committee and the amendment was dropped from the bill.

Weaver and Nichols remained relentless. In order to find a way to reintroduce the Upper River Project into the Rivers and harbors bill, he Missouri River Navigation Association met again in November 1926. It was decided that an amendment would be introduced on the floor of the Senate, similar to what had been done earlier that year on the floor of the House. Missouri Valley representatives were able to garner substantial support by aligning with representatives from the northeast who had their own agendas, and the bill, along with the Upper Missouri Project, was passed into law in January 1927. In addition to the Upper Missouri Project the bill contained an authorization for the Corps of Engineers to investigate the possibility of a nine-foot navigation channel downstream of Kansas City. With construction underway for a barge channel of this depth on the Mississippi it became evident that the same size would be required on the Missouri in order to maintain its economic feasibility.

Even after its approval in the Annual Rivers and Harbors bill, the Upper Missouri Project only received $45,000 in spring 1927, while the reach from Kansas City to the mouth was appropriated $2M. Later the next year, when Herbert Hoover was elected president there were high hopes among channelization enthusiasts in light of his speech in 1925 at the Missouri River Navigation Conference. In March 1929, after taking office, James W. Good, Hoover’s secretary of war, granted $6M in allocations for channelization from Kansas City to the mouth and allocated $1M for work on the barge channel from Kansas City to St. Joseph. Residents along the upper part of the proposed channelized river were unsatisfied and in May 1929 representatives met with Good to argue that the $7M allowance for channelization should be equally distributed along the river from the mouth to Sioux City. Good did not relent, contending that the most cost effective approach was to channelize the river downstream of Kansas City before commencing full-scale work further upstream. Good did however appropriate an additional $1.5M to the Upper River Project later that year and as well as an additional $7M for work below Kansas City.

By this time the Lower Mississippi as well as the Ohio, from its mouth to Pittsburgh, had already been deepened to a nine-foot channel and a six-foot barge channel was well under construction on the Upper Mississippi. In October 1929 President Hoover spoke at an event in Louisville, Kentucky commemorating the Ohio River's inclusion in the Cross of Commerce. In his speech, Hoover emphasized the necessity of a standard 9-foot channel throughout the entirety of the inland waterways system. Although the 6-foot channel from Kansas City to the mouth was far from finished, the Missouri River Navigation Association called for another amendment to the next Rivers and Harbors bill to include authorization for a nine-foot channel. Such a project was further endorsed by Major Gordon R. Young, head of the Kansas City District of the Corps of Engineers, who wrote a report in winter 1929-1930 to defend its economic feasibility.

When Young's report came to the desk of Brigadier General Herbert Deakyne, who since his first rejection of the Missouri River navigation project had become chairman of the Board of Engineers, he rejected the conclusions. Deakyne argued that further studies were necessary to investigate whether the Missouri had enough discharge to sustain a 9-foot channel. He further wanted to know how the river would react to such changes. Furthermore, Deakyne was unconvinced that a 9-foot barge channel could be achieved.

Upon receiving back his rejected study, Young, who wanted to include the 9-foot channel in that year's Rivers and Harbors bill, quickly wrote another report outlining the feasibility of constructing the deepened channel. He asserted that similar engineering methods employed in obtaining a 6-foot depth could be used to further confine the river. Additionally, Young estimated that the cost of deepening the channel would be $27M beyond the funds needed to complete the 6-foot channel. Once completed, Young sent his report to the division engineer in St. Louis, Lieutenant Colonel George R. Spalding, who forwarded the report on to his superiors in Washington with an addendum. Spalding disagreed with Young's conclusions and suggested that test channel of 9-foot be constructed along the Missouri. Deakyne and the Board of Engineers agreed with Spalding.

In 1930, when James Good was succeeded by Patrick Hurley as secretary of war, the Hoover administration reinforced its support of the inland waterways system. Hurley further clarified though, that their support was limited to the system as a whole, rather than independent sections. This meant that until the Kansas City-to-the-mouth reach was finished the Upper River Project was not likely to receive significant funding. Additionally, there was not prospective financial support from the federal government for a channel depth of 9 feet.

To the dismay of Missouri Valley residents and politicians, in late 1930, Chief of Engineers Lytle Brown asked for an appropriation of only $800,000 to be spent on the Upper River Project. To remedy this, a group of prominent men from the Missouri Valley led by Arthur Weaver met with President Hoover in December 1930. The group requested $10M for channelization above Kansas City. While their requests were not met, the project did acquire over $2.5M by the end of the year. Unfortunately for those further up the river, these funds were almost exclusively used for work between Kansas City and St. Joseph. The following fall men of the Missouri River Navigation Association again traveled to Washington. This time the group, again led by Weaver, met with Hurley, the secretary or war, to request funds to spent at St. Joseph, Omaha, and Sioux City. Their requests were not met and the War Department requested only $1.4M of congressional appropriations for the Upper River Project. Again disappointed, in December 1931, representatives from the Missouri Valley again met with President Hoover with Weaver as their spokesman. By the end of the 1932 fiscal year, only $1.1M had been allocated to the Upper River Project.

Channelization between the mouth and Kansas City, on the other hand, remained well funded. In the four years from 1929 to 1932 to project was given an average of almost $12M per year. While the channelization techniques were, for the most part, the same as in previous years, the Corps had modified its pile dike construction. Willow curtains were no longer employed in the dikes. Instead, clusters of piles replaced single piles. The structure was made by attaching the clusters to a horizontal pile with wire. This modification facilitated siltation.

As a result of the increased funding for channelization downstream of Kansas City the years from 1929 to 1932 saw 10,000 to 13,000 men annually being employed on the river by both the Corps and private contractors. In 1929, channelization efforts used 56 pile drivers at once. Pile drivers were only removed from the work out of necessity, for oiling or repair. In 1930the number of pile drivers increased to 72. Schneiers (1999) writes that the laborers "slept on government quarterboats that lined the riverbank near a construction site." The work followed the natural schedule of the river. Schneiders (1999) continues, "During the months of March, April, and May… the engineers pushed the construction of pile dikes, with the goal of having the dikes in place before the start of the June Rise." Due to the incredibly high suspended sediment content contained in the summer rise some dikes were able to be completely covered after a single rise. Additionally, the focused flow scoured the bed, deepening the channel to the desired 6-foot depth. Following the summer rise, once water levels had reduced, the Corps focused their efforts on revetments. The winter months saw a decrease in work as the temperatures dropped and hazards increased. Work during these months was usually confined to repairs or reinforcements on existing structures. By 1932 the Corps estimated that channelization had been achieved on 95% of the river downstream of Kansas City.

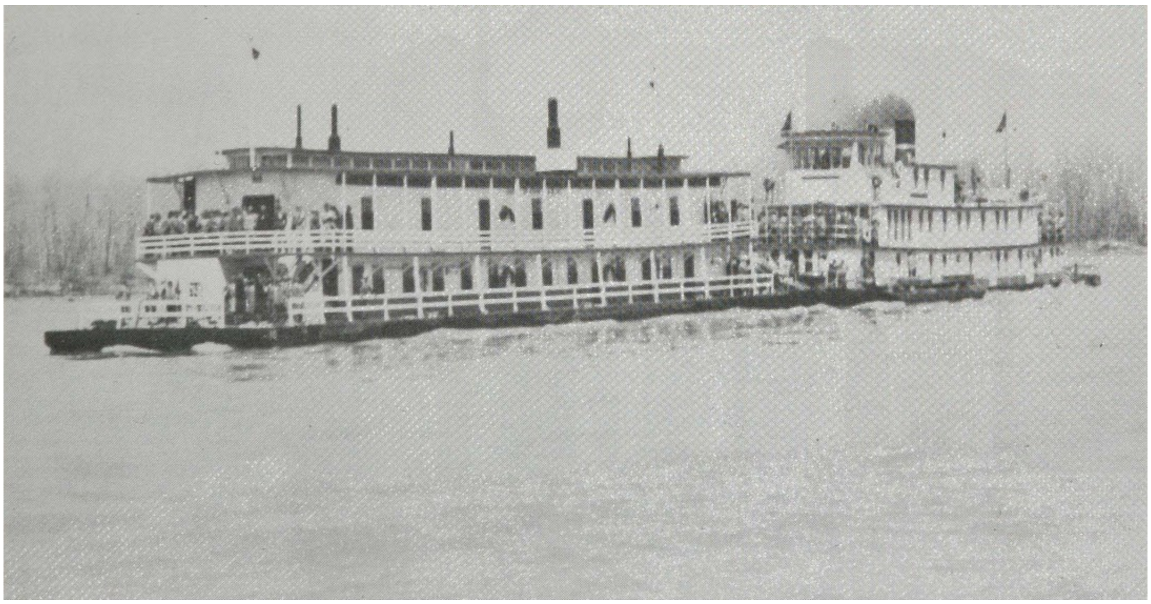


Figure 23 - A 1930s Quarterboat (Branyan 1974)

In summer 1932 Secretary of War Hurley, along with other prominent men including the chairman of the Inland Waterways Corporation, the division engineer of the Upper Mississippi Valley Division, and the new district engineer at the Kansas City District, traveled from the mouth of the Missouri to Kansas City. Hurley's expedition was partly to inspect the six-foot navigation channel that was almost completed and partly to promote Hoover in the forthcoming presidential election. Upon landing in Kansas City without any problems on the river, Hurley exclaimed, "The Missouri River between Kansas City and St. Louis has been conquered by engineers." Hurley and his party, without realizing it, only made it up the channelized reach as a result of the June rise.

After the rise passed so did the river's ability to be navigated by barge. Instead of 1932 bringing a resurge in freight traffic on the river the Missouri Valley suffered through the throes of drought and economic depression.

Hoover lost the 1932 election to Franklin D. Roosevelt. With a promise of a "new deal" Missouri Valley residents were unsure what this meant for their once thriving artery. During his first "fireside chat," Roosevelt spoke at length about his plan for work in the Tennessee Valley, employing thousands and building dams, explicitly referring to it as a "forerunner of similar projects".

As mentioned before, it became clear to the Corps by early 1930s, that if a navigable water depth was going to be maintained in the Missouri River channel then flow rates would have to be modified. This led to Public-Works Project Number 30, approved in October 1933; the Fort Peck Dam.

By the time construction began for Fort Peck Dam in fall 1933, construction for the navigation channel downstream of Sioux City was well under way. With a labor force of 4,000 men, by June the Upper River Project had nearly been completed as far north as St. Joseph. In fall 1934 the Corps had used the $3.6M allocated it and completed the six-foot navigation channel downstream of Kansas City. If February 1935, after all the funds for the Upper River Project had been spent, Missouri River Navigation Association members traveled to Washington for the purpose of acquiring additional funds. The group, led by Arthur Weaver of Falls City, Nebraska, requested an appropriation of $35M to complete the six-foot channel as far north as Sioux City. When May came and no funds had been allocated yet, Weaver again traveled to Washington and by the middle of the month Ickes had allocated $10M for the Upper River Project. While not enough to complete channelization to Sioux City, the funds were sufficient to complete work as far as Omaha. Despite not receiving the volume of funds requested the project moved forward and by May 1939 the fist barge had docked in Omaha having traveled up the channelized river on the spring rise. Following this the Corps was able to focus its efforts on the reach between Omaha and Sioux City.

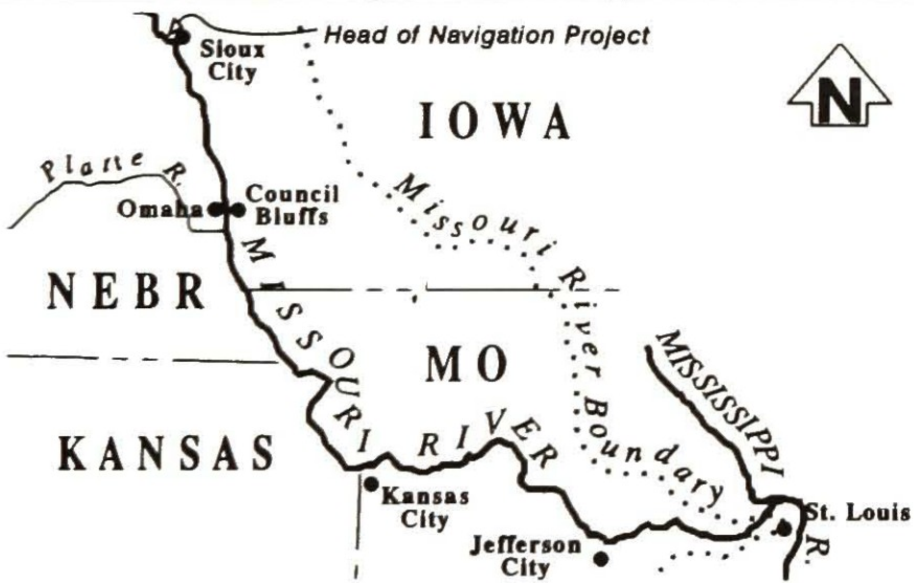


Figure 24 - Missouri River Navigation Channel (Ferrell 1993)

South of Sioux City the Missouri River Valley broadens dramatically. That, and the fact that the valley floor consisted of highly erodible alluvial sediments, caused the Missouri to not only widen but to have large bends. This exacerbated channelization efforts for the reach. The methods of construction imposed on this section were similar to the techniques used in downstream sections with one exception. Due to the increase in channel width, the length of pile dikes was also increased. Additionally by this time the Corps had been constructing their mattresses out of lumber instead of the willow mattresses common in earlier times. Snag removal and timber-clearing also accompanied the building of dikes and revetment. In fact, an arguably greater number of snags were removed from the river than those that were taken out during the steamboat era of the nineteenth century.

In June 1940 the navigation channel was considered practically completed, save a few difficult bends, from Omaha to Sioux City. At the end of a the month a towboat owned by Mobil Oil Corporation made its way up the channel to Sioux City as a crowd of several thousand gathered to witness the historic event. Unfortunately, the vessel encountered a shoal within sight of the dock and was unable to free itself. Government boats were required to release the boat before it made its arrival at port.

Although construction of the navigation channel had practically been completed, environmental and economic circumstances conspired to keep the Missouri free from regular transportation. With the prolonged drought the river was unable to maintain a channel deep enough to insure barge traffic. Grounding on shoals and sand bars was too common and breaking bulk to decrease draft was too expensive. Additionally, the Great Depression had at the least discouraged, and at the most prohibited, the instigation of commercial travel due to the financial risks associated with the highly variable river. The onset of war in Europe and Asia in the early 1940s, as well, caused federal appropriations to be shifted away from river development.

Prior to the flood of 1952, funding for Gavins Point and Oahe Dams were substantially reduced, in order to allocate additional funds to the war in Korea. Following the flood, however, interest was renewed in the necessity of flow control structures on the main-stem Missouri. It was relatively easy for General Lewis Pick and Colonel Henry J. Hoeffer of the Omaha District to convince politicians that a main-stem system of reservoirs could have, not only lessened the flooding, but prevented it altogether. Additionally, in July 1952 Fort Randall Dam was closed and the river's flow began filling the coursing through the structure's outlet tunnels. The Corps' aim was to complete the dam to the point of being able to curb any potential flood the following year. Schneiders (1999) records, "In November Fort Randall's reservoir began to fill, achieving a depth of thirty-five feet at the dam face by spring 1953 and stretching approximately twenty-three miles upstream."

In the mid-1950s, after closure of Fort Randall Dam, work was able to recommence repairing and completing the navigation channel downstream of Sioux City. During the channelization work of the 1920s and 1930s the Corps employed thousands of men doing hard manual labor to complete navigation structures. With the more favorable economic climate of the 1950s and 1960s the Corps used heavy equipment and technology to complete channelization construction. Furthermore, the objectives of the training structures had somewhat changed. Although a navigable barge channel remained significant, the importance of bank stabilization became just as essential.

Also affecting construction was the closing of dams on the Missouri main-stem. These lateral obstructions significantly reduced the sediment content traveling downstream. As a result of the decreased sediment content as well as the additional objectives, channelization techniques and structures had to be altered and to that end the Corps employed the use of toe trench revetments, large amounts of stone, pile dikes, and the pilot canal. The newer channelization techniques were additionally desirable because their effects were quickly felt, as realignment could occur in a matter of days or less.

The power wielded by the Corps reached its height in 1955 with the redirecting of the Missouri to flow under the Decatur Bridge. The bridge had been completed in 1951 500 feet west of the actual channel. The Burt County Bridge Commission was permitted by the Corps to construct the bridge only if it was built over the future channel. The bridge sat completed with no water underneath from 1951 until 1955 when the Corps began its diversion of the river. In July 1955 the Corps orchestrated a significant decrease in flow from Fort Randall Dam in order to close Gavins Point Dam and complete the diversion at the Decatur Dry Land Bridge. Through use of pile dike revetments the Corps framed a pilot channel. When the low flow from the decrease in dam release reached the bridge, the Corps removed the plug and river began to adapt, shifting its position to the pilot channel.

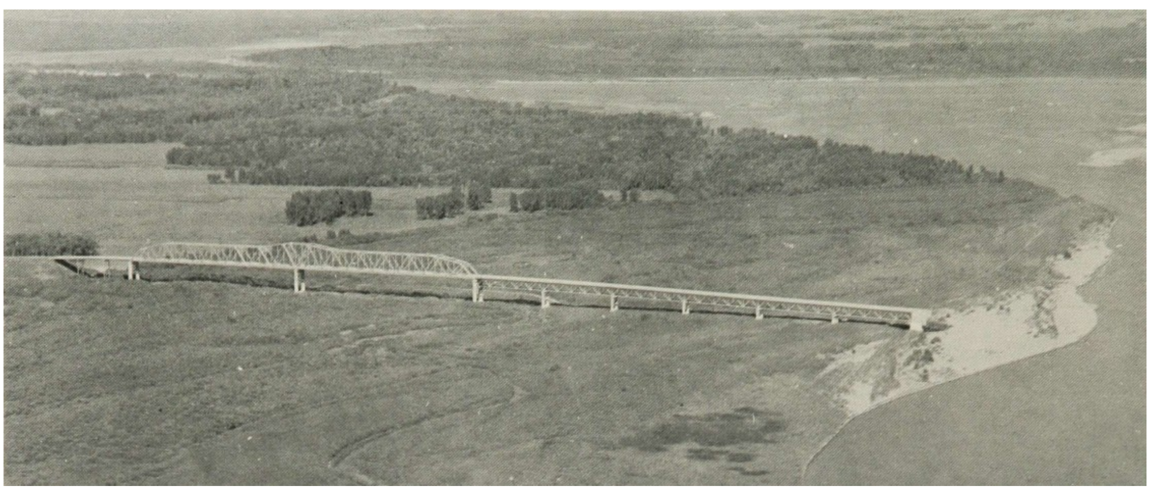


Figure 25 - Decatur Dry Land Bridge (Corps of Engineers 1985)

Unfortunately, even with the completion of the 9-foot navigation channel from Sioux City to the mouth, the Missouri River has seen nowhere near the amount of commercial barge traffic that was anticipated. The railroad remains a competitor to river transportation. Furthermore, the cost of moving freight on the Missouri is 55% higher than the cost of barging on the Upper Mississippi River. Nevertheless, the training structures are maintained even though, as Baumel and Van Der Kamp (2003) note, "The public cost of providing navigation on the Missouri River exceeds the benefits to shippers."

