3.4 GEOLOGY AND GEOMORPHOLOGY

3.4.1 Introduction

The nature of the Missouri River system has changed dramatically during the 20th century. This change has resulted from many factors, including construction of upstream dams along the river system and construction of the BSNP by the USACE. Prior to these changes, the Missouri River comprised a wide, braided, sediment-laden river that at times extended up to 5 miles across the floodplain during flood events. After these physical changes, the river was converted to an approximately 600-foot-wide navigation channel designed to efficiently convey river traffic and require little maintenance dredging.

The USACE has permitted commercial dredging in select areas within the active river channel. In its 2006/2007 dredging permit decision (see Section 3.2.6), the USACE determined that geomorphologic river bed degradation has occurred along major portions of the LOMR. The river bed degradation identified by the USACE has lowered water levels, undermined certain revetments, and left some municipal water intakes above the waterline at low flows. While these and other impacts to infrastructure have not yet been widespread, evidence gathered to date indicates that river bed degradation has occurred over extensive portions of the river and that it may continue. River bed degradation can produce widespread effects on the ecology of the river by changing the water depths of in-river habitats and the water table and water surface elevations in adjacent floodplains. It has been determined that several tributaries to the Missouri River are experiencing headcuts and erosion due to river bed degradation in the mainstem LOMR (USACE 2009a).

This section of the EIS provides an assessment of the existing condition of river bed degradation in the LOMR based on the interaction of anthropogenic and natural factors. This assessment can be used to determine a sustainable level of annual river bed dredging in key river reaches. These sustainable dredging levels can be used to compare potential river bed degradation impacts associated with the Proposed Action and a set of alternatives to that action as determined by the USACE.

3.4.2 Geologic Setting

The geologic history of the Missouri River provides a framework for understanding the modern geomorphic characteristics of the river system. For much of the length of the LOMR, the present-day Missouri River flows in a bedrock valley that was initially carved by glacial-fed rivers and outburst floods, and subsequently filled by glacial till and outwash alluvium from successive episodes of

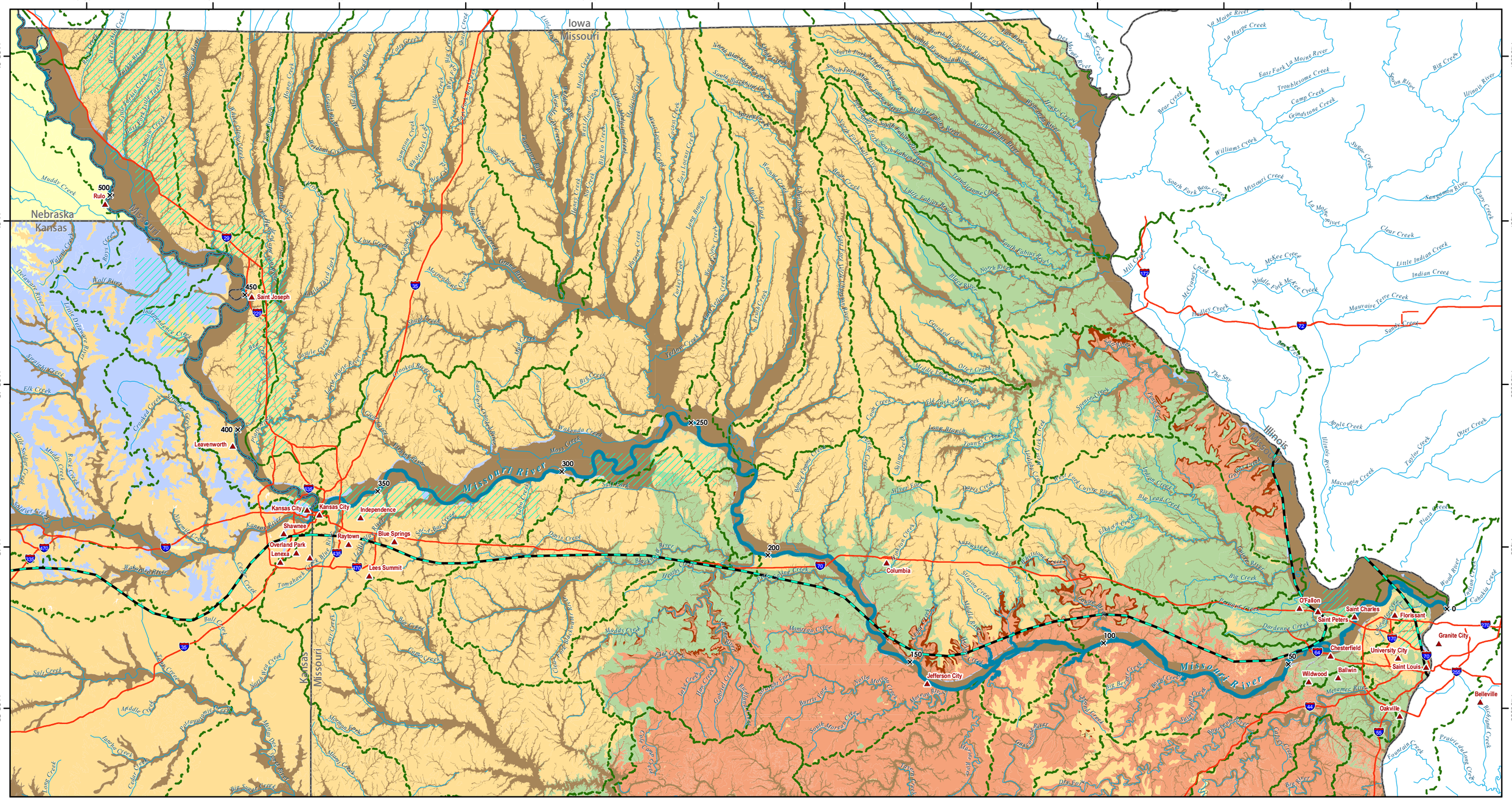
glaciation (Colgan 1999). After the final glacial recession, the river naturally migrated between the river valley walls with much less erosive power than when glacial melt waters carved the landscape. Although the modern LOMR no longer shifts its main channel side-to-side in the river valley because it is confined by engineering structures built over the past century, it still erodes the unconsolidated sand and gravel deposits that fill the river valley and make up the river bed.