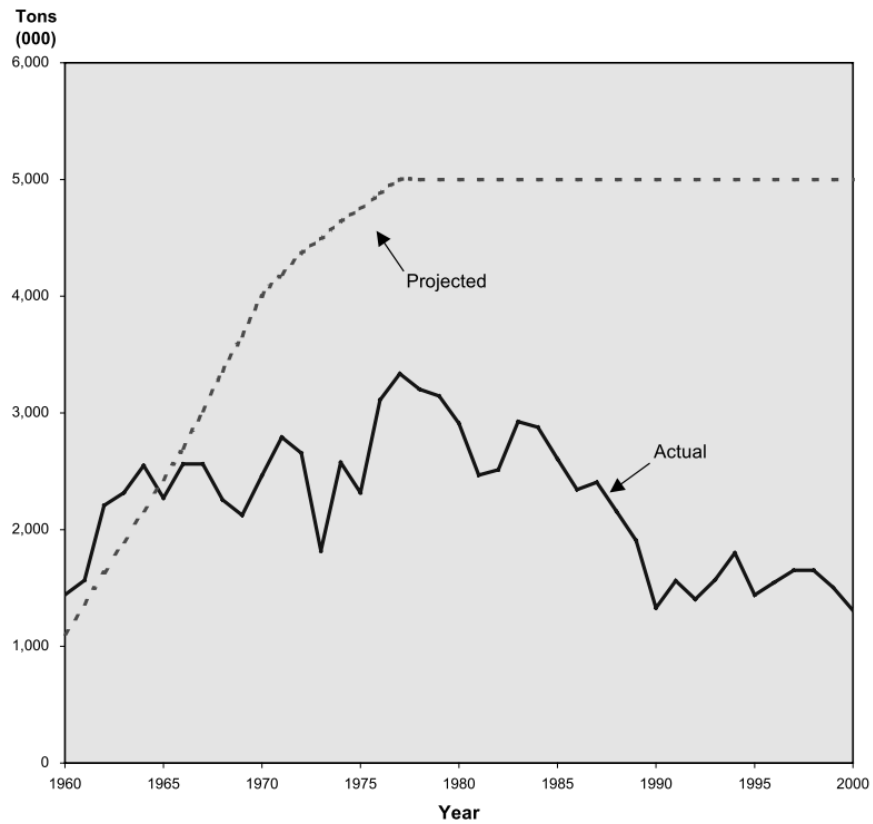


Figure 26 - Commerical barge Traffic on the Missouri, 1960-2000
(Baumel and Van Der Kamp 2003)

Despite the fact that channelization work had been occurring on the Missouri since the late nineteenth century, by the 1950s the channel still acted relatively independently from training works, meandering and eroding its own path. Although, by the 2000s Bruce Babbitt (2005), former Secretary of the Interior, was able to call it a "dead snake, rigid, unable to move, constricted by the levees along its banks." Sayre and Kennedy (1978) write that the Missouri River, just as before large-scale channelization and regulations actions, continues to be a “dynamic system which responds in complex ways to both natural and man-induced changes in its inputs (water and sediment discharges) and boundaries.” This dynamic aspect though, is no longer manifested through a lateral-shifting, meandering channel. Instead, the river’s power is applied to the bed through dynamic incision.

Pemberton and Lara (1984) note that degradation “occurs in any moveable river but is more severe when associated with restrictions in river widths.” There are many natural features of a river inherit to meandering that may cause constrictions. Man-made structures as well, contribute to width restriction. Some of the anthropogenic constrictions recorded by Pemberton and Lara include, “spur dikes, groins, riprapped banks, or bridge abutments used to control main channel movement.” Simon and Rinaldi (2006), likewise state that channelization efforts aiming to, “(1) reducing flood magnitude and frequency, (2) improving navigation, (3) controlling bank erosion, (4) relocating for infrastructure construction… can represent a direct, drastic form of anthropogenic disturbance to a fluvial system.” Channelization makes use of training structures, generally termed dikes and revetments. Thomas and Watt (1913) define dikes as, “The structures used for guiding a stream by confining and directing the water at bars or shoals, and for closing secondary arms of a river.” Derrick, Gernand, and Crutchfield (1989), also provides a definition for dike:

> A structure extending outward from the bank toward the channel normal to or at an angle to the flow of the river. The purpose is to redirect or confine the main streamflow to increase navigation depth and/or prevent bank scour. Other names used: groin, cross dike, spur dike, spur dam, cross dam, wing dam, spur, and jetty.

The structures have been used on the Missouri River to direct flow and provide bank stabilization, not only to decrease channel width but to assist in reorienting the river for bend cutoffs as well.

Dikes and Revetments

As of 1989 there were 3,560 dikes in the Missouri River from Rulo, Nebraska to the mouth, the area managed by the Kansas City District (Derrick, Gernand and Crutchfield 1989). Dikes have the effect of constricted the active width of the channel, thereby increasing its velocity. The heightened velocity then deepens the channel. Significant amounts of local scour due to turbulence are also common around dikes.

Copeland (1983) notes that, "On the Missouri River, dikes are generally oriented downstream with an angle of 75°". Although, he additionally says, "The effective length (projection normal to the current) apparently is a more significant factor than the spur dike angle in providing bank protection."

There are three principal types of dikes that have been employed by the Corps of Engineers. The pile dike, the first kind of dike used to channelize the Missouri in the latter part of the nineteenth century, is defined by Derrick et al. (1989) as:

> A permeable structure built of from one to five rows of piles or clumps usually angled normal to river flow. Designed to reduce the water velocity as streamflow passes through the dike so that sediment deposition occurs, mostly downstream of the dike. This causes the main channel to carry a larger proportion of the water, thereby increasing currents and sediment transport capacity.

The second type is the stone dike. They are impermeable and made from stone. Derrick et al. (1989) writes that they are, "Designed to direct flow away from the banks to increase navigation depths or to prevent bank erosion." The final type is the stone-filled pile dike, somewhat of a combination between the former two. Derrick et al. (1989) defines this type of dike as:

> (a) A damaged or deteriorated pile dike that has been repaired by dumping stone along its length to a specified elevation, usually midbank height. (b) A dike built in stages for reasons of economy. The piles are driven, the river deposits fill around the piles, and stone is dumped on top of the river fill. The piling enables the stones to stand on a steeper slope than the natural angle of repose for additional savings.

All three dike types are found on the Missouri river.

Dikes are often accompanied by revetments to provide additional bank stabilization. Shields, Cooper, and Testa (1995) estimate that of the Missouri River managed by the Corps' Kansas City District (Rulo, Nebraska to the mouth), approximately 60% of bankline is revetted. Revetments provide rigidity to banks that erodible alluvial sediments cannot. Consequently, the river can no longer erode its bank to meander within the valley. Sayre and Kennedy (1978) write, "Friable, easily eroded banks can contribute major quantities of sediment to a stream."

Sayre and Kennedy (1978) conclude that, "Among the foregoing factors which tend to alter the sediment-transport capacity of a stream, training structures and flow regulation are judged to be of primary and equal importance." The Corps of Engineers (2009b) additionally concede to the effect of training structures on degradation, saying "In reaches where material extraction results in a lower streambed, the streambed does not readily recover. This lack of recovery is consistent with the self-scouring design and function of the dikes/revetments."

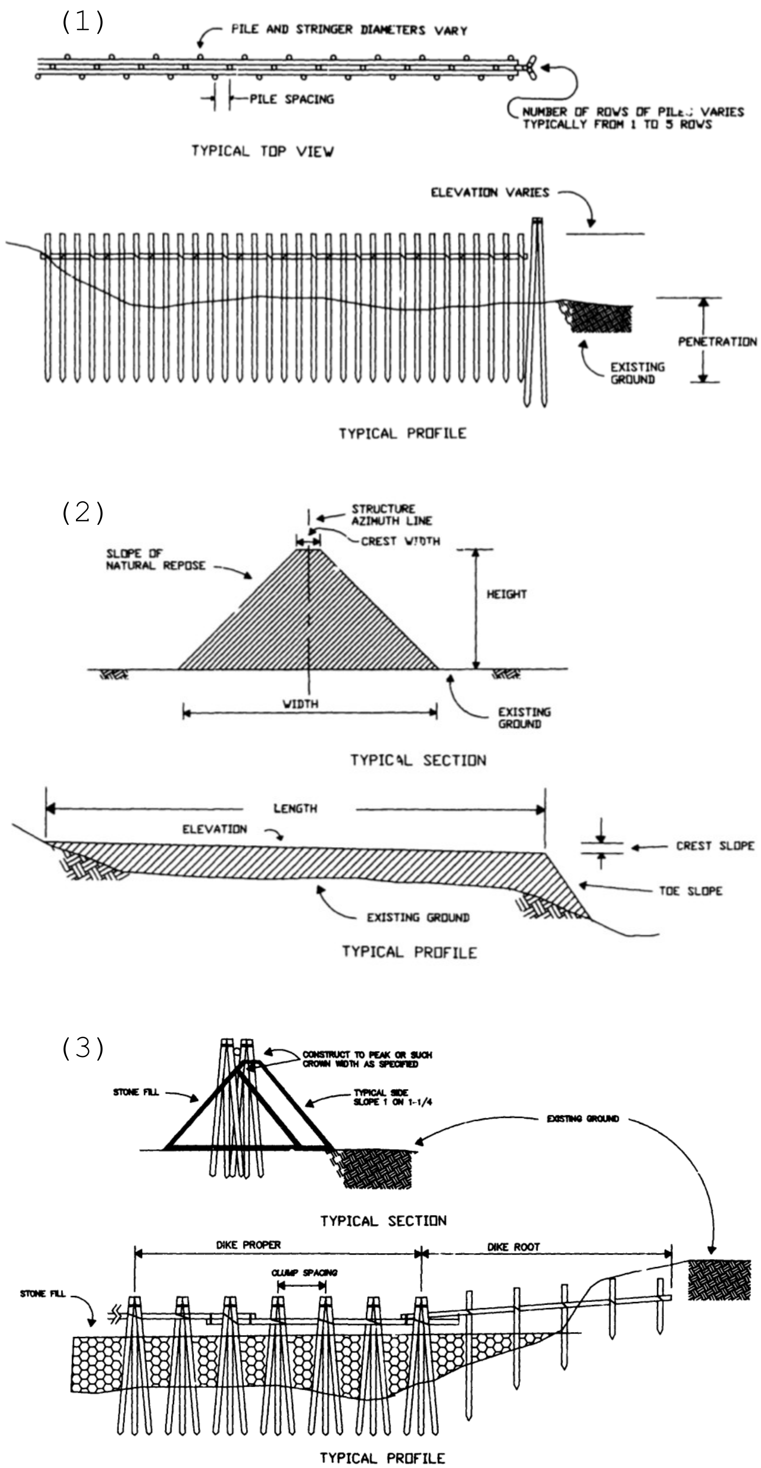


Figure 27 - Typical Dikes on the Missouri River: (1) Pile Dike; (2) Stone Dike; and (3) Stone-Filled Pile Dike (Derrick, Gernand and Crutchfield 1989)

Table 3 - Dikes in the Kansas City District, Missouri River Division based on 1985 Project Maps (Derrick, Gernand and Crutchfield 1989)

		Type of Dike		
	River Miles	**Stone**	**Pile**	**Stone-Filled Pile**
	498 to 490	10	10	27
	490 to 480	27	7	31
	480 to 470	35	3	33
	470 to 460	34	7	58
	460 to 450	24	10	41
	450 to 440	29	6	37
	440 to 430	22	9	42
	430 to 420	25	11	35
	420 to 410	27	15	31
	410 to 400	33	7	44
	400 to 390	35	9	27
	390 to 380	24	8	39
	380 to 370	17	8	19
	370 to 360	28	9	22
	360 to 350	16	13	38
	350 to 340	20	11	52
	340 to 330	35	21	30
	330 to 320	17	20	35
	320 to 310	17	26	32
	310 to 300	20	13	34
	300 to 290	29	13	26
	290 to 280	16	17	30
From Rulo, NE	280 to 270	24	19	24
to the mouth	270 to 260	23	16	48
	260 to 250	31	10	34
	250 to 240	27	16	22
	240 to 230	26	16	28
	230 to 220	21	10	43
	220 to 210	42	3	17
	210 to 200	40	10	21
	200 to 190	31	15	30
	190 to 180	24	16	39
	180 to 170	30	15	28
	170 to 160	28	3	18
	160 to 150	20	7	39
	150 to 140	40	11	30
	140 to 130	23	28	35
	130 to 120	24	16	26
	120 to 110	33	6	23
	110 to 100	29	13	32
	100 to 90	39	10	20
	90 to 80	41	5	27
	80 to 70	23	18	33
	70 to 60	15	15	39
	60 to 50	16	9	27
	50 to 40	23	10	41
	40 to 30	31	18	28
	30 to 20	30	7	34
	20 to 10	34	13	35
	10 to 0	23	12	45
	Totals	**1331**	**600**	**1629**

Cutoffs

Simons and Şentürk (1992) define a cutoff as, “A natural or artificial channel that shortens the length of a stream; natural cutoffs may occur either across the neck of a meander loop (neck cutoffs) or across a point bar (chute cutoffs).” Cutoffs, common to channelization efforts, are sometimes designed to aid in flood control or navigation purposes. Natural cutoffs occur as well, though, and are common on free flowing alluvial rivers.

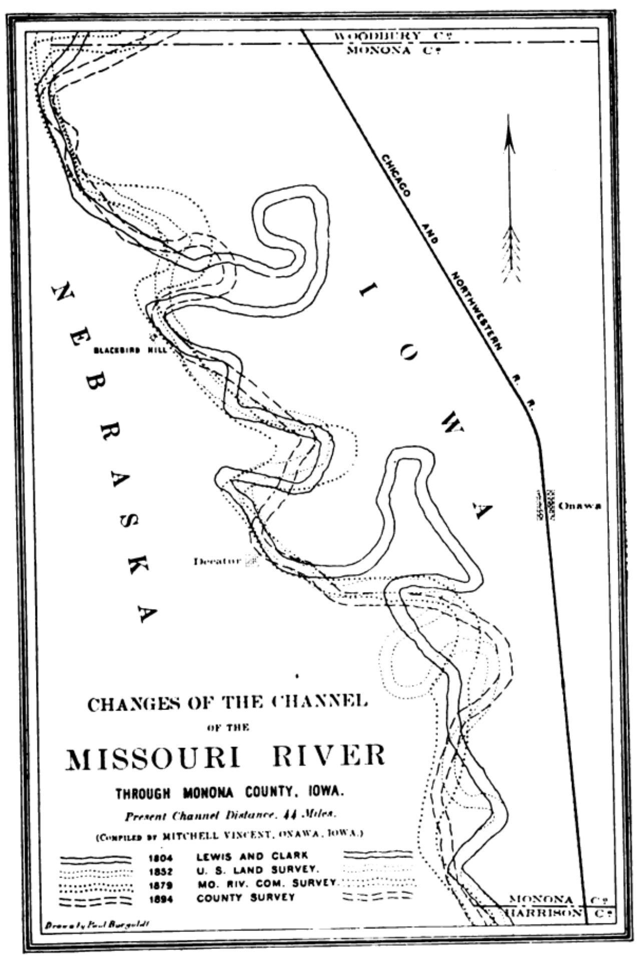


Figure 28 - Predevelopment Changes in the Missouri River Channel
(Chittenden 1903)

Prior to channelization, natural cutoffs were common the Missouri River. After a number of relatively dry years in the early 1800s, the heavy precipitation of the mid-1800s and the flood of 1844 in particular, caused a number of meander cutoffs. Additional floods that occurred prior to channelization, such as the flood of 1915, continued to reshape the river by naturally shortening its length.

Julien, Shah-Fairbank, and Kim (2008) note, "There are two types of natural cutoffs that occur. The first natural cutoff is a neck cut off… The second type is a chute cutoff." Neck cutoffs occur as the sinuousity of a meander increases. The river deposits sediment at its bank on the inside of the curve while simultaneously eroding material from its bank on the outside of the curve. If the process continues the channel will eventually cut through and the neck will disappear. An oxbow lake forms if the cutoff bend is sealed form the channel. Julien et al. (2008) describe that chute cutoffs occur "when successive high water flows develop a chute across the inside of point bar." Both types of natural cutoffs decrease the length and sinuousity of the stream while, at the same time, increasing its slope and sediment transport capacity.

As a part of channelization and flood control of the Missouri River and in order to facilitate barge traffic, a number of engineered cutoffs were made to eliminate long bends. A few specific cases of engineered cutoffs are further detailed, but the list presented is in no respective exhaustive. Numerous additional engineered cutoffs occurred at locations throughout channelization efforts, such as the aforementioned redirection that occurred at the Decatur Dry Land Bridge in 1955. Documented by Schneiders (1996) and the Corps of Engineers (1976) (1983), some of the engineered cutoffs made by the Omaha District in the 1950s and 1960s include Snyder, Winnebago, Tieville, Glover's Point, Omadi, Blackbird, Decatur, and Louisville Bends.