3.4.2.1 Bedrock Geology and Valley Widths

Bedrock underlying the LOMR valley influences the width of the river valley bottom, the number of rock outcrops along the river, and the composition of coarse material found in the river. Key features of the LOMR valley geology relevant to river bed degradation are shown in Figure 3.4-1, including bedrock geology; the maximum extent of glaciations; post-glacial valley-bottom alluvial deposits; and glacially-derived, wind-deposited loess units. At approximately RM 250, a change in valley bedrock geology occurs, from softer and more erodible bedrock in upriver areas to harder and less erodible bedrock downriver from that point. This bedrock geology, in combination with the physical effects of past glaciation, influenced the width of the river valley and the dimensions of the natural floodplain prior to human modifications.

Bedrock Control on Valley and Floodplain Widths

Downriver from Rulo (RM 498), the bedrock transitions from Late Pennsylvanian-age (320 to 280 million years before present [BP]) and Mississippian-age (345 to 320 million years BP) limestones, cherts, and dolomites around RM 250 to Ordovician-age (500 to 425 million years BP) dolomites and sandstones near RM 226 (Figure 3.4-1). Outcrops near the river in the Jefferson City area consist of Ordovician-age dolomites and sandstones. Near the confluence of the Missouri and Mississippi Rivers, geologic outcrops consist of Pennsylvanian-age sandstone and limestone, Mississippian-age limestone and shales, and nearby occurrences of Ordovician-age dolomites and limestones (St. Louis County Department of Planning 2006). In general, the strata are not significantly deformed and dip gently to



1:1,600,000

0 10 20 30 40 50 Miles

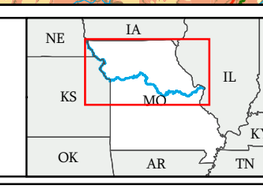
0 25 50 75 Kilometers

Legend

- River Mile
- City/Town
- Interstate Highway
- Southern Extent of Glaciation
- Watershed Boundary
- Alluvium
- Loess (>16' thick)
- Ordovician
- Silurian-Devonian
- Mississippian
- Pennsylvanian
- Permian/Mesozoic/Tertiary
- Quaternary

Figure 3.4-1
Geologic Setting

Missouri River Commercial Dredging EIS



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the north and west (Colgan 1999). Quaternary-age deposits consist of glacially deposited till, drift, and alluvium and extensive deposits of loess—a fine, wind-deposited silt (Gentile et al. n.d). The historical floodplain of the Missouri River has extensive fine sand and silt deposits.

Table 3.4-1 lists the average valley widths, and Figure 3.4-2 shows the valley bottoms for each segment. (Figure 3.4-2 also shows other features that are discussed in later sections.) The upper end of the St. Joseph segment near Rulo, Nebraska is one of two areas where the river valley widens significantly. The other is in the Waverly segment. Below Rulo, Nebraska, the LOMR valley narrows toward the Kansas City segment (2.75 miles wide) and then widens downriver toward the Waverly segment (6.5 miles wide). Portions of the Kansas City metropolitan area lie in the valley bottom near the confluence of the Missouri and Kansas Rivers. An extensive system of federal levees and floodwalls protects this low-lying area from flooding (Figure 3.4-2, Kansas City Segment, Sheet 2).

Table 3.4-1 Average Valley Widths of the Lower Missouri River

Segment	Average Valley Width (miles)
St. Joseph	3.46
Kansas City	2.75
Waverly	6.50
Jefferson City	2.85
St. Charles	2.84

In the Waverly segment between the Little Blue River (RM 340) and Glasgow, Missouri (RM 266), the LOMR flows through softer bedrock; consequently, it has a comparatively wide valley (5–18 miles) (USACE 2004). Below Glasgow, in the Jefferson City segment, the LOMR enters more resistant bedrock, and the valley narrows to an average of 2.8 miles through the St. Charles segment until it emerges into the Mississippi River Valley at approximately RM 25. The more resistant bedrock below Glasgow tends to control the channel and valley morphology (Figure 3.4-1) (Spooner 2001). Because of the narrower river valley, more development occurred on the bluffs of the river valley rather than in the floodplain, therefore, less infrastructure and engineering structures such as federal levees are in the valley bottom below approximately RM 226.