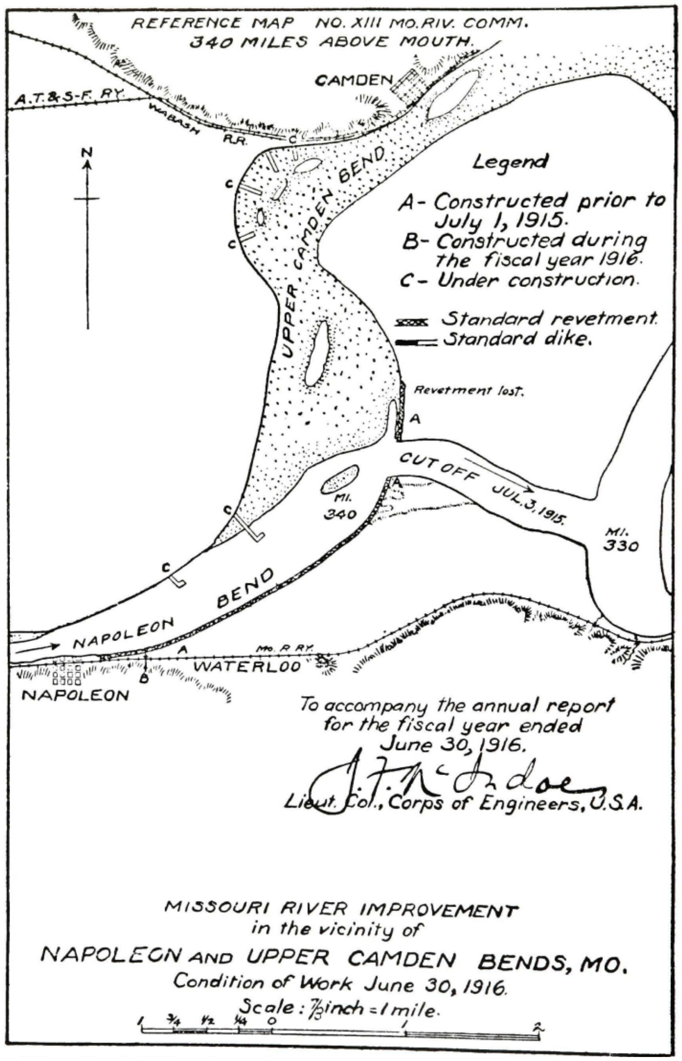


Figure 29 - Upper Camden Bend Cutoff (Branyan 1974)

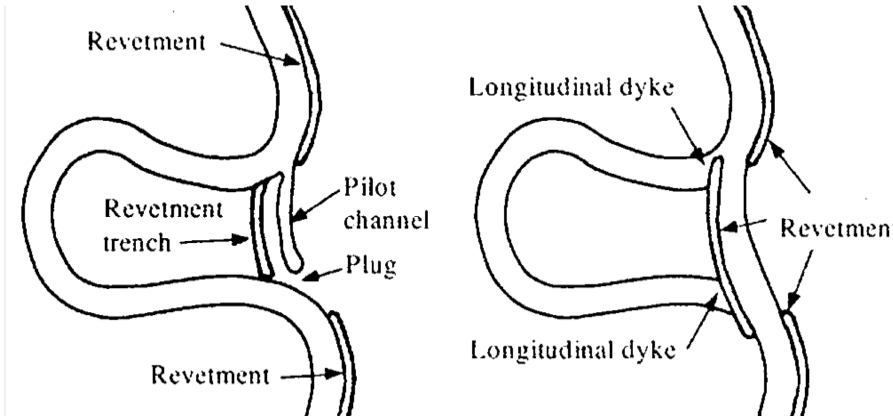


Figure 30 - Engineered Cutoff (Julien, Shah-Fairbank and Kim 2008)

Big Blue Bend Cutoff

In 1940 the Corps set out to soften the curve of a harsh turn in the river on the north edge of Jackson County, Missouri. Branyan (1974) writes, “a treacherous ninety degree turn with unpredictable currents, Big Blue Bend not only posed a danger for shipping, but made bank stabilization and flow control difficult as well.” As a result, the Corps planned a gentler bend to improve navigation and water level. Because of its close proximity to downtown Kansas City (only 8 miles downstream) the project garnered local interest, particularly with the *Kansas City Star*. The Corps had developed a new course for the river and in April 1940 the plug was removed allowing the river to make its way through the gentler wide, gentle bend.

Liberty Bend Cutoff

Another important bend in the Kansas City area, just downstream of where the Big Blue cutoff had occurred, was the Liberty Bend. Branyan records that, “A study had been authorized in 1939 and preliminary report presented in 1940, but no action was taken until after the war.” Although the primary goal of the 8 mile reduction was flood control, there were positive navigation aspects as well. In spring 1947, the Corps began construction of the cutoff. First, a bridge over the location of the new channel was constructed, then a cut was made at the Blue Mills Bend. Ferrell (1995) records, "The channel cuts were about 10 feet wide and 15 feet deep. The Engineers expected the river to scour out a channel about 1,000 feet wide." On 16 April 1949 the cutoff was opened and gained such national attention that the event was even covered by the *New York Times*.

As mentioned previously, a host of additional cutoffs were made along the river for the purpose of both flood control and navigation. These cutoffs served to reduce the length of the river, increasing both the slope and the sediment transport capacity. Branyan (1974) notes that, "In the years after completion [of the Liberty Bend Cutoff] it scoured even more river bottom and worked further upstream than expected."

Table 4 - Changes in distances between locations on the Lower Missouri River (Cardno ENTRIX 2011)

	Missouri River Length between Locations (miles)			1890–1960 Change in Length	
Locations	**1890**	**1941**	**1960**	**Miles**	**Percent**
Sioux City to Omaha	147.7	128.0	116.4	-31.3	-21.2
Omaha to Nebraska City	52.1	52.7	54.0	1.9	3.6
Nebraska City to St. Joseph	129.0	119.3	114.0	-15.0	-11.6
St. Joseph to Kansas City	88.0	82.5	81.8	-6.2	-7.1
Kansas City to Waverly	91.5	80.3	72.7	-18.8	-20.5
Waverly to Boonville	93.8	101.0	96.8	3.0	3.2
Boonville to Hermann	101.9	99.3	98.7	-3.2	-3.1
Hermann to mouth	103.5	96.9	97.9	-5.6	-5.4
Total (Sioux City to mouth)	**807.5**	**760.0**	**732.3**	**-75.2**	**-9.3**

Sayre and Kennedy (1978) write that changes in slope "due to shortening by cut-offs and straightening increases the velocity and sediment-transport capacity of the river, which leads to a reach of degradation which generally propagates upstream as a head cut." With the extensive amount of channelization that has occurred on the Missouri River, its length has been significantly reduced. Richardson and Christian (1976) report, "the thalweg distance from Sioux City, Iowa to the confluence was decreased 75 miles (mile 807.5 in 1890 to mile 732.3 in 1960)." The Corps of Engineers (2009b) concludes, "Cutoffs have contributed to degradation in certain reaches of the Missouri River."

Flood Events

The impact that flooding can have on the morphology of river system is evident through a survey of the changes made in the Missouri River prior to development. The effects of flood, though, are accelerated due to human development. Levees, for example, focus the flood waters to the main channel rather than allowing the increased flow to spread out across the river's floodplain.

Historical Flooding

The Missouri River Valley has experienced a number of significant flood events since large numbers of Euro-American settlers occupied the region beginning in the early nineteenth century. Even though large scale reservoirs with a purpose of flood control were completed in the 1960s, major flood events since that time, and especially in the last couple decades, show their ineffectiveness to prevent significant flooding downstream, particularly on the lower river. A summarization of select major flood events is presented, although the list is by no means exhaustive or all inclusive.

Table 5 - Selected major floods on the Missouri River at Kansas City, MO
(Fishel, Searcy and Rainwater 1963)

Date	Gage height (feet)	Elevation above mean sea level (feet)
June 16, 1844	38.0	753.8
Apr. 30, 1881	26.3	742.1
June 1, 2, 1903	35.0	750.8
July 8, 1904	25.2	741.0
June 15, 1908	30.2	746.0
July 13, 1909	27.0	742.8
July 21, 1915	29.0	744.8
June 9, 1917	26.5	742.3
June 18, 1943	29.10	744.89
Apr. 24, 1944	27.67	743.46
June 18, 1945	25.30	741.09
June 25, 1947	27.01	742.80
July 14, 1951	36.2	752.0
Apr. 24, 1952	30.63	746.42

1844

Although no official records are available, the flood of 1844 is widely accepted as the greatest known flood on the lower Missouri River. Ferrell (1993) writes, "[T]he river in flood is estimated to have discharged 900,000 cubic feet per second at its mouth." Following a significant period of low precipitation in the previous years, causing the river to form large bends and meanders, the increased flow that occurred in 1844 severed the bends, making numerous natural cutoffs as the river exerted its full power on its own banks. Subsequent times of high flow had similar effect, such as a significant flood event that occurred in 1857, although later floods were exacerbated due to width restrictions imposed by channelization and levees.

1881

Just a month after Major Charles Suter presented his report on the viability of a navigation channel in the Missouri to Congress the flood of 1881 was being fully felt, although the flood itself began the previous fall. In October of 1880 the Midwest was pummeled with winter storms and record-breaking low temperatures. As spring began the temperatures rose and the frozen river began moving at Fort Buford. A Corps of Engineers (1985) publication writes, “Below Yankton, Dakota Territory, no January thaw occurred. The ground remained frozen solid and the ice in the river became 50 inches thick. The melted snow accumulated behind ice dams… One such obstruction extended for 15 miles.”

Warmer weather in March contributed to the breaking of a massive ice gorge. Although still overlain by solid ice the river moved downstream plowing through its path each sheet of ice that lay in front of it. As the river made its course through to warmer weather downstream the river continued to swell as rain commenced and rising temperatures melted snow cover. In the introduction to Stanely Vestal’s *The Missouri* (1996), Dayton Duncan describes the immense power contained by the Missouri in winter:

> Huge sheets of ice floated past – a silent armada heading downstream as if on some deadly serious mission. I was awestruck by their quiet majesty, the great inexorable force of nature they revealed. Nothing, it seemed could stop something so powerful.

Indeed, such a force is not easily stopped. The destructive power of the river in the winter of 1880-1881 hit hardest in the Dakota Territory communities of Yankton, Green Island, Gayville, Meckling, Vermillion, Burbank, and Elk Point, although significant damage occurred all along the river valley (Schneiders, Unruly River: Two Centuries of Change Along the Missouri 1999). The figure below shows the extremely high water level experienced in Omaha, Nebraska.

Figure 31 - 1881 Flood in Omaha (Omaha Public Library 2002)

The sudden rise in river level coupled with high winds, a spring blizzard, and dropping temperatures made the event extremely dangerous. Fortunately, human deaths seem to have been kept rather low (an estimated 15 people in the valley from Yankton to Sioux City). Livestock casualties, on the other hand, were immense in number. 50,000 head of cattle perished according to an estimate by the *Sioux City Journal*. Other property damage was vast as well, with the city of Green Island only having one surviving building. Additionally, flood waters remained high midway through the summer, slowing transportation in the valley as well as preventing farmers from planting crops.

The 1881 flood further contributed to the accelerating view of the Missouri as a force in need of improvements. No longer was the river seen as the main artery of civilization in the valley but as a nuisance, endangering the agricultural lands of valley farmers. Valley residents became increasingly aware of the danger imposed on their communities as the Missouri experienced its biannual rises. Those with their hand in the steamboat business, who saw their boats ravaged by the rivers power, saw in channelization the opportunity to regain losses due, not only to flooding, but railroad competition as well.

1903

Just one year after Congress had eliminated the Missouri River Commission a 100-year flood event revived channelization interests. The great flood of 1903 was due to a combination of the Missouri's annual rise and heavy precipitation throughout the Midwest. Schneiders (1999) records that, "five to fifteen inches of rain fell in May 1903 in the Kaw River basin west of Kansas City and in the area to the north of it encompassing southeastern Nebraska, southwestern Iowa, northeastern Kansas, and northwestern Missouri." When the runoff from the rain filled the Kaw it recorded the second-highest level experienced by European-Americans. Due to the already swelled level of the Missouri from to the summer rise, when the additional flow from the Kaw reached the confluence both Kansas City, Kansas and Missouri were inundated with the influx. Schneiders comments, "Of seventeen bridges across the Kaw in the Kansas City area, sixteen washed downstream." The Missouri's flow on 1 June 1903, nearly 550,000 cubic feet per second (cfs), was almost three and half times greater than the historical average flow during the month of June. 22,000 people were left homeless as a direct result of flooding.

This rare natural occurrence strengthened the diminished emphasis on the need for improvements on the Missouri River. Engineers and valley residents both supposed that the effects of the flood were exacerbated by the widening, slow moving river. Had the Missouri River's channel been straight with a higher velocity, they reckoned, floods would move through communities much quicker. Consequently, just days after the flood had receded, Captain Hiram Chittenden, a Corps of Engineers officer in Sioux City, recommended for Kansas City, Missouri Mayor James A. Reed and other officials from Kansas City to request that Congress reestablish Missouri River channelization. Only this time the channelization would not be for the purpose of fostering barge traffic, but for flood control and protection.

1943

The year of 1943 was a definitive time for Missouri River development. During this year the valley experienced three significant flood events. The first began in late March. As temperatures rapidly increased in the upper Midwest, the snow melt quickly as well, and without having time to soak through the soils or evaporate, the melted water became runoff, filling the Missouri and its tributaries. The swollen Missouri made its way down the valley being further increased by large tributaries such as the James and Big Sioux Rivers. As the river traversed its course east and south it broke dikes and levees inundating communities and agricultural lands along the way. North and South Dakota were hit first, but the most severe flooding occurred between Yankton and Omaha. All told the first flood covered 700,000 acres, leaving damages estimated to be $8M.

A second event, occurring in May, was caused by significant rains that fell in the basins of the Grand, Gasconade, and Osage Rivers. The only affected reach of the Missouri Valley was the lowest 140 miles above the mouth, but the impact was considerable. Surpassing the level of the superflood of 1844 this rise caused 540,000 acres of agricultural land to be inundated.

Figure 32 - 1943 Flood in Bismarck, North Dakota (Ferrell 1993)

The third flood event of 1943 can be attributed to two climatic events. First, by June the temperatures had raised to levels sufficient to melt the snow in the basins regions at higher elevations. This snowmelt drained into the Yellowstone River, below Fort Peck Dam beginning a sufficiently large June rise. As the rise was making its way down the Nebraska-Iowa border the second factor occurred. The lower Midwest, particularly Kansas and Missouri, were plagued with a series of heavy thunderstorms. Flooding was similar to the events of the 1903 flood, as the Kaw River's elevated flow reached the already swollen Missouri at Kansas City. The third deluge covered 960,000 of agricultural land between St. Joseph and mouth, bringing the total farmland area inundated from the spring/summer floods to around 1.8M acres. It was estimated that the three combined events caused damage equaling $47.3M.

Further aggravating the effects of flooding was the US involvement in World War II. The rising flood waters closed railroads and disrupted river traffic. Furthermore, the farmlands that remained inundated were prevented from yielding necessary crops to supply American soldiers in Europe and Asia. The floods, Schneiders (1999) writes, "damaged military installations, delayed the training of troops, and required the diversion of supplies and equipment slated for the war front to the flood zone."

The floods of 1943 caused a significant shift in public opinion of the river and consequently spurred the developments that would be implemented later that year. While residents and representatives of the northern basin states of Montana and the Dakotas had been pushing for damming projects for a number of years, the lower states resisted, remembering the low flows of the 1930s. The states who had been working so hard for a navigation channel were worried that water required to maintain the required depth, would be withheld in the reservoirs. After the 1943 floods, though, residents in states of the lower basin changed their tune, realizing that a dam-building program might be the only way to protect their farms and communities from the chronic flooding. Furthermore, the floods wreaked havoc on the training structures that channelized the river putting their beloved navigation channel in jeopardy (Schneiders, Unruly River: Two Centuries of Change Along the Missouri 1999).

1952

The winter of 1951-1952 proved to be harshest winter for the Great Plains than had ever been experienced since the region was settled by European-Americans. Over two foot of snow dropped on Pierre, South Dakota from 6 to 21 December. Sustained frigid winds made it impossible to keep roads cleared as it drifted back onto newly plowed sections. Moreover, in January 1952, when Corps officials traveled into the mountains to measure the snowpack, their measurements indicated snow with high moisture content at higher levels than any previously recorded. With the unusually high amounts of snowfall, Corps officials and meteorologists for the USGS warned valley citizens of the looming flood.

When spring came and temperatures rose the snowpack melted. Since the ground underneath remained frozen the melted snow had no opportunity to soak into the soils and instead drained to the upper Missouri's tributaries. Schneiders (1999) reports that significant flooding occurred on the Milk and Little Missouri Rivers and Beaver Creek, inundating communities along the way. When the flooded tributaries reached the Missouri, water levels soared. The flood coursed downstream swallowing cities in its path: Bismarck, North Dakota; Pierre and Chamberlain, South Dakota; South Sioux City, Nebraska. Amazingly, many of the cities in western Iowa were spared, although heavy damage was sustained on agricultural lands and farmsteads. At Omaha, Nebraska, the Corps ordered National Guard troops to use sandbags and a wooden fence to elevate the height of the levee from 31.5 to 34 feet. The efforts were rewarded when the structure held as a 30-foot crest passed Omaha on 17 April 1952. All told, the flood wreaked havoc totaling $179M in damages. Fortunately, though, no human lives were claimed.

The estimated monetary damage does not include the damage sustained on the constructed navigation channel downstream of Sioux City. As the flood water descended the river pile dikes and revetment were eroded, undermined, and outflanked. After 1944 the Corps had claimed that 687.3 miles of navigation channel were completed. Following the flood of 1952 only 511.4 miles remained intact. The damage wrought on channelization structures was so extensive, in part, because navigation channel construction on the northern part of the Upper River Project had begun before the flow regulating structures of the Pick-Sloan Plan were constructed.

1993

Although records remained unbroken, precipitation was higher than normal throughout winter 1993-1993 and spring 1993. The Corps of Engineers (1994) records, “A wet-weather pattern persisted over the upper Midwest for about six months.” Significant rainfall events were experienced throughout the summer as well, from June to August. A particular period in late July saw rainfall up to 13 inches throughout areas of Nebraska, Kansas, North Dakota, Missouri, and Iowa. As a result, “Portions of the Missouri River were above flood stage for several months.”

Figure 33 - 1993 Flood in Kansas City (Corps of Engineers 2009a)

Dams held back a portion of floodwaters resulting from rainfall and snowmelt throughout Montana and the Dakotas. Record amounts of runoff in the Missouri basin downstream of Omaha, though, rendered the main-stem reservoir system useless in preventing a flood in the lower river. Numerous levees were breached throughout the Missouri Valley. The Corps of Engineers (1994) reports that in the Omaha District, “13 of the federally constructed levees and 16 of the eligible [for the Public Law 84-99 Program] constructed levees were damaged, as were 137 of the over levees." Likewise the report states, "A total of 52 federal levees, all of the federal levees in the Kansas City District's area of responsibility, were damaged." With numerous other damages as well, the report records, "The flooding of the Mississippi and Missouri rivers resulted in the death of 47 people and caused between $15 and $20 billion in damage."

2011

Most recently the Missouri River rose out of its main channel to inundate its floodway in 2011. The Corps of Engineers (2012a) attributes the massive flooding to "record setting rainfall and snowmelt" that resulting in "approximately 49 million acre feet of runoff" during the spring and summer. "Despite valiant water regulation and flood fighting efforts, devastation and disruption were massive." The flood moved slowly through the valley. Some levees were overtopped, but nearly all were saturated for months beyond their intended loading, usually only a few days to weeks. "All told, the event caused moderate to extensive damage to roughly 75 federal levees (and many more non-federal levees) within the basin due to overtopping, erosion, and underseepage."

Due to high velocities contributable to width constrictions in the floodplain, the flood waters also caused extensive damage to training works in the river channel. The Corps of Engineers (2012a) records, "Recreation facilities, plant and wildlife habitat, and historic tribal sites along the river channel were also impacted by the force of the flood waters." The prolonged flood lasted from May to October, closing several bridges and hundreds of miles of railroad tracks. The incredible amounts of runoff led to record releases from Missouri's main-stem dams. The Corps of Engineers (2012a) recorded:

“65,900 cfs and Fort Peck; 150,000 cfs at Garrison; 160,000 cfs at Oahe; 166,000 cfs at Big Bend; 166,000 cfs at Fort Randall; and 160,000 cfs at Gavins Point.”

Figure 34 - 2011 Flood near Omaha (Corps of Engineers 2012a)

Levees

By the 1940s numerous levees constructed by private farmers and land owners had been built adjacent to the river, but as one Corps of Engineers (1947) publication stated, “These levees have been constructed in a piece-meal fashion, and in general provide partial and uncertain protection and increase the flood hazard in adjacent areas.” With the passing of the Flood Control Acts of 1932, 1941, 1944, though, the Corps of Engineers was given authority to construct levees and floodwalls in order to provide protection to communities and agricultural lands. The Flood Control Act of 1944 authorized the Pick-Sloan Plan, which in part was designed for flood control on the Missouri River, included construction of 1,500 miles of levees, lining either side of the river from Sioux City to the mouth (Reuss 2005). Pick recommended that the “levees be designed to have a 3-foot freeboard" and estimated a total cost of $65M (Corps of Engineers 1985).

Branyan (1974) reports that by the early 1970s, when the 9-foot navigation channel from Sioux City to the mouth had been completed, the Corps of Engineers had constructed about 20% of the levee projects, totaling approximately 200 miles of levee. In 2011 the Corps of Engineers claimed 144.2 miles of levee along the Missouri River below Rulo, Nebraska with additional non-federal levees located along the river as well (Cardno ENTRIX 2011).

Galay (1983) reports that intense flood events "may result in abnormal degradation… and extensive bank erosion is also not uncommon." Oftentimes, though, as the Corps of Engineers (2009b) points out, the short-term scour that occurs due to floods will recover. Although, at Kansas City they report that several feet may be eroded from the bed in a single flood event adding, "in some cases, even though the riverbed recovers most of the loss within a couple of years following the flood event, the riverbed fails to make a full recovery." The Great Flood of 1993, for example, caused an immediate bed lowering of 8 feet, but recovered to the point of a net loss of only 2 feet.

A Corps of Engineers (2012a) publication states, "Although levees protect property within the floodplain, they also reduce the flow area available for the passage of flood waters, resulting in higher and faster water flow during high water events." In turn, any effect that flooding alone might have on the erosive capabilities of the river is enhanced and the phenomena of degradation specifically is increased.

Table 6 - Federal levees on the Lower Missouri River (Cardno ENTRIX 2011)

Levee Unit[a]	River Mile	Areas Protected (acres)	Affected Population	Investment (2010 dollars)	Damages Prevented to Property through 2009 (dollars)
R-513-512	497.5–495	11,800	17	8,065,000	6,534,000
R-500	484.4–480	1,550	--	795,000	1,272,000
L-497	482.4–476.7	6,840	18	17,779,000	5,650,000
L-488	475.3–465.2	8,365	5	44,649,000	7,009,000
R-482	468.4–458	4,730	12	15,178,000	3,943,000
L-476	461.0–454.0	6,000	136	23,710,000	4,605,000
R-471-460	456.5–441.8	13,424	1,631	637,810,000	8,0085,000
L-455	445.6–437.6	7,519	3,838	1,594,126,000	179,084,000
L-448-443	437.6–428	18,080	48	80,771,000	17,922,000
R-440	431–424.3	4,100	--	250,000	4,681,000
L-408	401.3–391.5	9,595	219	29,850,000	10,112,000
L-400	391–385	9,595	6	21,140,000	4,331,000
Kansas City's seven levees[b]	374–354.0	153,000	23,124	18,793,000,000	5,783,116,000
L-385	372.1-375.9	1,566	731	460,382,000	Unknown
R-351	350–339.7	8,861	265	15,000,000	5,033,000
L-246	250–239	25,000	161	36,784,000	28,688,000
L-234/Lower Chariton	238.8–227.3	19,200	72	30,717,000	14,545,000
New Haven	81.7–81.4	15	15	10,847,000	19,114,000
Total	**144.2**	**309,240**	**30,298**	**21,820,853,000**	**6,175,724,000**

Note: -- = Not available.

[a] R and L refer to right and left descending banks, respectively. The number is the river mile at the center point of the levee at the time it was authorized. The river miles do not match up exactly now, because of river cutoffs constructed since the levee was authorized.

[b] Includes Fairfax-Jersey Creek, North Kansas City, Central Industrial District, East Bottoms, Birmingham, Armourdale, and Argentine Levee Units.

As has been mentioned previously, the consequences of flooding on the geomorphology of the Missouri River can be clearly seen throughout predevelopment flooding and its associated changes. The fact that the current river, though, now is confined, not only in its main channel by training works, but additionally in its floodplain by levee systems, causes the increased flow inherit to flood events to exert its erosive energy on the channel bed.

Dredging

Sayre and Kennedy (1978) write, "The process of dredging can cause a temporary increase in turbulence and a corresponding rise in the suspended-sediment discharge of a stream in the vicinity of the dredge." Galay (1983) notes, "The removal of part or all of the bed material results in a lower transport rate and therefore in slope flattening below the point of sediment removal." He additionally writes:

> The excavation of bed material, or gravel mining, leads to both upstream and downstream progressing degradation on the main river… Whenever the bed of a river is lowered significantly due to gravel mining, local water levels drop resulting in an M-2 backwater curve and subsequent upstream and downstream progressing degradation.

The effects of dredging, particularly in the Missouri River have been studied in great detail by Cardno ENTRIX, as a part of *Missouri River Commercial Dredging, Final Environmental Impact Statement* (2011). Additionally, the Corps of Engineers (1990) have conducted in depth studies regarding dredging effects on the Kansas River. It has been widely recognized that dredging causes significant disruptions to natural sediment processes in rivers. Although federal permits are required to engage in commercial dredging, the activity remains "prevalent in selected reaches of the lower 498 miles of the Missouri River and on the lower Kansas River" (Corps of Engineers 2009b).

Data displayed graphically in the illustration below suggests that the relationship between dredging and bed degradation are, at the very least, correlated. When one takes into account that "the rate of bed degradation in the Kansas City reach of the Missouri river has substantially increased since the mid-1990s" and "dredging taken from the Kansas City reach has more than doubled in that same time period," the activity appears to bear considerable responsibility for bed lowering.

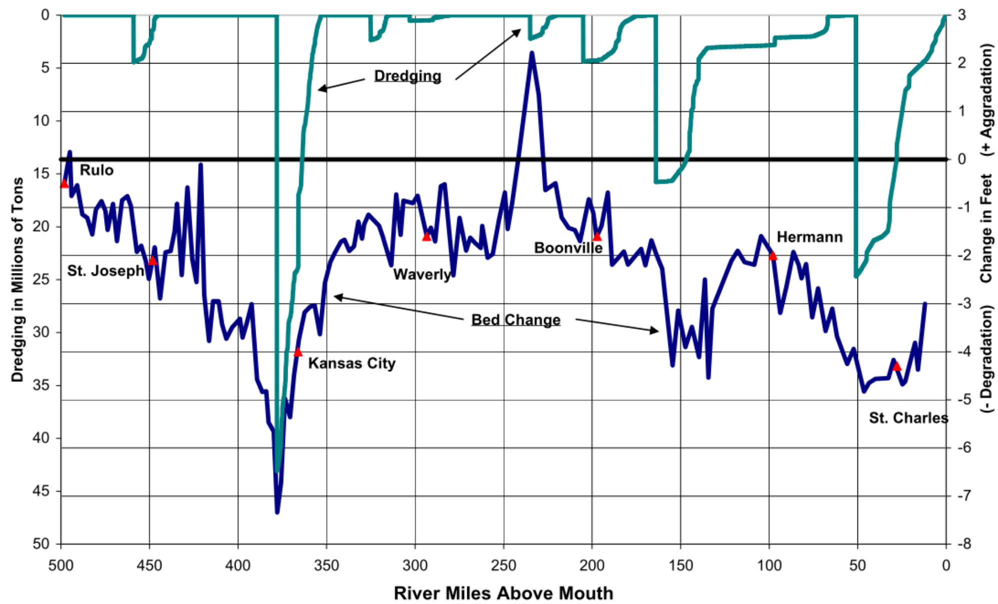


Figure 35 - Dredging Quantity and Change in Low Water Profile between 1990 and 2005 (Corps of Engineers 2009b)

Land-Use Change

Changes that occur in ground cover in the drainage basin of a river have a direct impact on the stream itself. Sayre and Kennedy (1978) write:

> It is well established that changes in watershed treatment can have significant effects on the rate at which sediment reaches a stream channel, the character of the sediment, and the temporal distribution of sediment supply to the river during and after a storm.

Deforestation coupled urbanization is definitely common in the Missouri River Basin. While the two subjects of land cover change are definitely related and oftentimes occur concurrently, they will be looked at separately, as each comes with its own effects. Changes in land cover in the Missouri River Valley at Bismarck, North Dakota are shown below. Note that deforestation as well as the agricultural growth and urbanization have occurred in the valley. It is also important to note that land-use changes such as deforestation and urbanization occur throughout the basin, not just in the river valley. The effects of land-use change on the hydrology, and consequently morphology, of streams in smaller basins has been documented at length by Booth (1990), Leopold (1972), and others.

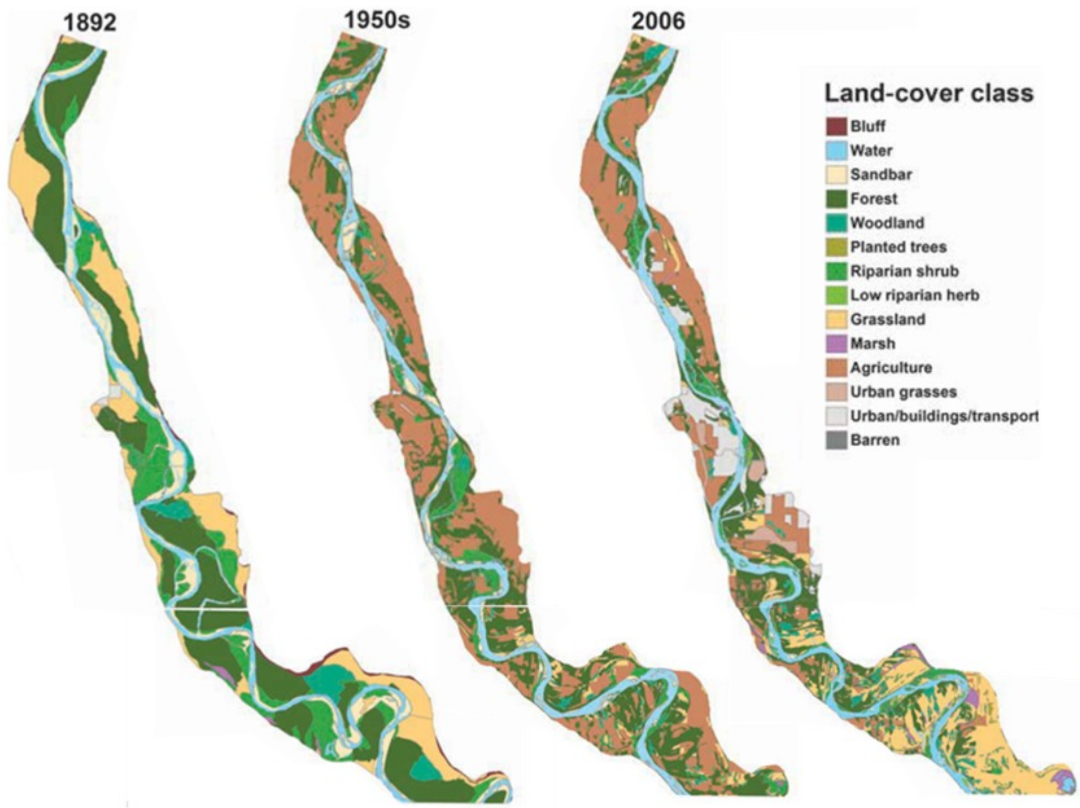


Figure 36 - Land-Use Change at Bismarck, North Dakota (Johnson, et al. 2012)

Deforestation

Intrinsic in development is deforestation. While timber for use as a building material certainly contributes to the removal of trees, more importantly, deforestation occurs so that the occupied land can be utilized for some other purpose. In addition to removal directly by humans Johnson et al. (2012) assert that dams, though their disruption of natural peak flows, also have contributed to deforestation. During rainfall events a significant portion of the rainfall is intercepted by tree cover. When the tree cover is removed the rain falls to the ground and is either carried overland as runoff or infiltrates the soils. Generally following deforestation a larger portion is drained as runoff as precipitation falls a faster rate than the water is able to filter through the ground soils. Kuchment (2004) notes, “As a consequence, flood runoff and peak discharges may significantly increase.”

In addition to rainfall, deforestation can affect the fate of precipitation in the form of snow. A large percentage of snow, like rain, is intercepted by tree cover. Research by Gelfan, Pomeroy, and Kuchment (2004) concluded that, “Average snow accumulation was 15% higher in the open catchment, largely due to a lack of intercepted snow sublimation.” Furthermore, due to the shade provided by tree cover, temperatures remain lower in areas that are forested. Gelfan et al. (2004) add, “Melt rates were 23% higher in the open than in the forest, but the effect on melt duration was suppressed by the smaller premelt accumulation in the forest.” La Frenierre (n.d.) reports, “Some studies suggest that stream discharge may increase as much as 50% as a result of deforestation.” But, as Kuchment (2004) includes, “Long-term observations have also shown the strong dependence of runoff volume on the type of vegetal cover.” A USGS (1998) report estimates that forest cover in the flood plain reduced from 76% in the 1800s to 13% in 1972, while the same period experienced an increase in agricultural lands from 18% to 83%.

Urbanization

Effects of deforestation are exacerbated when the cleared area is urbanized. Not only has interceptive vegetation and tree cover been removed, but pervious soils are replaced by impervious concrete or other manmade materials. Booth (1990) notes that, "Urbanization has an… impact on basin hydrology and channel form, by dramatically increasing the frequency of large flood flows." Obviously, river reaches that are directly adjacent to urban areas realize effects at a greater magnitude. Kuchment (2004) notices, "The rainfall runoff from urbanized areas is mainly generated as overland flow and reaches the river drainage system very quickly. Accordingly, the rainfall flood volumes may increase by several times, and the peaks of the hydrographs may increase by 10-15 times." Of course, there are many factors that affect the extent of the increase in runoff due to installation of impervious ground cover. Consequently, Guo (2007), states, "Using 5% imperviousness as the predevelopment condition, the 100-year peak discharge can be 2.8 times higher and the runoff volume can be 1.4 times higher when the watershed imperviousness increases to 60%."

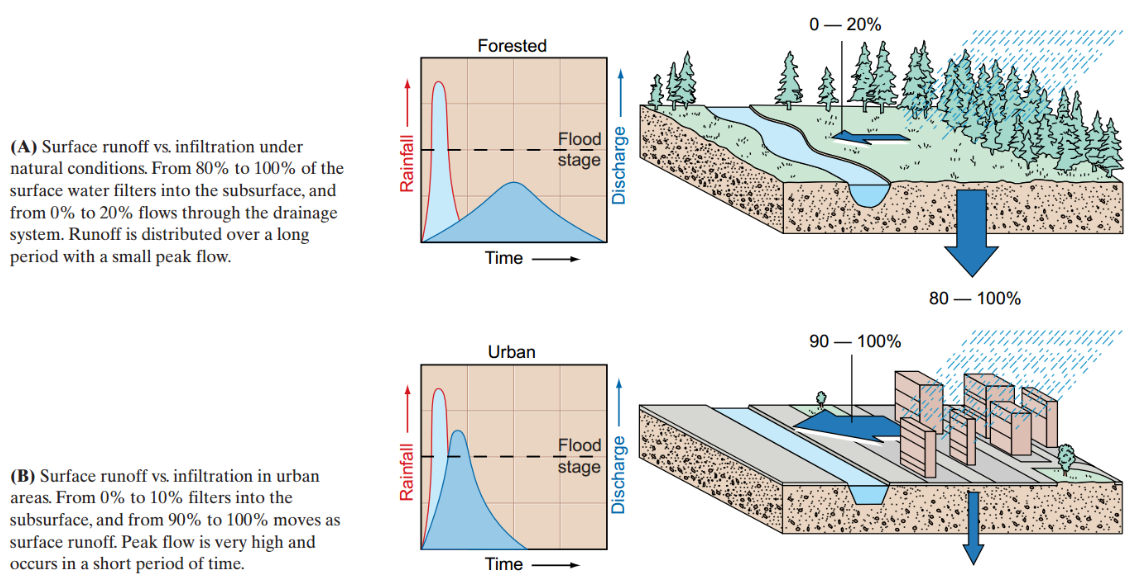


Figure 37 - Deforestation/urbanization Effects on Runoff (Hamblin and Christiansen 2003)

The catchment area of the Missouri River certainly has undergone, and is still currently undergoing, significant changes regarding ground cover. While there has definitely been a rise in recent years to conscious efforts to mitigate effects from deforestation and urbanization, the change in ground cover continues to proceed. In the years from 2003 to 2009 Nowak and Greenfield (2012) report for Kansas City, MO a decrease in tree cover area by 160 ha/yr coupled with an increase in impervious cover of 270 ha/yr.