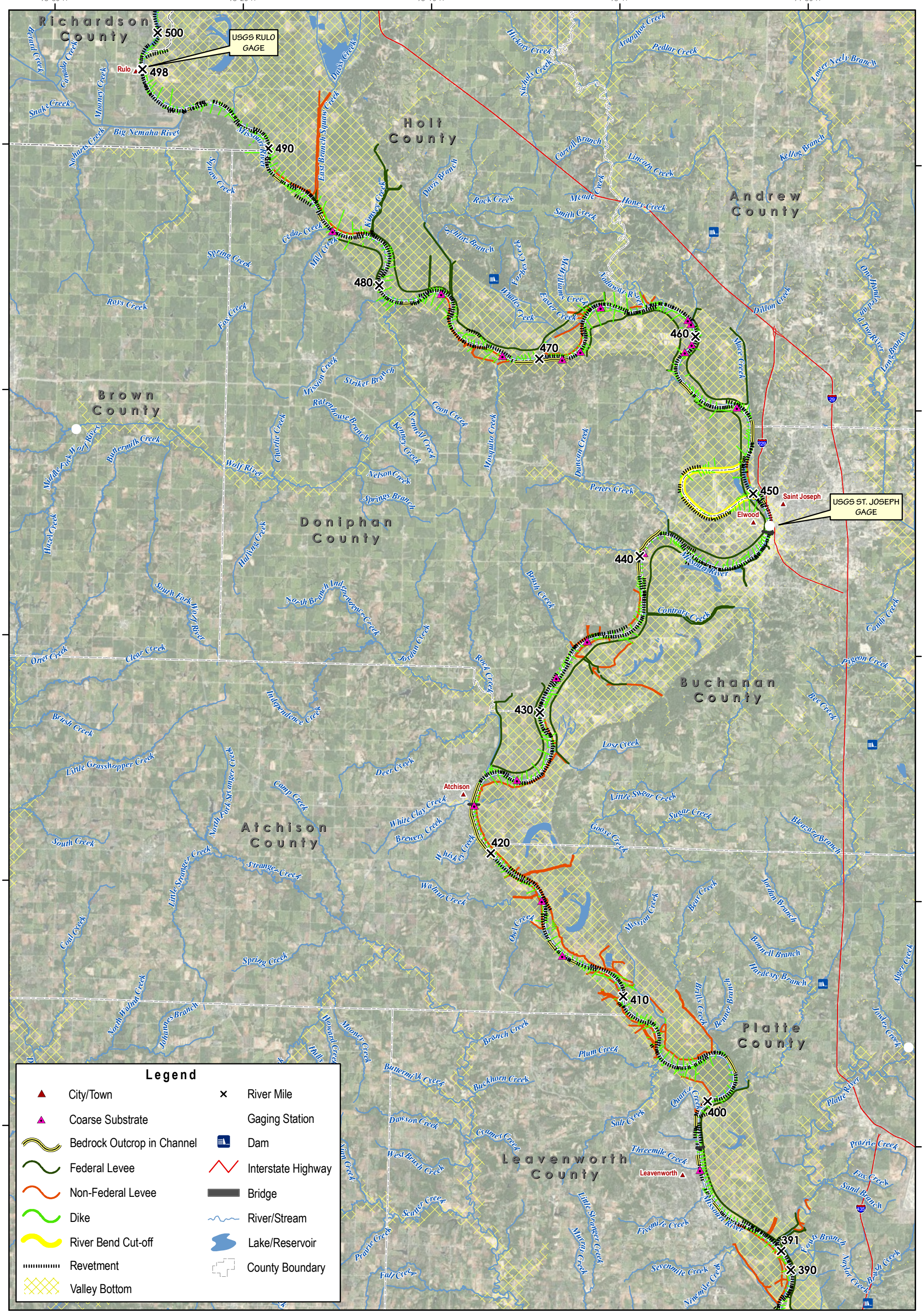
Bedrock Outcrops and Coarse Substrate Patches

Figure 3.4-2 shows the locations of bedrock outcrops and coarse substrate patches in the river channel that were mapped as part of a study on pallid sturgeon habitat (Laustrup, Jacobson, and Simpkins 2007). Bedrock outcrops are solid bedrock exposures in the river bank that constrain the river. Coarse substrate patches are areas greater than 1,076[1] square feet with coarse material (defined by the authors of the study as material ranging from 2 millimeters [mm] to 4 meters [m]). Coarse substrate patches are composed of colluvial deposits from hill slopes, alluvial fan deposits from tributary inputs, glacial drift or till deposits, channel bars formed from transported coarse sediment, and constructed enhancement projects (Laustrup, Jacobson, and Simpkins 2007). These areas may be important as aquatic habitat and resistant to erosion. Table 3.4-2 lists the length of bedrock outcrops and the number of coarse substrate patches by segment in the LOMR. The lower segments on the LOMR have more bedrock outcrops and coarse substrate patches than the higher segments. The increasing bedrock exposure and coarse material in the river are likely due to the constrained nature of the lower valley, the harder bedrock underlying the valley, and possibly inputs of coarse material from the Ozark Plateau from the south. Coarse substrate patches between Kansas City and Rulo are predominantly comprised of material originally placed as engineered structures, such as dikes, that subsequently eroded or were dismantled and left in the river (Laustrup, Jacobson, and Simpkins 2007). These substrate patches are identified as “engineered deposits.”

Table 3.4-2 Bedrock Outcrops and Coarse Substrate Patches in the Lower Missouri River

Feature	St. Joseph	Kansas City	Waverly	Jefferson City	St. Charles
Bedrock Outcrops (miles)					
Left bank	2.3	0.4	0.1	7.6	15.1
Right bank	13.1	1.1	7.7	27	24.9
Average for segment (mile/mile)	0.14	0.04	0.07	0.29	0.31
Coarse Substrate Patches (count)					
Left bank	0	3	2	9	26
Channel bar	6	8	3	19	17
Right bank	14	1	2	19	28
Average for segment (count/mile)	0.19	0.35	0.07	0.39	0.55

[1] The patch size was based on a minimum patch size of 100 square meters used in Laustrup et al (2007).



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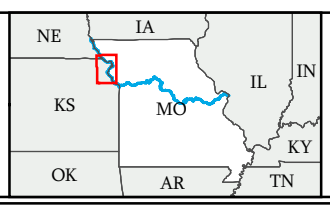
0 5 Kilometers

Figure 3.4-2
Geomorphic Features of the
Lower Missouri River by Segment
Sheet 1 - St. Joseph Segment

Missouri River Commercial Dredging EIS



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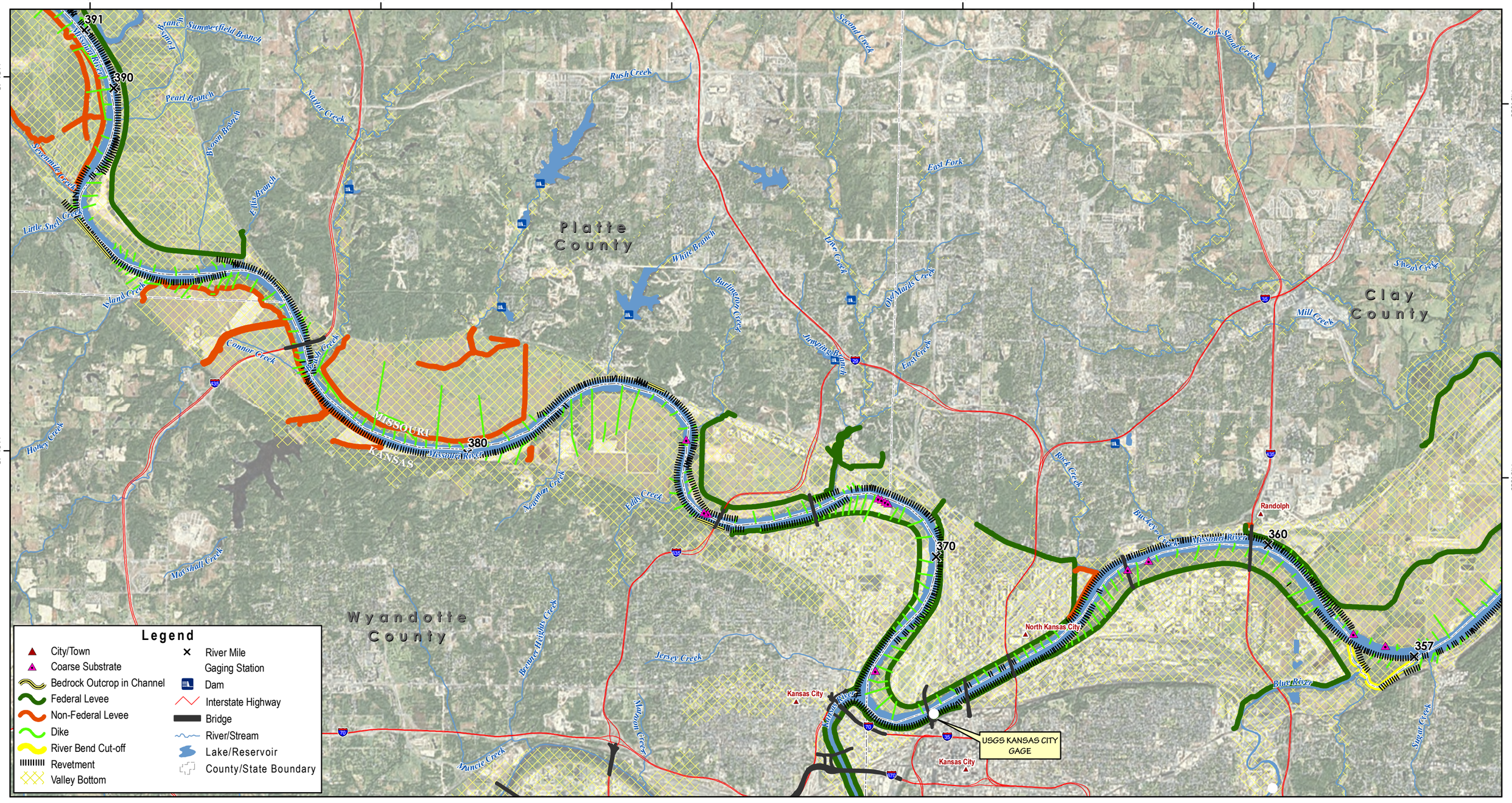

0 2.5 5 Miles

0 2.5 5 Kilometers

Figure 3.4-2
Geomorphic Features of the Lower Missouri River by Segment
Sheet 2 - Kansas City Segment