Tributaries

Because the relationship between a river and its tributaries are of such a high degree that significant changes or development in one can have major effects in the other, it is advantageous to consider some major tributaries to the Missouri. A river cannot be viewed independently from its tributaries and therefore the "interconnected dynamic system…should be treated as a whole" (Sayre and Kennedy 1978). To this end the two most significant tributaries to the lower Missouri River will be considered, the Platte and the Kansas Rivers.

Platte River

The Platte River, along with its parent rivers, the North and South Platte, has undergone significant changes due to anthropogenic changes. Both parent rivers originate in the Rocky Mountains of Colorado and each make their course before joining in in west-central Nebraska to form the Platte, which in turn, flows east before its mouth at the Missouri River on the eastern border of Nebraska. Simons and Simons (1994) write:

> The Platte River, including its major tributaries the North and South Platte Rivers, have experienced considerable changes over the past century. As general development of the basin occurred it was converted, at least in part, from the "Great American Desert" to a significant zone of agricultural production.

Occupying the states of Wyoming, Colorado, and Nebraska, the Platte River system was a key geographical feature for westward settlements, as Schumm explains in "Rivers and Humans - Unintended Consequences" (2007). He states:

> The Platte River valley was the route of pioneers travelling to Oregon and California in the mid-nineteeth century. The Oregon Trail followed the south bank of the river and the Mormon Trail occupied the north side. The pioneers travelling along the river were astonished by its morphological and hydrologic character, which was so different from rivers east of the Missouri and Mississippi Rivers. In fact, the rivers of the Platte River system were classic examples of braided rivers, and were cited as such in geomorphology texts.

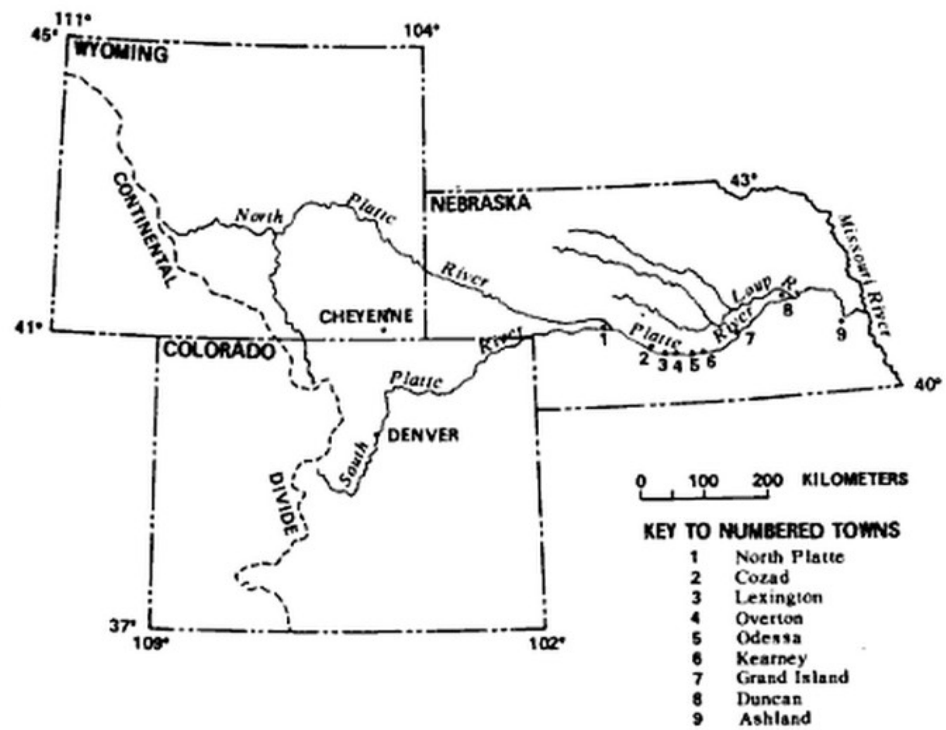


Figure 38 - Platte River (Eschner 1983)

Schumm (1985) further explains in "Patterns of Alluvial Rivers" that the term "river metamorphosis" is used to describe changes that "drastically and totally alter river morphology." The South Platte River, Schumm asserts, has undergone such extensive change that the term is applicable. Historically, the South Platte experienced significant seasonal variations in discharge due to snowmelt. As the river descended into the plains the flow volume decreased as result of seepage and evaporation. Throughout the mid to late nineteenth century, though, in response to gold rushes in Colorado, development began on the river in the form of irrigation diversions. Over time the once "textbook" example of a braided stream became a well defined channel.

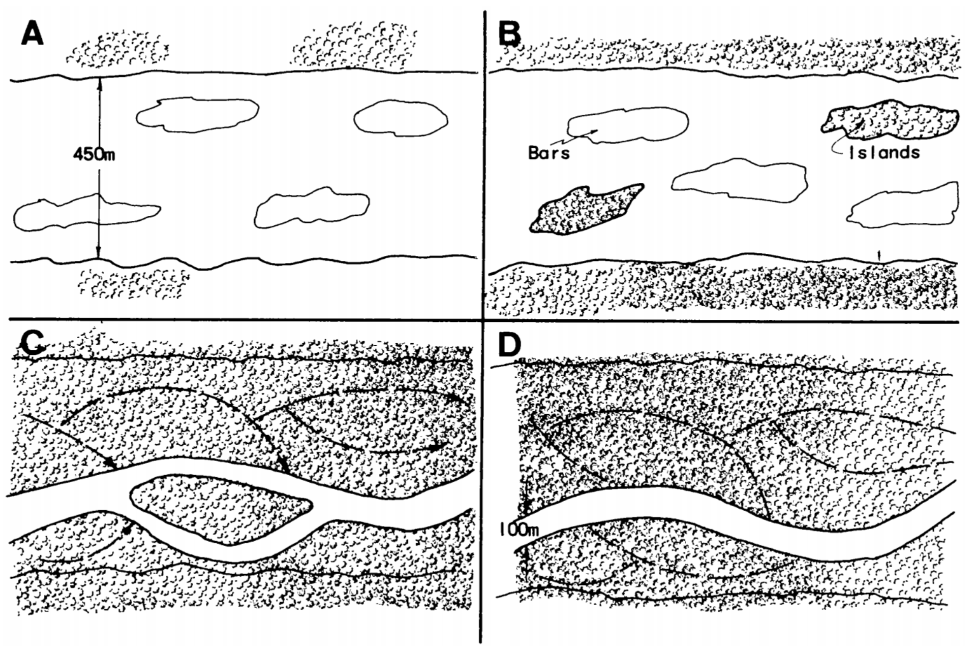


Figure 39 - South Platte River Metamorphosis. A) Early 19th Century: irregular discharge, transitory bars. B) Late 19th Century: perennial discharge, islands with vegetation. C) Early 20th Century: single dominant thalweg, established vegetation, bars became islands. D) Present Day: single channel, no islands (Schumm 1985)

The South Platte's partner, so to speak, the North Platte has under gone similar changes, as well as the stream formed at their confluence, the Platte River. Flows in the North Platte and Platte Rivers, like the South Platte, were historically quite variable. Williams (1978) reports that the rivers have undergone significant geomorphologic changes as a result of a number of diversions and impoundments, mostly for agricultural purposes. Additionally, there is significantly more riparian vegetation than in years past;

not only owing to flow changes, but perhaps influencing continual changes as well. Williams writes,

> [T]here have been no significant long-term trends or changes in total annual precipitation for [cities along the rivers] during the period 1900-74. Therefore, any observed long-term changes in streamflow probably are not attributable to changes in climate.

The North and Platte Rivers, although still maintaining a braided channel pattern, have undergone significant width reductions probably due to decreases in flow. Williams (1978) reports that average yearly peak flows at North Platte decreased from 511 cubic meters per second before April 1909 to just 72 cubic meters per second after October 1957. Regarding width reduction he reports that from Minatare on the North Platte to Overton on the Platte channel "the channel in 1969 (and 1977) was only about 0.1-0.2 as wide as the 1865 channel." Downstream the Platte experienced additional width reductions, although not as drastic. "From Overton to Grand Island (a distance of about 115 river km) the channel in 1969-77 was about 0.6-0.7 as wide as it was in 1865." He concludes:

> In the absence of any significant climatic shifts, the various channel changes described above most likely are due to the rather systematic decrease in water discharge (and possibly sediment discharge) that has occurred… The decrease in water discharge (both peak flows and mean annual flows) probably is due to the creation of on-stream reservoirs and the greater consumptive use of river water.

The decreased width and associated increase in vegetation as well as decreases in both peak and average flows has the potential for significant implications on the Missouri River. Although, upstream of the Kansas City reach, Nebraska City, for example, has experienced aggradation rather than degradation. With this reach of sediment deposition between the mouth of the Platte River and the downstream reach of severe degradation, it seems that the Platte River may not contribute significantly to sediment rates at the Kansas City reach.

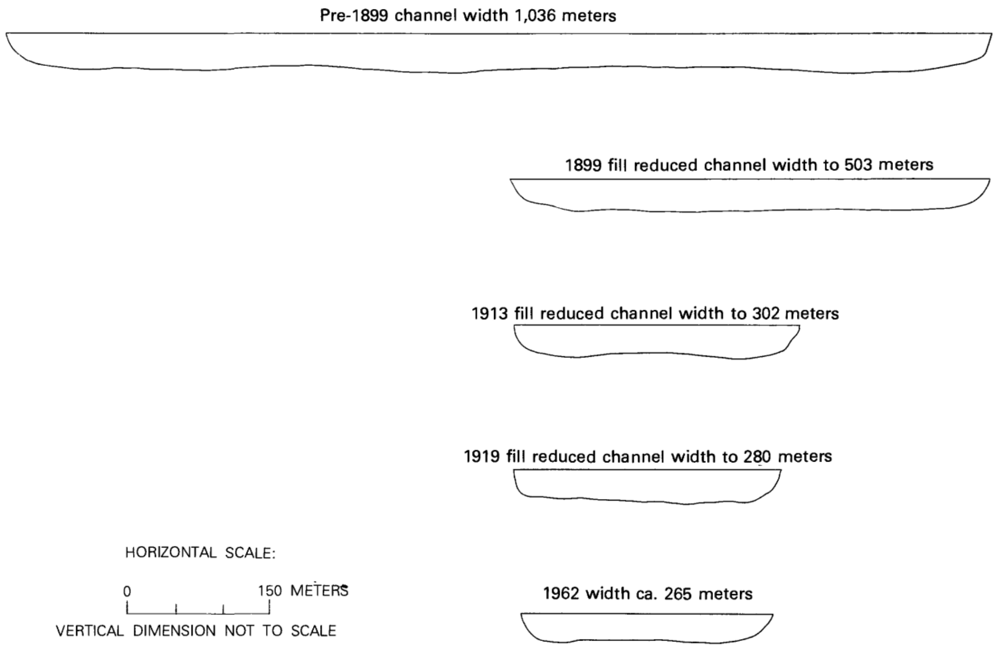


Figure 40 - Channel Width changes of the Platte River near Grand Island, Nebraska (Williams 1978)

Kansas River

If the distance from Kansas City to the mouth of the Platte is any reason to discount its influence on degradation the opposite may be true of the Kansas (or Kaw) River, whose mouth occurs in the heart of the Kansas City reach. Formed by the confluence of the Republican and Smoky Hill Rivers, the Kansas River flows eastward for approximately 170 miles before joining with the Missouri River. The Kansas, like most western rivers has been heavily developed. Levees line the floodplain adjacent to the river and numerous reservoirs and irrigation diversions exist on its tributaries.

In the mid-1980s the Corps of Engineers' Kansas City District published a study conducted by Simons, Li, and Associates, *Analysis of Channel Degradation and Bank*

Erosion in the Lower Kansas River (1984). The report concluded that both natural processes and human influences have resulted in degradation of certain reaches. Human activities cited as having been significant include "sand and gravel mining, construction of reservoirs on major tributaries, channelization for flood control and various channel structures to control lateral and vertical movement of the channel."

Certain hard points occur throughout the length of the river and act to prevent upstream- progressing degradation. These "channel controls," Simons, Li, and Associates (1984) report are both natural and man-made. The two major man-made controls are Bowersock Dam, located at RM 51.8 in Lawrence, and the Johnson County weir, located at RM 15.0. Bowersock Dam, the site of a hydroelectric power plant, was originally constructed in 1872 has undergone significant changes due to repairs and updates. The Johnson County weir was constructed in concert with the Johnson County Water District No. 1 intake structure located on the right bank of the river at RM 15.0 (Corps of Engineers 2010). Additionally, there are over 50 miles of dike or revetment that also act as controls, limiting the lateral movement of the river. Bedrock outcrops also exist at several sites and may act as controls, although their effect is judged to be inconsequential (Simons, Li, and Associates 1984).

Significant dredging has taken place on the lower river and is considered to be a major contributor to degradation (Corps of Engineers 1990). The fact that degradation has occurred both downstream and upstream of the Johnson County weir suggests that the river generally flows with a sediment deficit. It is possible that this is due, at least in part, downstream of the weir, to degradation on the Missouri. Galay (1983) writes that "the initiation of… degradation along a main stem of a river system quickly results in degradation working up the tributaries." Although, Simons, Li, and Associates conclude that there is "a direct relationship between the dredging activity and channel degradation…" while, "lowering of the base level of the Missouri River has had an insignificant impact on the degradation… in the lower Kansas River." Consequently, it may be more likely that the Kansas River is affecting the Missouri. Sayre and Kennedy (1978) write, "Most sediment is carried to rivers by its tributaries." With the Kansas River flowing with a deficiency of sediment, the Missouri may inherit that sediment debt.

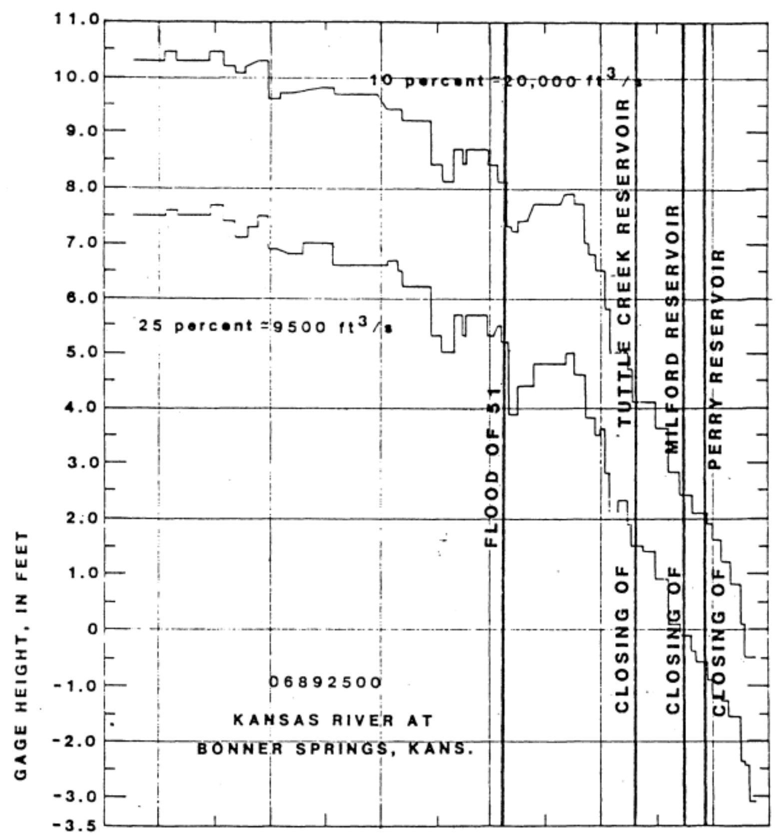


Figure 41 - Stage versus Time for the 10 and 25 Percent Flows on the Kansas River at Bonner Springs (Simons, Li, and Associates 1984)

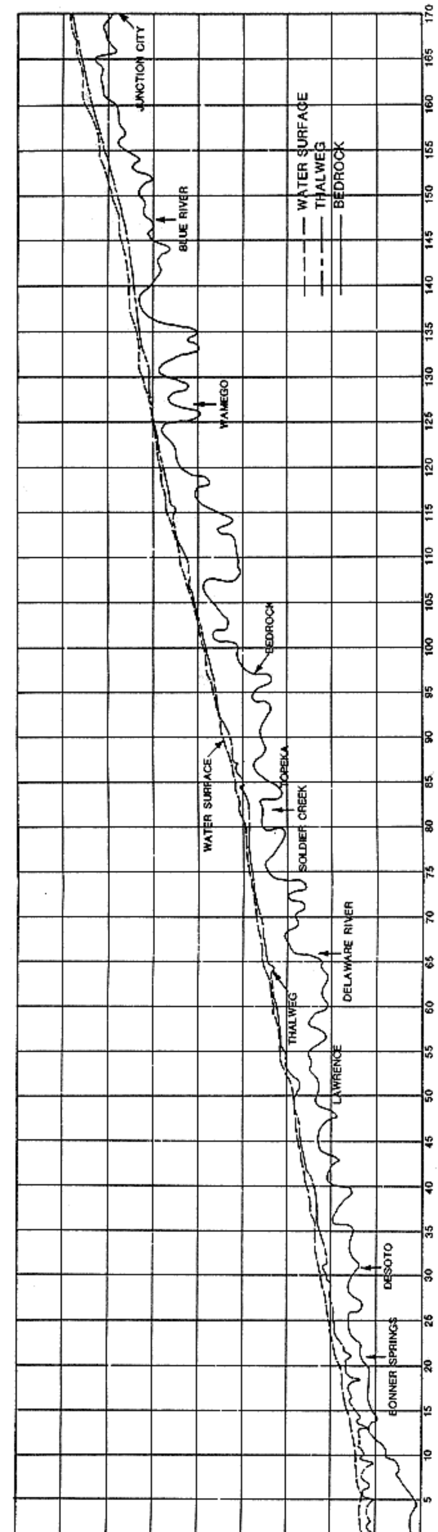


Figure 42 - Bedrock, thalweg, and water-surface profiles of the Kansas River (Simons, Li, and Associates 1984)

Most Probable Causes

In summarizing the *Degradation and Aggradation of the Missouri River* workshop held in Omaha, Nebraska, addressing the bed incision occurring from Gavins Point downstream to the mouth of the Platte River, Sayre and Kennedy (1978) report that a consensus was never reached on how much influence anthropogenic causes had on degradation as opposed to natural causes. Certainly, the river system is complex, containing a large number of variables (both man-made and natural) that are difficult to put into perspective. Still, assessments can be made to identify, at the very least, the probable cause of riverbed degradation.

The degradation experienced at Kansas City is somewhat unique in that the reaches immediately on either side, both upstream and downstream, are not experiencing significant bed lowering. Making difficult the task of determining causes to degradation is the subject of equifinality. Schumm (2005) writes:

> We do know a great deal about the causes of incision, and it is a prime example of equifinality or convergence because there are many causes of channel incision, but they all produce the same general result.

With so many possible factors causing the same effect it can be difficult to determine which factors prove influential. Furthermore, one cause is certainly not the only significant influence on the sediment imbalance that is occurring. Nevertheless, it is possible to arrive at some conclusion of at least the most probable causes to degradation.

Of the factors previously mentioned that have possible effects on degradation there are at least a few that probably do not apply at Kansas City. Main-stem reservoir dams are most likely not related to the degradation in the Lower Missouri River. Although the upstream dams certainly trap soils carried by the flow and release sediment-starved water, the fact that aggradation has occurred in reaches between the final dam and Kansas City suggests that whatever effect the reservoirs have on sediment supply is largely discounted by the time the flow reaches the degrading channel. Dams may also contribute to degradation through their disruption of natural flow rates. The Missouri River, though, has experienced dampened peak flows which would facilitate aggradation rather than degradation.

In all likelihood, degradation at Kansas City is also not due to effects transferred from the Platte River. This is largely for the same reason that dams prove inconsequential. The Platte River's confluence with the Missouri is upstream of reaches that are experiencing aggradation. Therefore, it is logical to conclude that the Platte River does not contribute to degradation downstream of those reaches.

Channelization, on the other hand, probably does contribute to degradation, at least to some degree. Training structures such as dikes and revetment are probably not significant causes, demonstrated by the fact that the entire length of the Lower Missouri River, from Sioux City to the mouth, has been "trained" by these structures, yet the whole length does not experience bed incision, although, the self-scouring quality of training structures can exacerbate other causes of degradation. Length shortening associated with channelization probably does affect degradation, as can be seen through an analysis of reaches where significant cutoffs were made. The greatest length reductions occurred in reaches that also suffer from degradation.

Land-use change may contribute slightly to degradation, but its significance may be outweighed by other more influential effects. This conclusion is reached, in part, due to the fact that land-use change occurred throughout the degrading areas quite some time prior to the instigation of incision. Additionally, other areas adjacent to the river that have experienced extensive deforestation as well as urbanization do not experience degradation.

The influence of floods as well is likely a cause of degradation. Effects of flooding are further exacerbated by levees, constricting the flood flow to the main channel rather than allowing the swollen discharge to spread out across the floodplain. As noted previously, it is common for significant short-term scour to occur during flood events followed by a period of recovery. It is also common, though, that the period of recovery does not restore the riverbed elevation to that experienced before the flood occurred. Accumulating over an extended period of time, the effect of numerous flood events, although infrequent, can compound and cause a major reduction in bed elevation.

The effect of the Kansas River on degradation of the Missouri is probably significant. As was discussed before, the lower Kansas River, as well, suffers from degradation that has be attributed to extensive dredging operations. The fact that the mouth of the Kansas River (approximately RM367.4) occurs in the middle of the Kansas City reach (approximately RM400 to RM350) cannot be overlooked. Although the relationship between the two flows is complex there is likely an influence of the Kansas on the Missouri.

Finally, dredging, also, is likely a significant contributor to the degradation phenomena. Large amounts bed material extraction that coincide, both in time and magnitude, with degradation rates indicates that commercial dredging is a primary cause of bed incision.

CHAPTER 3

IMPACTS OF DEGRADATION

Introduction

As has been noted, both natural and human induced changes to a river system have the potential to bring about a disruption to sediment equilibrium for a reach, thereby initiating degradation. An unstable channel, in the form of a reduced bed elevation, whether natural or anthropogenic, can have a number of secondary impacts. Simon and Rinaldi (2006) note, "The causes of river channel incision are numerous, but the morphological effects and hazards associated with incised channels are often similar." Two specific categories of major concern will be examined: (a) ecologic; and (b) economic. While there may exist other categories of impacts, such as esthetic and recreational, these imacts are considered inconsequential when evaluated against impacts from the aforementioned categories, and therefore will not be discussed (Corps of Engineers 1990).

River bed degradation has the potential to impact other aspects of river morphology as well. The most obvious effect is in regards to stage. A lowered river bed creates a correspondingly lowered water level. The USGS regularly monitors stages with gauging stations at numerous places on a great number of rivers across the country. Stage lowering can be observed on river reaches that experience degradation by examining the lowering stage at a gauge station over time. Adverse residual effects from a lowered stage can be observed in many other impacts.

Lowering of the riverbed can also provoke bank erosion and channel widening. As the flow attempts to achieve its sediment transport capacity it may take up soils from the bank, eroding the side of the channel. As the bank erodes the channel widens. Of course, many reaches that suffer from bed incision also are held to a constant width by certain training structures. This can further promote degradation of the bed since soils from the bank are not available and the river cannot widen to decrease velocity.

Additionally, adverse effects from bed degradation can be transferred to tributaries. Galay (1983) writes, “A drop in the main level of main river frequently causes degradation problems along major tributaries.” Consequently, the ecological and economic impacts that the Missouri has the potential to experience may be seen on its tributaries also as upstream proceeding degradation is transferred to their beds.

Ecological Impacts

Changes to river morphology are felt greatly in the ecological realm as a large number of riparian and freshwater organisms require specific conditions for survival. These effects can be either due to degradation specifically or additional results from the causes of degradation. Channelization of the river, as mentioned before, often seeks to mitigate flood flows and confine the channel to a uniform width and depth for navigation. These actions increase slope and thereby also increase velocity. Gordon et al. (2004) writes:

> In terms of habitat, channelization reduces the structural diversity of streams through reduction in meanders, smoothing of pools and riffles and irregular bank boundaries and removal of snags and riparian vegetation. This not only reduces

> the total amount of stream area and shoreline length for habitation but also eliminates the natural diversity of velocity and substrate patterns. Fish no longer have backwaters, pools or low-velocity regions for refuge during high flows and fish eggs may be swept downstream by the higher velocities.

Dams likewise, which have the effect of inducing channel degradation downstream of the reservoir, also have a significant effect on biota of the region. The impounded area, immediately upstream from the barrage, which had once been a lotic ecosystem, that is, an ecosystem with moving water, becomes altered to a lentic ecosystem, that is, an ecosystem with relatively still terrestrial waters. Many organisms are not adapted to the environment resulting from such a change. Adverse effects are felt downstream of the reservoir as well. Gorden et al. (2004) again notes:

> Altered flow regimes can influence oxygen levels, temperature, suspended solids, drift of organisms and cycling of organic matter and other nutrients, as well as having direct impacts on biota. Sudden fluctuations in flow, for example, can wash away deposited eggs or leave fish, crustaceans and mollusks stranded out of water.

Land use changes, such as deforestation or urbanization, which often increase runoff, not only have the potential to cause degradation, but are also likely to have adverse effects on freshwater and riparian biology. The specific results of land use changes are difficult to identify because changes to the catchment area are often accompanied by channelization efforts which compound the problems associated with deforestations, increased peak flows with a reduced duration.

Bank instability and erosion, coupled with consequent channel widening, is also very likely to impact area ecology. These changes can increase the suspended load in the river which can, in turn, increase siltation and reduce light transmission. Erosion of the bank can destroy riparian habitat and biology. Diverse numbers of birds, mammals, and other terrestrial animals often rely on this critical habitat, which occurs at the land/river interface (Corps of Engineers 1990).

As discussed above, an obvious side effect of degradation is the resultant lowered water levels. This can also affect the water table levels in the adjacent floodplain. As the water level lowers in the river channel, the water level in the connected aquifer, likewise, decreases. Wetlands in the floodplain or riparian vegetation near the river that depend on water table elevations at a certain level can be adversely affected due to this change.

Degradation, while possibly not always the cause of, is certainly related to a host of ecologic concerns in riverine habitats. Restoration or rehabilitation of these habitats can become costly. In fact, ecological impacts could, in turn, become economic impacts as well. Alexander, Wilson, and Green (2012) writes:

> Although engineering in river systems has economic benefits to society, these benefits often come with ecological consequences that, if not fully considered, may eventually counterbalance some economic benefits or conflict with modern societal values.

The damming of the Missouri River main-stem, possibly exacerbated by associated channelization, has been shown to have an adverse effect on certain floodplain organisms (Johnson, et al. 2012). Ecological impacts of both dams and channelization on the lower Missouri River have been the subject of study by the USGS's Columbia Environmental Research Center (CERC) (1998). The report suggests that disruption to the natural flow pattern, particularly the absence of a spring and summer rise, has "Caused loss of spawning cues… Reduced productivity in the upper river reaches due to altered nutrient transport and cycling… Prevented seasonal fish and wildlife access to remaining off-channel backwaters and wetlands." Other direct impacts from dams, and induced degradation, include disruption to the natural sediment and organic material transport and prevention of upstream and downstream migration. The report additionally addressed channelization's effect, including the loss water surface and shallow-water habitat.

Development related to degradation has had considerable effects on at least three endangered or threatened species whose situation has been studied by numerous parties including the USGS (1998), Jacobson and Galat (2006), and Pokrefke et al. (1998). The pallid sturgeon (*Scaphirhynchus albus*) suffers from a lack of spawning cues inherit to the spring rise, while the piping plover (*Charadrius melodus*) and the least tern (*Sterna albifrons*) suffer from a loss of sandbars required for nesting.

The Kansas City reach in particular does not seem to host any threatened species that may be adversely affected, but certainly riparian trees and other vegetation, particularly in adjacent wetlands, dependent on consistently shallow groundwater levels could be directly impacted. Degradation could additionally eliminate low water habitats required by aquatic organisms (Corps of Engineers 2009b).

Economic Impacts

These impacts are generally a direct result of morphologic changes influenced by degradation. These changes have the potential to cause adverse effects to manmade structures, land adjacent to the river, and water supplies, that can large sums of money to remedy. One of the morphological effects of degradation mentioned earlier was the propensity to increase bank instability causing erosion and channel widening. As the bank erodes and the river widens the property-owner, whether public or private, adjacent to the river experiences loss of land.

Additionally, as sediments on the channel bed erode away bridge piles and piers may be undermined or become unstable. To maintain the safety of the roadway it becomes necessary to stabilize the structures to prevent failure and possible injury or worse. It is common for pipelines to span the river beneath the bed elevation. As the bed level decreases these structures may become exposed and it becomes necessary to either rebury the pipeline or secure it to the riverbed. Structures that aim at maintaining constant width or depth, such as dikes, revetments, and other channelization measures, may also be undermined.

Degradation of the riverbed also has high potential to render water supply intake ineffective or costly. As water surface levels decrease, the pumping capabilities of water intake structures that lie in the river may be greatly diminished or eradicated. Likewise, as aforementioned, water levels in the river can directly impact the water table level adjacent to the river. Water intakes located in wells will similarly be affected. This may result in a need for additional wells to be constructed or higher pumping costs due to increased pumping heads (Corps of Engineers 1990).

Economic impacts affecting the Kansas City reach are great and are likely to be the instigation required to counter degradation. Water intake structures, for example, are a particular area of concern. The Corps of Engineers (2009b) records, "[L]ow flows have forced [Kansas City] to spend more than $4 million to extend water intakes and drinking water pumps to reach lower river levels." River banks, as well as training structures and levees, are threatened by lowering bed levels. Addressing levees specifically, the Corps continues, "The evidence of eroded areas resulting from normal to moderate flows indicates that a major flood event would pose high risks of severe erosion and the probability of levee system failure." Such an event could potentially cost exorbitant amounts in damages to agriculture or communities. Infrastructure such as bridge abutments and piers could be undermined causing potentially fatal circumstances. Numerous state, local, and railroad bridges span the river and are threatened by progressive bed incision. Public and commercial pipeline crossings as well could be impacted at considerable costs (Corps of Engineers 2009b).

CHAPTER 4

EUROPEAN RIVER CASE STUDIES

Introduction

As was mentioned previously, degradation has become somewhat of an epidemic among rivers of the world. Europe, in particular, contains a number of major rivers that have experienced bed incision due to anthropogenic causes. Many public and private entities have undertaken the task of studying, and in turn applying, countermeasures to degradation. Three rivers that have experienced significant degradation are the Rhine, Danube, Elbe. In an effort to extrapolate possible solutions for the Missouri, the measures taken to combat degradation on these rivers will be examined.

Unfortunately, upon review of the sources documented it becomes clear that the main purpose of these European rivers is navigation. Consequently, any measures used to counter degradation are designed around that objective. This is made clear in the title alone of Mosselman et al.'s *Sustainable river fairway maintenance and improvement* (2004), which covers all three aforementioned rivers.

River Rhine

From its source in the Swiss Alps and running a course of roughly 1,235 km to its deposition in the North Sea, the Rhine is one of the longest rivers in Europe. By providing the Port of Rotterdam access with the hinterland, the Rhine is also one of the most important rivers to the continent. The Rhine flows through the countries of

Switzerland, France, Germany, and the Netherlands before depositing into the North Sea. Having a catchment area of 170,000 km^2, its drainage extends to include the countries of Italy, Austria, Lichtenstein, Luxemburg, and Belgium.

Over the last several centuries, and particularly the last two, the Rhine has become increasingly important to the economies of inland Europe, carrying more transport than any other waterway in the world. Consequently, the river has become the object of a number of training works. These engineering projects, while serving to yield a specific positive outcome from the river, also inadvertently interrupt natural processes, disturbing the entrained soils as well as the sediment transport potential of the river.

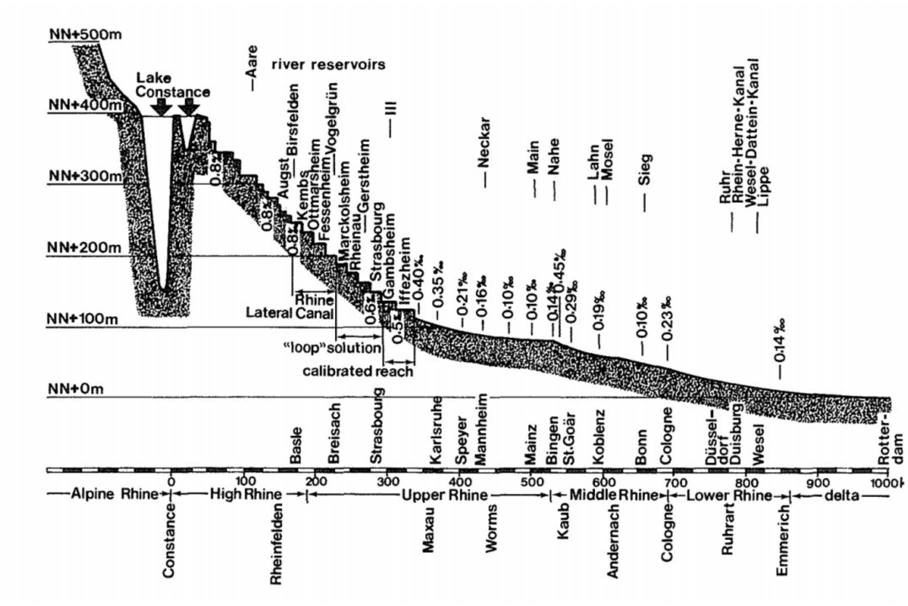


Figure 43 - Longitudinal Profile of the Rhine (Volker and Henry 1988)

Historically, floods have caused major problems to the communities along the upper Rhine. Aside from the devastating effects of destroyed villages and deceased people and livestock, floods dating back to 1306 and their associated course changes caused problems to sovereign states and the establishment of a border between them. As a result, in 1815 Johann Gottlieb Tulla devised a plan to concentrate the flow of the upper Rhine into one channel. The objective of Tulla's plan was entirely related to flood control as opposed to later developments associated with navigation and power usage. Within the braided channel a number of regulation works were implemented over a 40 year period. Kern (1992) notes:

> Between Basel, Switzerland and Strasbourg, France a total volume of about 9 10^6 m^3 of earth had to be transported for the construction of some 440 km of levees and dams… The River naturally eroded an additional 4 10^9 m^3 to form its new channel bed… Tulla did not completely cut off the floodplains from the Rhine, as his successors did… Supported by diversion structures, the river naturally cut its meanders. These new channels initiated erosion and only the river banks were stabilized in order to maintain the projected channel.

Following the completion of Tulla's regulation works in 1880 a certain amount of protection from severe floods was achieved but the channel continued to be sporadic in regard to gravel bars and scour holes. From 1907 to 1939, as navigation became increasingly important, groynes were installed to maintain constant depth and reduced the channel width to 70-150 m. In addition to this, levees were built to provide further protection for the growing population located in the upper Rhine Valley. Much more recently, the Rhine-Main-Danube Canal has been accomplished.

The channelization planned by Tulla had the objective of bed erosion in order to lower flood and groundwater levels. These efforts resulted in almost 4 m bed degradation. The material that was eroded from the channel upstream was carried and deposited further downstream. This aggradation was noted to occur around rkm 260.

A number of impoundments along the Rhine also contribute to the phenomena of bed down-cutting. Between 1928 and 1977 ten reservoirs were constructed between Basel (rkm 150) and Iffezheim (rkm 334) on the Franco-German border. This effect is especially felt downstream of the Iffezheim barrage, constructed in the 1970s. Any bed-load material being transported by the river upstream of the hydraulic structure comes to an abrupt stop at the lock. As a result of this and other impoundment weirs, the natural supply of material is inhibited to the Upper Rhine. The river attempts to correct this sediment starved condition and reach its transport potential by eroding material from the riverbed.