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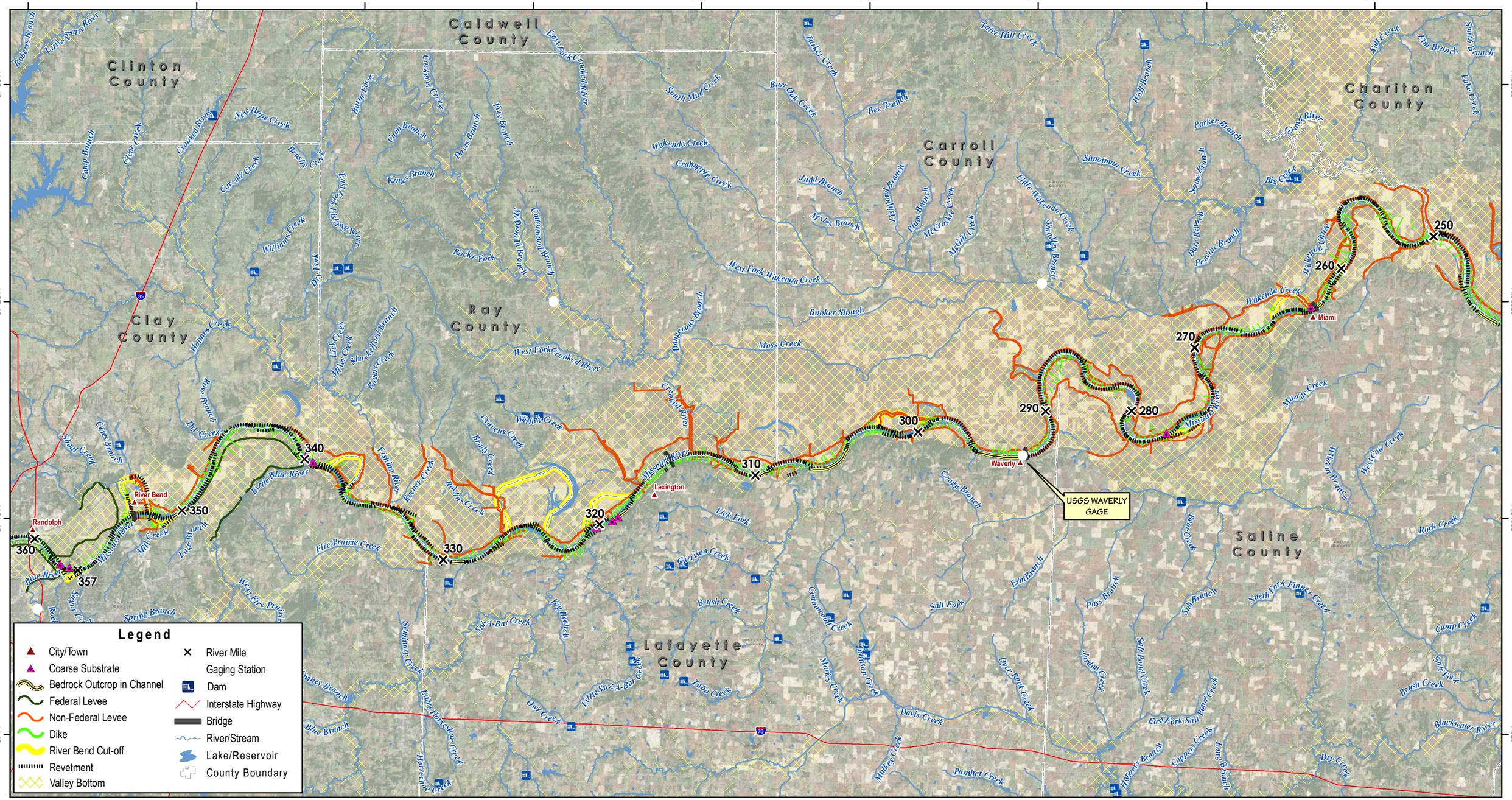

Figure 3.4-2
Geomorphic Features of the Lower Missouri River by Segment
Sheet 3 - Waverly Segment

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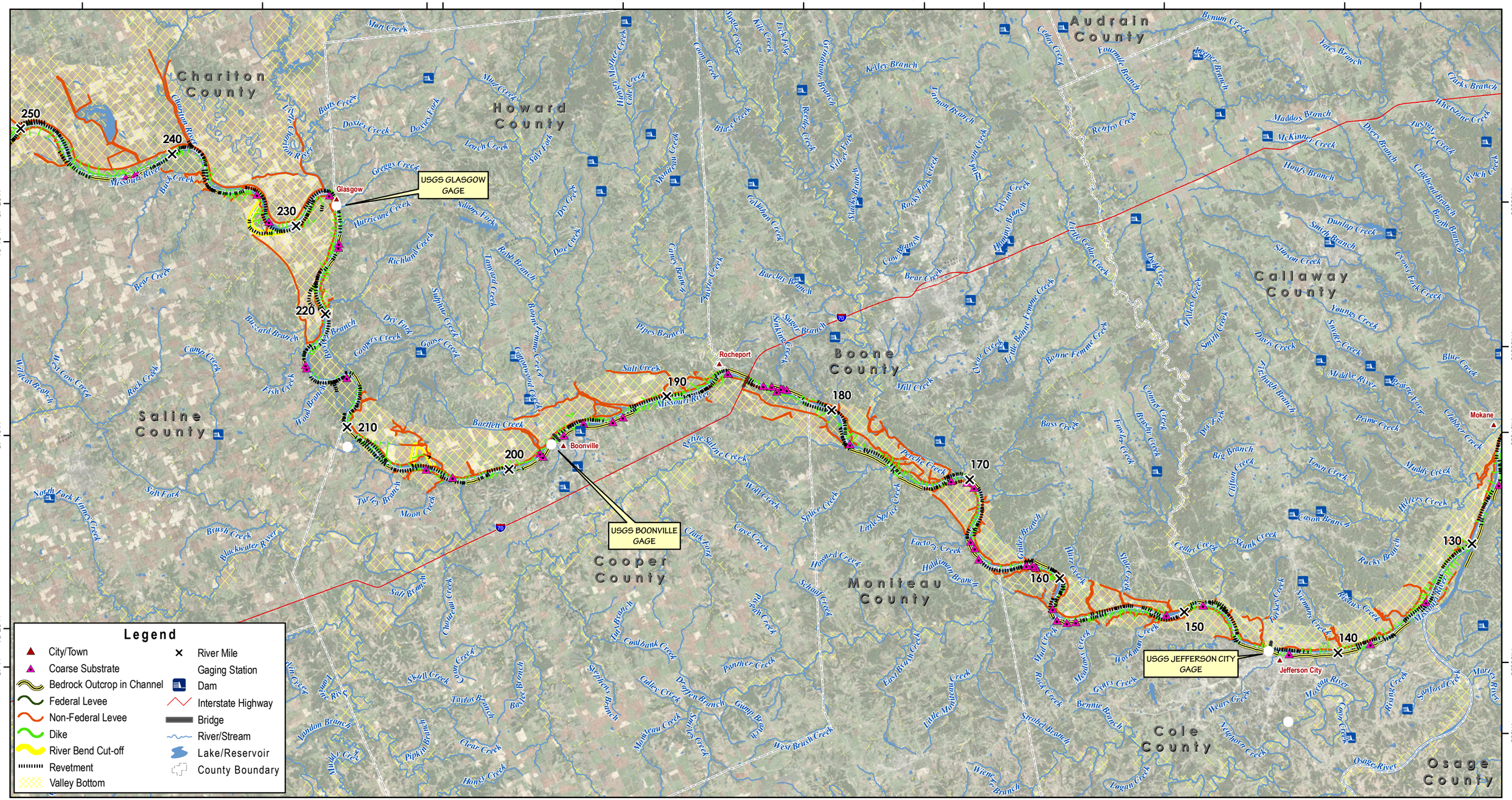
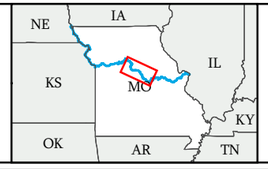


0 10 20 Miles

0 10 20 Kilometers

Figure 3.4-2
Geomorphic Features of the Lower Missouri River by Segment
Sheet 4 - Jefferson City Segment

Missouri River Commercial Dredging EIS



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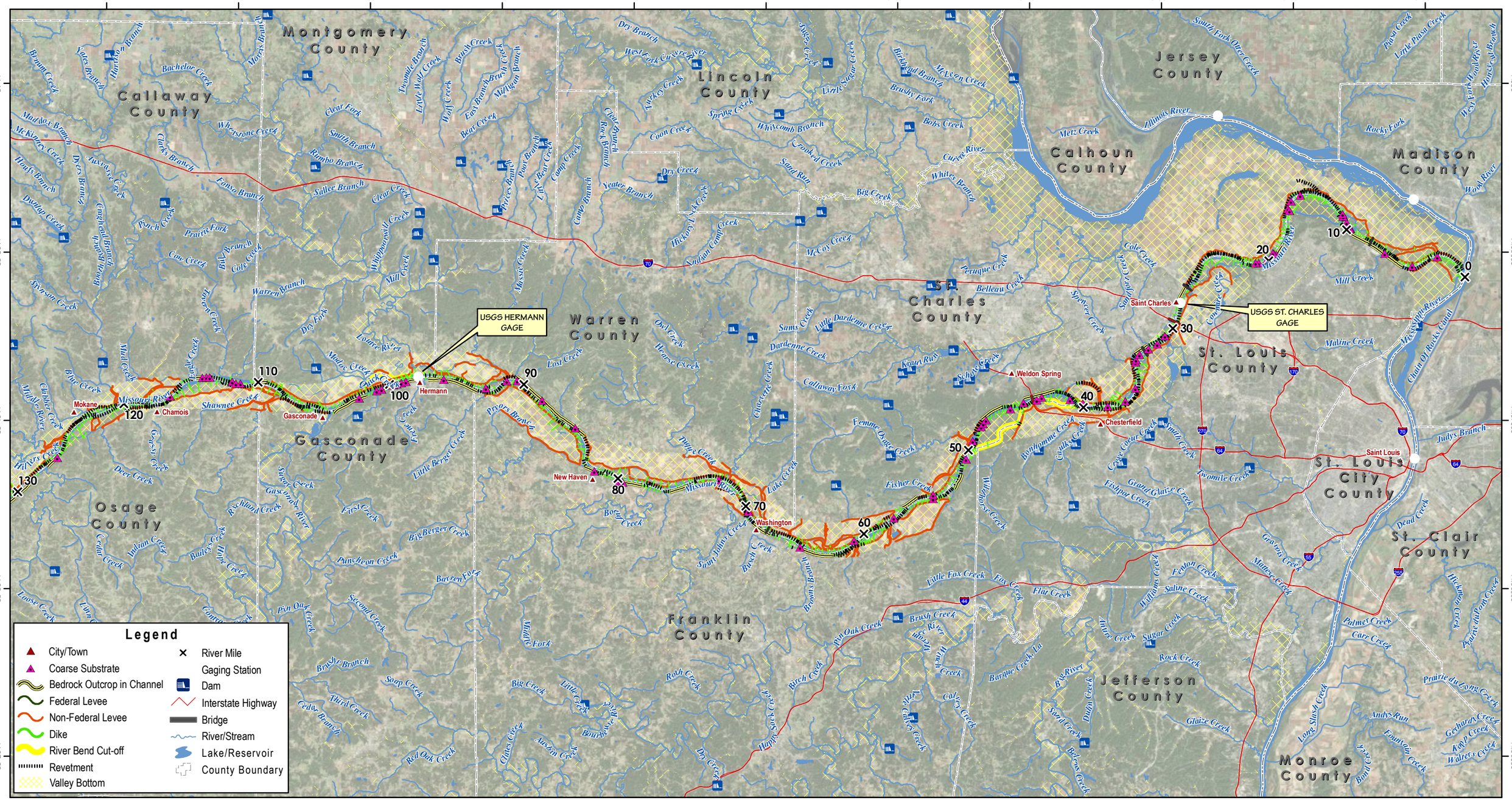

Figure 3.4-2
Geomorphic Features of the Lower Missouri River by Segment
Sheet 5 - St. Charles Segment

Missouri River Commercial Dredging EIS

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3.4.2.2 Effects of Glaciation

Multiple episodes of glaciation occurred on the North American continent over the past 3 million years, but only a few glacial advances reached the present-day location of the Missouri River. The most extensive glaciation occurred between 780,000 and 620,000 years BP. Glaciation from this event significantly altered the drainage patterns of northwestern Missouri and northeastern Kansas. The advancing ice obliterated the existing drainage patterns, and a new course for the Missouri River was established in a post-glacial valley northwest of Kansas City and connected with the existing lower Kansas River valley between Kansas City and the confluence with the Grand River.