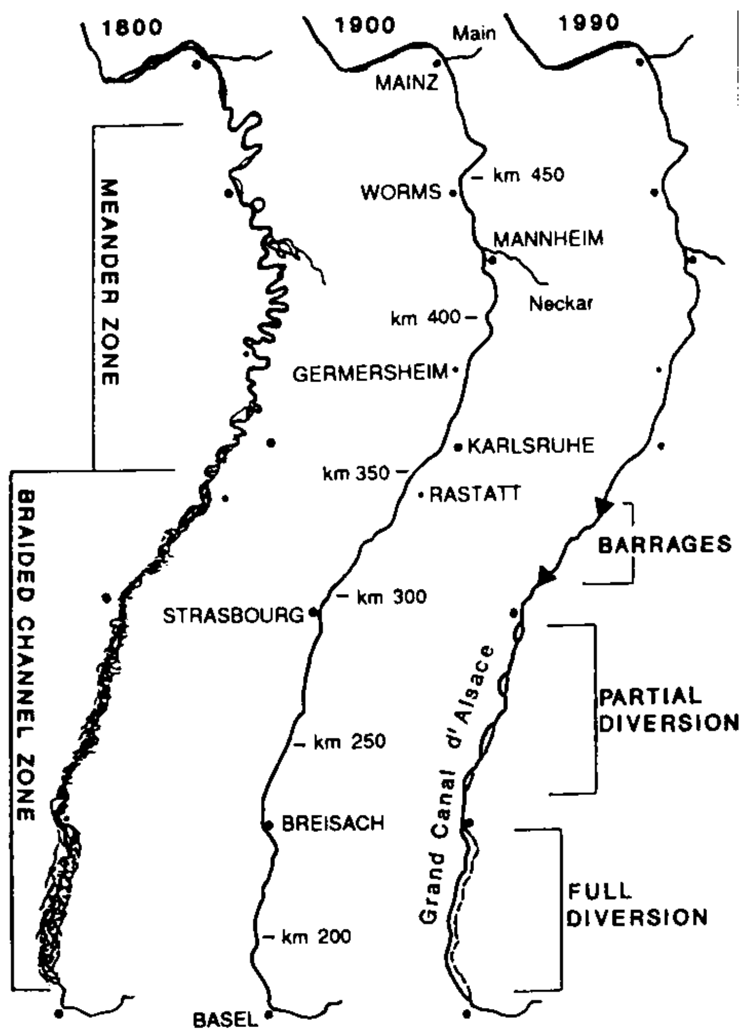


Figure 44 - Development and Straightening of the Upper Rhine River
(Kern 1992)

This erosion of the riverbed is felt clear into the delta reach of the Rhine and even across its bifurcation into the Waal, the Rhine's main delta branch. The degradation and remediation is an endeavor that has been taken on by a number of groups in both Germany and the Netherlands including: Weichert et al. (2010), Dröge and Gölz (1992), Yossef, Zagonjolli, and Sloff (2008), Gölz (2002), (2008), Kern (1992), Scheilen and Havinga (2010), Akkerman et al. (2006), and Mosselman (2009), as well as others.

Research done by these groups regarding solutions to riverbed degradation seem to agree that artificial bed-load supply must be included in a comprehensive mitigation strategy. Kern (1992) records a successful instance of controlling bed degradation downstream of the last dam south of Karlsruhe by artificially introducing sediment to the river. In regard to the river system as a whole, Kern (1992) observes:

> Sediment transport and river-bed changes are restricted to those sections where free-flow conditions still exist. This is true for the reach downstream of the last dam at Iffezheim (345 km) as well as for small upstream sections in the old channel with low water levels. Weir constructions in these sections are used to sustain groundwater levels. Restoration of morphodynamics means that the channel must be widened and bank protection works removed. This can be accomplished only in certain areas, because navigation must be guaranteed by an international convention… Erosion problems downstream of Iffezheim might possibly be terminated by the addition of oversized grains instead of a natural grain size distribution. Eventually an armoured river bed might develop hindering further bed erosion up to a certain threshold.

River Danube

With its beginning in the Black Forest of Western Germany, the river Danube flows for approximately 2,850 km before reaching its mouth at the Black Sea. En route to its termination the Danube makes contact with nine countries: Germany, Austria, Slovakia, Hungary, Croatia, Serbia, Bulgaria, Romania, and Ukraine. The river's basin reaches out to an area of over 801,460 km², covering approximately 10% of continental

Europe and extending to the countries of Albania, Bosnia and Herzegovina, Italy, Macedonia, Moldova, Montenegro, Poland, Slovak Republic, Slovenia, and Switzerland. With a total of 19 countries, no watershed in the world is shared by so many nations. Due to its length and location, it is one the most significant waterways in Europe (International Commision for the Protection of the Danube River 2012).

The Danube is generally separated into three sections. The length from the headwaters to the Devín Gate constitutes the Upper Danube. The Middle Danube extends from there to the Iron Gate. Finally, the Lower Danube finishes the course discharging over 6000 m^3/s into the Black Sea.

Figure 45 - Danube Catchment Basin (SedNet 2009)

Lóczy (2007) states that, "Although the first towing paths were carved into the cliffs of the Iron Gate Gorge under Emperor Trajan around 100 AD, regular traffic was started by the Danube Steamboat Navigation Company (DDSG) only in 1837." Lóczy continues, "Today the Danube is navigable with small vessels to Ulm [rkm 2586], with ships above 1300t volume to Regensburg [rkm 2379].” Lóczy additionally addresses its significance to the region, not only commercially, but culturally as well. He writes:

> The Danube functions as a reserve for drinking, industrial and irrigation water; a source for generating electricity; an artery for navigation, an area for recreation. It is also an embodiment of scenic beauty and a source of inspiration for writers (Jules Verne’s novel ‘Le pilote du Danube’), poets (the Hungarian Attila József’s philosophical poem ‘By the Danube’), and composers (Johann Strauss’ waltz ‘The Blue Danube’).

Due to its importance, especially for transportation, the Danube has become the subject of numerous river regulation structures. Muškatirović and Jovanović (1993) report that training works to mitigate impacts from flooding and also to improve navigation through Serbia date as far back as the mid nineteenth century. Between the years 1860 and 1918 this reach of the Danube experienced works including 70 km of revetments and 20 km of river bend cutoff channels, as well as other regulating structures. Habersack (1996) writes that, “The Danube [in Austria] … has about 30% of its course as free flowing sections.” Reckendorfer et al. (2005) note:

> Along the upper 1000 km of the river, from its source in the Black Forest (Baden-Wurttemberg) to the Slovak-Hungarian border, 56 dams have been constructed. Consequently, long free-flowing stretches in this region remain only at the mouth of the Isar in Bavaria, in the Wachau and east of Vienna. However, even these free-flowing stretches have not escaped the influence of the regulation measures. The Danube east of Vienna, historically braided, has been constrained by major regulation schemes that started in 1875.

Habersack (1996) identifies sedimentation behind dams as a contributor to degradation. Goda, Kalocsa, Tamás (2007) identify three primary causes of riverbed erosion on the Hungarian section of the Danube: (1) river regulation, (2) dredging, and (3) decrease of transported sediment. These three causes acknowledged for this reach are also likely causes throughout the entire length of the river. Dike and other means of fixing the horizontal alignment of the river had the original intention of increased navigability. Unfortunately these structures, along with meander cut-offs, have also caused increases to the sediment transport capacity causing erosion of the channel bed. Levees, likewise, had the purpose of flood protection, prohibiting inundation in adjacent lowland areas. These levees focused the flood flows in the main channel of the river rather than being able to spread as they would in a natural state (Brilly 2010).

Table 7 - A summary of medium-flow regulation of the Danube (Lóczy 2007)

Section	Date of main activities	Reduction of river length (%)	Measures
Upper Danube in Baden-Württemberg	1820-1890	-73	Channel straightening, cut-offs, flood-control dykes, bank stabilization
In Bavaria	1826-1867	-35	Channel straightening, cut-offs, flood-control dykes, bank stabilization, channel deepening by dredging and explosions
In Austria	1850-1914	ca. -15	By-channel closures, bank stabilization, flood-control dykes, training walls
Middle Danube in Hungary	1871-1914	-18	Flood-control dykes, by-channel closures, cut-offs, bank stabilization, groynes, confluence relocations, protecting walls along urban areas
In Serbia	1894-1977	ca. -10	Flood-control dykes, bank stabilization, groynes
Lower Danube in Romania/Bulgaria	No regulation	-	Only dredging and some bank stabilization, flood-control dykes
Danube Delta (Sulina branch)	1860-1901	-30	Straightening, dredging, longitudinal structures, canal building

At one time, the local construction industry benefited greatly from the gravel and sand mining that took place in the river. Goda et al. (2007) states that 70 million m^3 of sand and gravel were excavated from the river bed from 1960 to 1990. “Taking the affected stretch of the river into consideration, this removed mass would be enough to cause about 60 cm deepening of the bed." Dredging additionally breaks up the natural armored surface of the bed giving erosive forces less resistance.

Kern (1992) documents a specific case of degradation of the Danube in the German state of Baden-Württemberg:

> Regulation works, which started in the mid-nineteenth century, cut through all the meanders at the edge of the Swabian Alb and reduced the river length by 20% on some sections. The resulting higher gradient caused the channel bed to erode up to 2.5 m within 90 years. This led to a corresponding reduction of water levels. Since the groundwater level was also affected, the few remaining uncultivated wetland habitats also were endangered.

Similar to the Rhine, the Danube also experiences riverbed deepening as a result of lateral barriers. Bed-load transport comes to a halt at barrages and because of the decreased velocity in the reservoir, settling of suspended sediment also takes place. The river attempts to counter this sediment deficit downstream of the barrage by eroding the channel bed.

Sediment management strategies aimed at mitigation of riverbed erosion have been studied by a number of groups located in countries having contact with the Danube. These include Lower-Danube Environmental and Water Authority, EJC-TF, and Water Resources Research Centre in Hungary, University of Natural Resources & Applied Life Sciences in Austria, and Bavarian Institute of Water Resources Management in Germany.

As was the case with the Rhine, artificial sediment supply is seen as one of the primary techniques to minimize degradation. Weiss (1996) concludes that, "Sediment feeding should not be regarded as a universal remedy, but it should be integrated in to the overall concept of sediment management on the basis of river morphological investigations."

In the section of the Austrian Danube the "Integrated River Engineering Project" (IREP) has been formed to resolve interest differences between stakeholders. The IREP's chief objective is to prevent degradation of the riverbed that has been the result of regulation works and upstream impoundments. The solution the IREP has chosen to carry out this work is the addition of coarse gravel to the river, also known as "granulometric bed improvement" (Reckendorfer, et al. 2005). To this end, Rákóczi (n.d.) writes, "A natural coarse gravel material was selected (40/70 mm), coarser than the present bed material and the dumping of it have been started in 1996. The volume of introduced gravel varied from 7,500 to 190,000 m^3/yr."

Beginning in 1988 a program was initiated to address the degradation in the German state of Baden-Württemberg. Due to the fact that degradation resulted from shortening the length of the river, near the village of Blochingen a meander restoration project coupled with two gently sloping drop structures was implemented. The old meander, which had been cutoff in 1874, was restored and now carries a majority of the discharge during average flow conditions, while the old channel is mainly used during flood flows. This action has decreased the 100-year flood level in Blochingen 30-40 cm. Additionally, there is no bank protection within the new meander and a 100 m strip was purchased adjacent to the river in order to allow unrestricted bank erosion.

In order to mitigate degradation caused directly by commercial dredging, Goda et al. (2007) reports that, "it was necessary to decrease the dredged amounts as small as possible." They add, "Nowadays industrial dredging is not allowed. Only river regulation and maintenance of the navigation way can be the reasons for dredging."

River Elbe

Figure 46 - Elbe Catchment Basin (SedNet 2006)

Along with the Rhine and Danube, the Elbe is one of the three main river systems in the nation of Germany. The Elbe's influence, though, is greater than Germany alone. The river remains important to Central and Northern Europe. The river Elbe rises out of the Krkonose, or Giant Mountains, in the Czech Republic and runs its course for approximately 370 km before crossing into Germany. The river then travels about 720 km before depositing into the North Sea near Cuxhaven. With a catchment area of almost 148,250 km^2, the Elbe's drainage broadens to include small areas of both Poland and Austria. The river experiences a number of impoundments while in the Czech Republic, with only one dam on the river in Germany, located at Geesthacht, although, there are numerous impoundments in both Germany and the Czech Republic located on the tributaries to the Elbe (Adams, et al. 2008).

Like both the Rhine and the Danube, the Elbe experiences riverbed incision due to control structures such as dikes, which serve to decrease the active channel width thereby increasing velocity and sediment transport capacity. The Elbe also suffers from bed down-cutting as a result of the impoundments aforementioned which reduce the natural bed load supply from upstream.

In an attempt to preserve alluvial forests located in the floodplain, a project was undertaken by Water and Shipping Authority Dresden, Water and Shipping Directorate East, Federal Institute for Hydraulic Engineering, and Federal Institute of Hydrology to manage the bed load in what was called the “Erosionsstrecke”, from Torgau to Aken. The management strategy consisted of artificial bed load supply at four sites. The dumped material consisted of soils obtained from dredging sites in the river itself and adjacent gravel pits. 242,000 tons of material was dumped from 1996 to 2002 and after a break in 2003 dumping was resumed in 2004. The project aims to reduce bed degradation and decelerate the lowering of the river. At the time of publication a definitive assessment of the efficiency was not possible as long term monitoring was necessary to gauge the success (Gölz and Anlauf 2006).

Other entities have also evaluated sediment management strategies including Hamburg Port Authority (HPA) and Wasser-und Schifffahrtsverwaltung des Bundes (WSV) (2008), as well as others.

CHAPTER 5

DEGRADATION COUNTERMEASURES

Introduction

As a matter of convenience, and at the risk of oversimplification, countermeasures to bed lowering will be divided into three categories: hydraulic, bed resistance, and sediment budget. Just as it is likely that not just one, but numerous factors affect the forces that ultimately result in channel degradation, it is also likely that the most effective solution will be achieved by some combination of countermeasures.

Recovery vs. Rehabilitation

When speaking of mitigating a problem in the environment, the question of restoration or rehabilitation needs to be addressed. Rosgen (1997) defines restoration "in the purest sense" as "returning a steam to a pristine or to pre-disturbance condition." Rehabilitation, on the other hand, is described by Shields, Brookes, and Haltiner (1999) as "a partial return to pre-degradation condition (e.g. the exact channel planform) or function (e.g. providing habitat for certain species)." They further write:

> Stream corridor habitat degradation is often so pervasive in watersheds with incised channels that true restoration (a return to pre-degradation conditions) is usually impractical. For example, full restoration might require returning an urban or agricultural catchment to forest cover to regain rainfall runoff relationships… In view of these difficulties, rehabilitation…is often more practical than restoration…In view of the difficult and costly nature of restoration and even rehabilitation, the question arises as to why either should be attempted.

In the same vein, Jacobson and Galat (2006) write, “The process of restoring components of the ecosystem has been called *rehabilitation* or *naturalization* to distinguish it from holistic restoration.” Although, even if the Missouri has not been altered to such an extent that makes true restoration impossible, the actions required to bring the river back to a natural state may not be feasible, particularly economically. Namely, the removal of main-stem reservoirs and training structures, as well as a halt to all dredging activities, does not seem like a viable solution. As Jacobson and Galat (2006) note, “Because of the large economic benefits that accrue from engineering and active management of large rivers and flood plains, restoration to pre-managed conditions is seldom realistic.” Although Schneiders (1999), in summary of the changes wrought by development of the Missouri Valley, both to the stream corridor and to human perception of it, writes:

> Yet few individuals entertained any thoughts of simply letting the river go, of taking down the dams and training structures and abandoning the traditional paradigm, even though that seemingly radical alternative possessed many obvious, tangible advantages.

Sayre and Kennedy (1978) additionally write that the methods used to provide navigation, land reclamation, and other river objectives, continue to have “serious adverse impacts on fish and wildlife habitats, recreational use of the Missouri River, and the general river environment.” Supposing those actions did take place, it is not clear whether the economic benefits provided by the structures would be outdone by the economic benefits related to a completely natural river. Furthermore, the extent of morphological changes made to the river by man may be too great to be reversed in anything short of a geologic time scale. Still, this alternative brings to mind some significant ideas that are worthy of additional research to ascertain benefits and feasibility.

Natural Recovery

The first option for recovery of an incised channel is to take no action and allow the river to reach equilibrium by natural means alone. Shields et al. (1999) explains:

> Given enough time, the forces of nature will tend to restore the fluvial system to some state of dynamic equilibrium… However, the length of time required for this type of natural recovery may be unacceptable. Further, recovery of a meandering planform and development of a new floodplain require export of huge volumes of sediment, with adverse impacts both up- and downstream and damage to riparian lands and structures.

As mentioned previously, man-induced changes to a river system tend to "compress" geologic time and processes that would normally take centuries to millennia are completed in as little as a decade. This applies not only to degradation and other detrimental effects, but to mitigation techniques as well. Allowing the river to make completely natural adjustments to achieve equilibrium may take many years. As Shields et al. (1999) suggests:

> If funds for stabilization are severely limited and time is limitless, a "no action" approach to rehabilitation might be adopted, allowing nature to take its course in building a new, more stable fluvial system through natural processes of erosion and deposition.

Additionally, many of the man-made structures that promote degradation would further act to slow any natural recovery. Of course, any mitigation technique that is implemented will rely heavily on natural recovery to one extent or another, as natural processes continue to proceed.

Grade Control

The use of structures for grade control to establish a stable slope can be implemented through drop structures, such as weirs, or through sills. Watson and Biedenhard (1999) define grade control as, "adjusting or establishing the gradient of the channel." They go on to explain:

> There are basically two functions of grade control structures. One type of structure is designed to provide a hard point in the streambed that is capable of resisting erosive forces in the degradational zone… The second type of structure is designed to function by reducing the energy slope along the degradational zone.

Oftentimes a grade control structure performs only as one or the other, while other times the distinction may be blurred and the structure functions as both a bed control and hydraulic control structure. The use of grade control structures to mitigate degradation processes has been a major subject of study for the Demonstration Erosion Control (DEC) project. The DEC project was created in 1984 to address erosion issues in the Lower Mississippi Valley region of the Yazoo River Basin.

Research has seemed to show that grade control structures can be effectively used to arrest degradation on small scales. Simon and Darby (2002) found that "[Grade control structures] are most effective when they are used to prevent headward migrating knickpoints." Additionally, "for optimum effectiveness, [grade control structures] must be installed in incising channels early in the adjustment cycle." The ability of grade control structures to affect degradation only in a small scale, or local reach, is further expounded upon by Bravard, Kondlof, and Piégay (1999): "[Grade control structures] do not solve the incision problem downstream in cases of sediment starvation or increased shear stress resulting from channel confinement (e.g. by levees); rather they physically control the downward cutting of the river bed in one reach."