Glacial scour and melt water floods from this episode of glaciation over 600,000 years ago is evidenced in the deep valleys and trenches up to 240 feet deep in the bedrock underlying glacial deposits in the Kansas River and Missouri River Valleys in the Kansas City area. During glaciation and subsequent retreat, glacial lakes and spillways formed at the margin of the glacier, carving deep valleys in some areas and widening and deepening existing valleys such as the pre-glacial Kansas River (Colgan 1999). Figure 3.4-1 shows the maximum extent of this early episode of glaciation, which extended south of the LOMR above approximately RM 160 but did not reach the LOMR valley downriver of RM 160.

The most recent episode of glaciation, the Wisconsinian age (75,000 to 10,000 years BP), left extensive outwash deposits of sand and gravel alluvium in the river valleys—even though the glaciers did not extend as far south as Missouri. In a north-south cross section of the Missouri River near Kansas City, the thickness of surficial deposits varies depending on the depth to bedrock in the underlying bedrock valley. The upper 10–35 feet consist of recent (post-glacial) floodplain deposits of silt, clayey-silt, and fine-grained sand. The next 75–100 feet consist of sand and gravel deposited by the most recent Wisconsinian-age glaciers; and the deepest layer above bedrock consists of unsorted glacial till with boulders, sand, and clay likely deposited during the maximum extent of glaciation over 620,000 years ago (Gentile, Moberly, and Barnes n.d). The LOMR valley from approximately RM 226 to the confluence with the Mississippi River is also an alluvium-filled bedrock trench from 60 to 120 feet deep, with alluvium, sand and gravel, and sand, silt, and clay at shallower depths (Spooner 2001).

The Wisconsinian-age episode of glaciation also left deposits up to 100 feet deep of wind-blown loess covering extensive portions of the state (Howe 1968) (Figure 3.4-1). These deposits occur in the northern part of Missouri and western Iowa. As they erode, they contribute to the high suspended sediment loads in the tributaries that drain that region and to the mainstem LOMR (USACE 2009a).

3.4.3 Geomorphic Character of the Lower Missouri River

The pre-contact geomorphologic character of the LOMR, the subsequent human alterations of the LOMR, and the resulting changes to the characteristics of the river channel and floodplain are discussed in this section.

3.4.3.1 The Missouri River prior to Development

Prior to European settlement of the region, the LOMR channel and floodplain were very different from the channel and floodplain of the modern Missouri River system. The pre-settlement river, while still constrained in most places to the floodplain between the bedrock bluffs carved by glacial-era flows, migrated back and forth between valley walls in as little as 70 years (Schlindwein pers. comm.). It transported approximately five times the amount of suspended sediment as the modern river and was often obstructed by snags and trees that had eroded from the river banks. Mean velocities of the river prior to development were slightly lower than modern velocities, while maximum velocities were higher (Blevins 2006).

> The pre-regulation river was characterized by log jams, snags, whirlpools, chutes, bars, cut-off channels, and secondary channels around bars. The main channel typically had a deep thalweg (the deepest part of the river) that contained the faster-moving flow and a shallower section(s) on one or both sides of the channel … The cross-sectional shape of the main channel often exhibited a highly nonuniform velocity distribution (Hesse 1993). The main river channel's width was variable, ranging from roughly 1,000 to 10,000 feet wide during normal flow periods to 25,000 to 35,000 feet wide during floods (Schneiders 1999). (NRC 2002)

Maps from the Lewis and Clark expedition in the early 1800s and mapping efforts in the late 1800s provide information on the geomorphology of the river prior to engineered efforts to create a navigation channel. Figure 3.4-3 shows an example of the movement of the main channel within the river valley at the confluence of the Missouri and Kansas Rivers. The figure shows the river channel location in 1804–1806 compared to the present river channel. Since construction of the BSNP, the wide somewhat braided channel has narrowed considerably. In the early 1800s, the Missouri River at Kansas City was still confined within the bedrock bluffs on either side, but was much wider and less sinuous than the modern channel form (Figure 3.4-1). The main channel was approximately 0.25 mile wide, with some areas including side channels around islands ranging up to 1 mile wide. In contrast, the modern channel is consistently approximately 0.125 mile wide and flows in a different location.