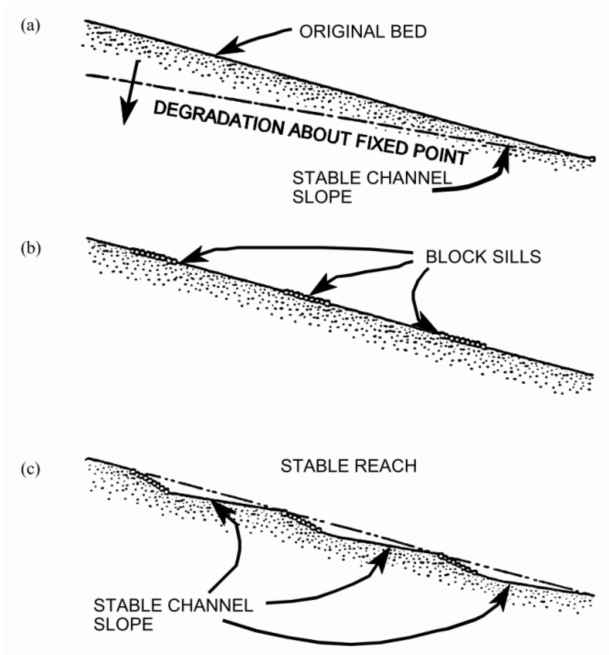


Figure 47 - Use of Bed Sills to Arrest Degradation (Watson and Biedenharn 1999)

The implementation of grade control structures involves a multi-faceted decision of placement and spacing. While the hydraulics of a site and the economic feasibility of placement are generally the deciding factor, Watson and Biedenhar (1999) note, "hydraulics and economics alone are usually not sufficient to define the optimum spacing for grade control structures. In practice, the hydraulic considerations must be integrated with a host of other factors, which vary from site to site." Simon and Darby (2002), in reporting the effectiveness of grade control structures on the Hotophia Creek in Mississippi, conclude that it would have been more effective "to allow the channel to undergo a more natural recovery, restricting grade control structure construction to one or two structures near the mouth."

In addition to only being effective for relatively short distances with headward incision, grade control structures have a number of other negative attributes that render them unreasonable for use on the Missouri River. As was previously discussed, bed degradation causes a significant decline in habitat for wildlife in the stream corridor. The use of weirs or other higher structures may introduce additional problems for aquatic organisms. Bravard et al. (1999) report that grade control structures "may also prevent upstream fish migration, and the fall over a high structure may injure downstream migrants." Sills, on the other hand, are described by Keshavarzi and Noori (2010) as being, "more beneficial to aquatic habitat resources than other types of bank protection, primarily because their presence causes a pool habitat to be created and maintained."

While degradation may be restrained over the reach where a grade control structure is implemented, there is inevitable scour downstream of the structure. This scour has the potential to undermine the structure itself, increasing the cost of such a measure, as structures must be either repaired or replaced (Bravard, Kondolf and Piégay 1999). A study performed by Bormann and Julien (1991) has sought to alleviate this problem by providing a way to predict scour and design protective measures accordingly.

In view of the fact that they are most effective in smaller rivers, and that additional degradation is guaranteed to occur downstream, grade control structures do not seem to be particularly effective in preventing further incision.

Dike Modification

A technique that authorities in the Netherlands have been looking into to arrest bed degradation on the River Rhine has been the modification of training structures, mostly in the form of lowering. By lowering and/or shortening dikes, a larger area of the channel is able to be utilized by the flow. The larger area has the potential to decrease the velocity, thereby also decreasing the sediment transport capacity.

Dike modification in the form of notching is also a possibility. In the mid-1970s the Corps of Engineers initiated a dike notching program whereby “notches were constructed by excavating a portion of existing stonefill structures or omitting repairs on small portions of damaged structures” (Corps of Engineers 1982). The goals of the program were:

> (1) To maintain the flood flow conveyance capability of the river channel.
> (2) To maintain and/or increase the amount of shallow water riverine habitat.
> (3) To obtain sufficient field data to evaluate the navigation channel and bank stabilization features, with a view to similar application to other appropratie waterways throughout the nation.

Pennington et al. (1988) record, “During the period 1974-80, approximately 1,306 dikes were notched: 344 were in the river between Sioux City, IA, and Rulo, NE, and 962 were constructed from Rulo to the mouth.” They further write, “The effects of dike notching are poorly understood but are generally considered to be beneficial to aquatic communities.”

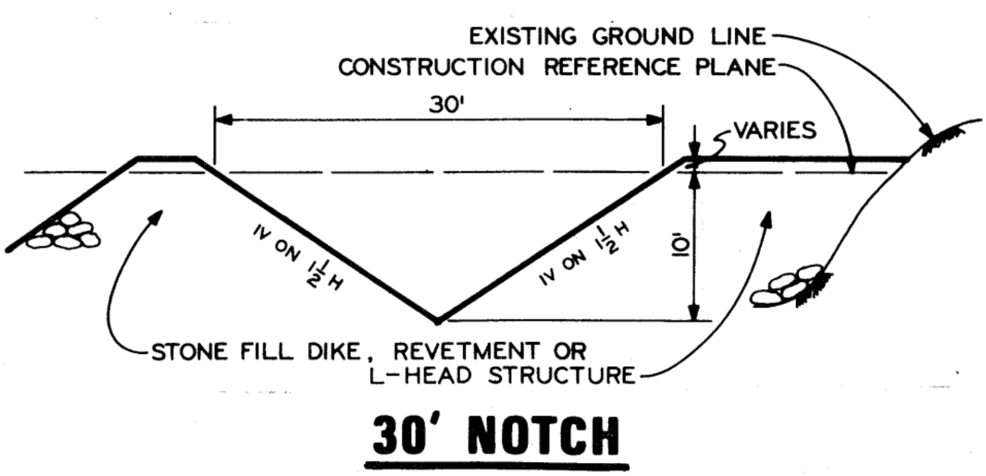


Figure 48 - Typical 30-foot Notch Section (Corps of Engineers 1982)

Although not an implicit goal of the program, it is possible that dike notching has a positive effect on river morphology, particularly relating to bed degradation. While the Pennington et al. (1988) report involved studies pertaining to physical parameters, the report was, by and large, ecological in scope. The objective statement reads:

> This study was conducted to provide information to describe and compare the quality and quantity of aquatic habitat in the vicinity of dikes of three types: notched, notched with a stone reef placed downstream, and unmodified (without a notch or stone reef).

Even so, with only 14 years between the first constructed notches in 1974 and the study's publication in 1988, any morphological changes caused by notching may not have been made manifest. Additional studies should address the observed effect, if any, that notching has had on channel geometry and morphology. A positive outcome could result in notching being used to combat degradation trends.

Meander/Side Channel Restoration

Length that was lost due to engineered cutoffs could be regained by reestablishing meanders or side cutoffs that have been severed. In regards to this option, though, the Corps of Engineers (2009b) states, "This alternative is unlikely due to changed land use subsequent to cutoffs occurring and the planning constraint of maintaining a navigation channel."

Bed Revetments

Bed revetments or other rigid bed structures can also be installed to provide the bed with an "armored" layer, protecting the underlain soils from erosion. Escarameia (1998) describes the use of revetments made with riprap, concrete, or a variety of other materials. While the implementation of rigid bed coverings certainly seems like it would arrest degradation it is economically not feasible to line the length of the Missouri that requires recovery actions. Furthermore, the sediment-starved condition would remain unsatisfied and perhaps only shift the process of degradation to a different reach without a protected bed.

Artificial Sediment Supply

Another of the measures that has been proven to be effect on European streams is artificial sediment supply. This consists of providing the channel with additional bed material. Fundamentally, it is attempting to provide an artificial dynamic equilibrium to the stream. In the cases on European rivers it was common to construct a sediment trap downstream. When degradation occurs upstream the soils are carried by the flow and deposited in the trap. The material in the trap is then taken and dumped back into the river upstream. Giri (2011) writes, "Sediment nourishment or sediment feeding is considered to have great potential to effectively reduce riverbed degradation."

Additionally, some European river cited, still heavily dependent on waterborne freight, require dredging in some areas to maintain a depth for navigation purposes. The material taken up to maintain a navigation channel can also be supplied back to the river in reaches where incision is occurring. The Missouri, on the other hand, experiences very little transportation in the form of commercial freight. As it is, dredging is likely a main cause of degradation. Additionally, the dredging that does take place supplies much needed materials for the local construction industry and so there is no excess of material to be dumped back into the stream.

Moreover, the practice of artificial sediment supply seems unsustainable, economically and environmentally. Although, it does seem to have somewhat of a positive side, as Weiss (1996) notes:

> Critics could view this as a measure which is not creating stable and durable conditions in the conventional sense of hydraulic engineering. Against this view, however, it must be recognized that reintroducing the bed load could be seen as "understanding" the river, in contrast to traditional hydraulic engineering measures, and therefore as a contribution to up-to-date ecologically-oriented river maintenance. In this way the present form of the river could be preserved close to its natural state and bed load transport maintained.

Unfortunately, "understanding" the river does not necessarily make a practice durable or sustainable. A practice that requires supplies and manpower over and over again for an indefinite amount of time seems to be an unreasonable approach. Perhaps artificial sediment supply works for those European streams where bed material is taken from the river for other purposes and is available to be supplied back to the river. The Missouri, though, has no sediment to spare.

Granulometric Bed Improvement

In many cases, a natural armoring occurs in erosive streams. Pemberton and Lara (1984) describe that, "[an armoring] layer develops as the finer material is sorted out and transported downstream. Vertical degradation occurs at a progressively slower rate until the armoring layer is of sufficient depth to inhibit the process." Livesey (1963) has shown some natural armoring occurred on the Missouri following the degradation that ensued after the closure of Fort Randall Dam. In this case, armoring occurred and degradation levels were not near as high as had been predicted. Additionally, the Missouri at Omaha seems to have undergone slight armoring from 1962-1966 (Corps of Engineers 1967). The portion of the river that suffers from the most aggressive degradation, though, has not seemed to experience natural armoring, at least, not armoring to the point of decreasing degradation rates.

One of the strategies mentioned that has been used with favorable results on some European river is granulometric bed improvement. Granulometric bed improvement is, in essence, gravel dumping. It consists of supplying artificial bed material of a slightly larger size than the current material to the channel bottom. The larger material, unable to be moved by the flow, serves as an armoring layer, protecting the natural bed material underneath. Jaeggi and Zarn (1999) report that artificial armor layering "designed according to the incipient motion criteria" can address excessive erosion in alpine rivers. Furthermore, Galay (1983) writes, "The possibility of artificially armoring a bed in order to stabilize a river appears feasible; the dumping of gravel over a reasonable length of river should rapidly result in armoring."

On the surface this method would appear to be sound, the extent of degradation on the Missouri may render this method ineffective, or at least, uneconomic. Given the fact that degradation poses a problem to such a great length of the river it does not seem feasible to supply artificial armoring in this way to the entire incising reach. The method, also, does nothing to alter the sediment carried versus sediment capacity of the flow at the root of degradation. Once the degrading reach is armored it is likely that the stream's power will be exerted to incise a different reach downstream. Furthermore, artificial sediment supply seems inconsistent with dredging activities and environmental policies related to SWPPPs and sediment runoff (40 CFR 122.44).

Modified Dredging Regulations

With commercial dredging being cited as perhaps the most influential effect on degradation it would seem that modifying current regulations might also carry the greatest impact in preventing further progression of incision. Of course, the main purpose of Missouri River dredging is, as Cardno ENTRIX (2011) reports, "to profitably extract sand and gravel from the Missouri River that meet certain specifications in order to supply the region's construction and manufacturing needs." Because much of the increase in dredging that has occurred in the Missouri River in last couple decades can be traced to significant reductions to the allowable amount of dredged material in the Kansas River, any modified regulations should be approached with caution. Some sort of economic analysis should be conducted so as to not strike a potential deathblow to the construction and manufacturing industries that rely on dredged materials (Corps of Engineers 1990).

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

Introduction

It was mentioned in the Introduction to this document was threefold in its purpose. These objectives were: (1) to examine the possible causes for bed instability on the Missouri River, (2) to review possible mitigation techniques to curb degradation effects, and (3) to provide recommendations concerning the direction of additional actions. For the sake of review, and at the risk of being redundant, the former two objectives will be summarized before the third is addressed.

Conclusions

It has become abundantly clear in recent years that the bed of the Missouri River at Kansas City has been degrading at an alarming rate, threatening the local riparian ecology as well as numerous structures that are either built into the river or depend on the river's water depth. Moreover, it seems evident that this down-cutting has been caused by man-made influences imposed on the river. As Sayre and Kennedy (1978) note, "The Missouri River and its tributaries clearly constitute a complex, interconnected dynamic system which should be treated as a whole." In spite of this, it certainly appears that although the entire Lower Missouri River is generally experiencing degradation, the incision in Kansas City is of a higher magnitude and is likely due to local conditions rather than changes to the system as a whole.

Causes of Degradation

In summarizing the different possibilities to sediment disruption, either in regard to sediment quantity or transport capacity, it was noted that there are most likely multiple causes. Of the possible causes, some were rejected, being considered more improbable than probable; most notably, main-stem reservoirs upstream and the effects from the Platte River. Aggradation in areas between these two causes and the Kansas City reach suggest that whatever impacts they may have on degradation is alleviated and some other effect is responsible further downstream. In fact, shown in reaches near and just downstream of the Platte River suggest that it may help balance the sediment deficiency experienced due to clear water releases from Gavins Point Dam.

Causes of degradation in Kansas City that have been deemed possible but perhaps not as influential as other causes include changes in land-use and certain channelization efforts. These effects are more likely causes of the historic degradation that has been generally occurring since the middle part of the twentieth century. The increased runoff from deforestation and urbanization coupled with the increased slope and the self-scouring nature of channelization serve to exacerbate the more recent causes of severe bed incision.

The more influential causes have been evaluated as major flood events and commercial dredging. It was noticed that significant scour was immediate during flood events, and although a certain level of recovery is generally made, the bed never reaches its previous elevation. Furthermore, dredging activities have dramatically increased during the same time period that degradation has worsened. Considered with the fact that reaches experiencing the greatest amount of degradation in the past decade or two are also the reaches that have experienced the greatest volume of bed material excavated, implies that commercial dredging plays a large role in bed downcutting.

Countermeasures to Degradation

Similar to causes, it is most likely that a solution to the inconsistency in sediment will be achieved through a number of countermeasures. Additionally, as was the case with the possible causes that were considered, a number of countermeasures can be discounted as relatively ineffective. Unfortunately the case studies regarding management of sediment problems in European rivers proved relatively unfruitful. With different economic situations in the rivers, it appears that none of the European solutions are applicable on the Missouri.

That being said, the causes that are least likely to be beneficial include natural recovery, artificial sediment supply, and, related to it, granulometric bed improvement. The fact that dredging has been estimated to be a significant cause of degradation, the idea of feeding dredged material back into the river seems terribly inconsistent. As for natural recovery, this option seems unreasonable given the rates at which degradation has been occurring. To do nothing could be potentially disastrous to the environment as well as critical infrastructure.

Countermeasures such as grade control structures, bed revetments, and meander/side channel restoration have been discounted as well, although maybe to a lesser degree than sediment feeding. Grade control structures and bed revetments do not necessarily solve the root problem of a sediment imbalance, but rather treat the symptom of degradation at a certain location. The river's energy, having not been used to entrain sediment over a rigid section is able to exert its energy downstream, transferring the scour from one section to another. The reconnecting of meanders and side channels is also considered an unlikely solution.

Dike modification has been implemented on the Missouri River for the purpose of ecosystem restoration, and in Europe for the purpose of curbing degradation. Although it is still largely unclear what the long-term effects of modifications such as lowering and notching are to channel geometry, initial studies suggest that no adverse effects have been associated with them. For this reason the method remains as a potential option to combat degradation.

In response to the theory that the most significant contribution to the recent surge in degradation lies with commercial dredging, perhaps the countermeasure most probable to succeed is a modification of dredging regulations. Ideally, although perhaps not realistically, all dredging operations would cease since it is quite clear (whether dredging is the most significant cause of degradation or not) that the Missouri River in Kansas City simply does not have bed material to spare.

Recommendations

Although, estimations and suppositions have been made as to what the most probable causes of degradation are, as well as the techniques to mitigate those problems, additional data is required to provide more satisfactory predictions and solutions. Although a definitive cause (or number of causes) is not likely to be found, a more complete and accurate estimate can be made. In order to achieve this it would be most beneficial to engage in a comprehensive sediment study of the Kansas City reach. A full accounting of all sediment in the system should be made with continual measurements being made upstream of Kansas City, at the mouth of the Kansas River, and downstream of Kansas City. Data regarding dredged material must also be incorporated. Keillor (2007) writes, “Mass balance modeling of [sediments] in a river reach…is like financial bookkeeping: it accounts for all inputs (receipts), outputs (disbursements), accumulations (savings), and losses in that area while keeping the equivalent of account balances.” This mass balance in regard to the sediment budget is critical in order to accurately evaluate the ultimate contributions and most effective solutions to degradation.

Once monitoring time has endured for a length long enough to provide sufficient data to postulate a more accurate assessment of the causes of degradation, plans for countermeasures can be planned to address those specific problems. Subsequent economic studies should also be conducted in order to determine the feasibility of any proposed actions. The study should include not only monetary and financial matters, but issues related to environmental economy as well, and any possible effects the proposed plans may have on the natural environment.

Mentioned numerous times previously, it is a fact that a river system and its associated tributaries are complex in their processes and relations to one another. Therefore, it is important that, although the degradation at Kansas City seems to be a relatively localized phenomenon, any action plan to counter the incision should view and analyze the river system as a whole.

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VITA

Jacob Alan Morgan was born on October 8, 1988, in Pocatello, Idaho. Around one year following his birth his family moved to Kansas City, Missouri where Jacob grew up and was educated in the Park Hill School District. In December of 2006 he graduated from Park H ill South High School a semester early to start the spring term at Florida College in Temple Terrace, Florida, where he graduated Cum Laude in May 2008 with an Associate of Arts degree. Upon graduating from Florida College, Mr. Morgan enrolled in Tennessee Technological University's Department of Civil & Environmental Engineering program where he graduated in May 2011 with a Bachelor of Science degree in Civil Engineering.

After completing his bachelor's degree, Mr. Morgan began working toward his Master of Science in Civil Engineering at the University of Missouri-Kansas City in August 2011. In September 2011 he accepted a position with Olsson Associates, a local engineering consulting firm, as a geotechnical laboratory technician. Upon completion of his degree requirements, Mr. Morgan intends to continue his educational career in pursuit of a Ph.D. in Civil Engineering.