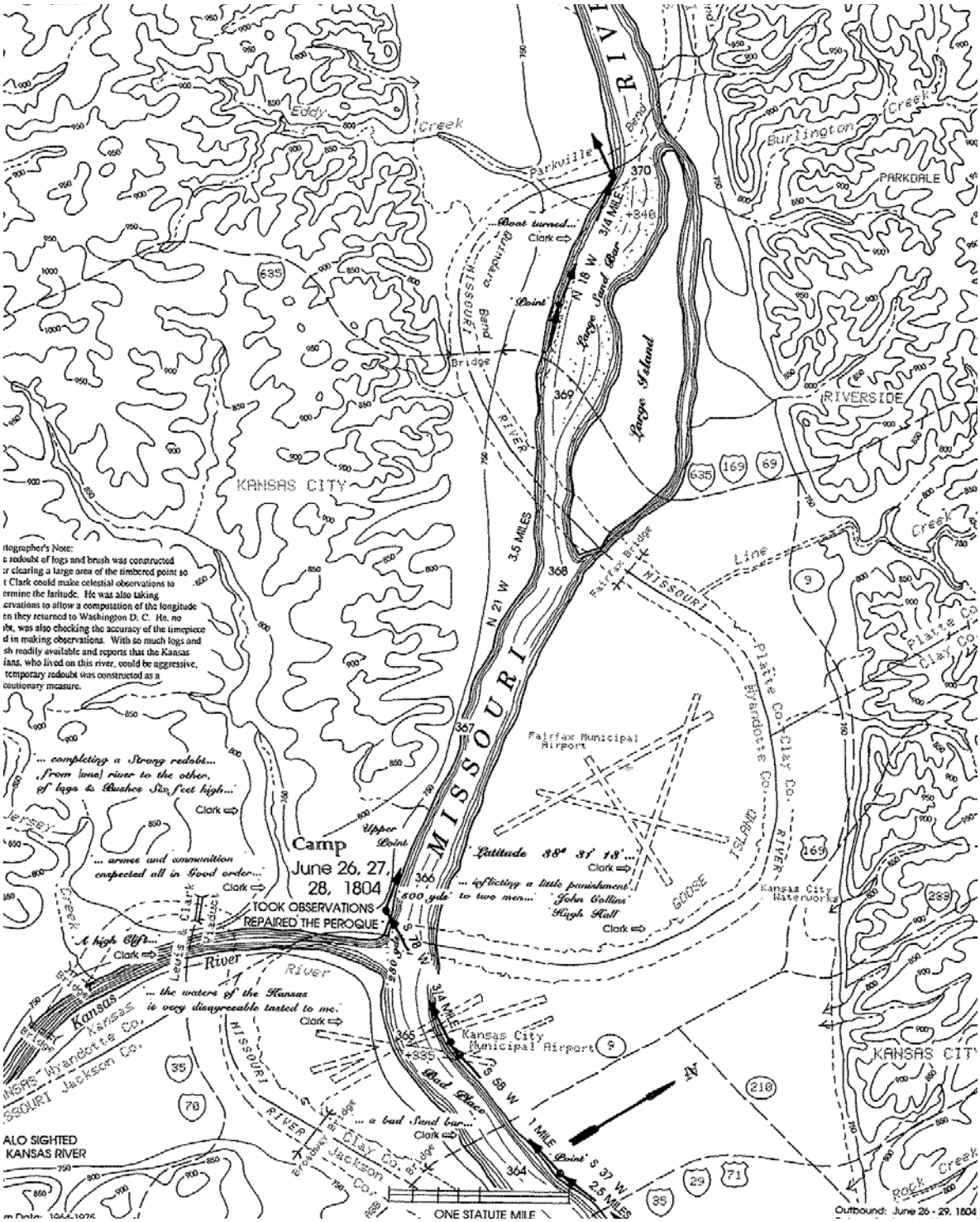


Figure 3.4-3 Map of the Missouri River at the Confluence with the Kansas River (RM 367.5) from the Time of the Lewis and Clark Expedition (1804–1806), with an Overlay of the Modern Missouri River

Source: Plamondon 2000.

3.4.3.2 Alterations of the Missouri River

As described in Section 3.2.4, six dams were constructed on the upper portion of the Missouri River, and the BSNP (consisting of dikes, revetments, and cutoffs) was constructed on the LOMR.

Dams

The construction of six mainstem dams significantly altered the Missouri River while creating the largest reservoir system in North America (Jacobson et al. 2009). Operation of these dams has changed the Missouri River flow regime, water temperatures, and sediment fluxes. The effects of the dams are most dramatic in the upper portion of the river. Although the effects of the dams diminish farther downriver as numerous tributaries contribute sediment and flows to the mainstem, hydrographs and suspended sediment loads are still affected all the way to the confluence with the Mississippi River. In addition, water releases from the dams are managed to reduce spring flood pulses and to augment late-summer and fall flows to improve river navigation.

The Bank Stabilization and Navigation Project

To meet the BSNP objectives of bank stabilization and navigation, the river was trained into a series of smoothly curved bends of the appropriate radii and channel width. The overall effect of the BSNP was to change the geomorphologic character of the river from a wide, braided, free-moving river with multiple channels and with relatively unrestricted access to its floodplain to a more stable, single-channel river suitable for navigation (USACE 1980). Typical BSNP engineered structures include the system of dikes and revetments, river bed and side channel cutoffs, and levees. The following sections describe these structures and their impacts in more detail.

Dikes

Various techniques, including fascine pile and concrete crib dikes and “Kellner jetties,” were used to train the river channel to cease meandering and remain in one location. Prior to 1930, dikes were used primarily to stabilize banks. During the 1930s, long dikes were built perpendicular to the flow across chutes and side channels and inside bank lines to promote sediment accretion in those places and confine the river to the intended navigation channel. Before 1949, pike dikes and woven mattress revetments were the standard methods; in 1949, the Office of Chief Engineers approved the use of quarry–run stone as an alternative construction method for river improvements projects (USACE 1996). By 1960, the modern river channel had been established and the 1930-era dikes were mostly covered

by accreted land. After 1960, low-elevation dikes (dike sills) and L-shaped dikes and revetments were introduced. These dikes were generally shorter and built off of the land that had previously accreted behind the first phase of dikes. Dikes prior to 1960 were generally constructed to the height of the navigation flow, while dikes constructed after 1960 were built to be overtopped for a portion of the navigation season (USACE 1980). Throughout the 1980s, dikes were extended to focus flows into the navigation channel, and more recently were notched in some areas to make the flows less constrictive and to produce shallow-water habitat.

Figure 3.4-4 shows the number of dikes constructed on the LOMR since 1880. With more than 4,500 dikes built between Rulo, Nebraska and the confluence with the Mississippi River, there is an average of nine dikes per mile. The highest density is in the St. Joseph segment, and the lowest is in the Kansas City segment (Table 3.4-3). It is estimated that, because of the BSNP, the active channel top width has decreased by approximately two-thirds, resulting in approximately 150 square miles of accreted land throughout the length of the BSNP (Jacobson et al. 2009).

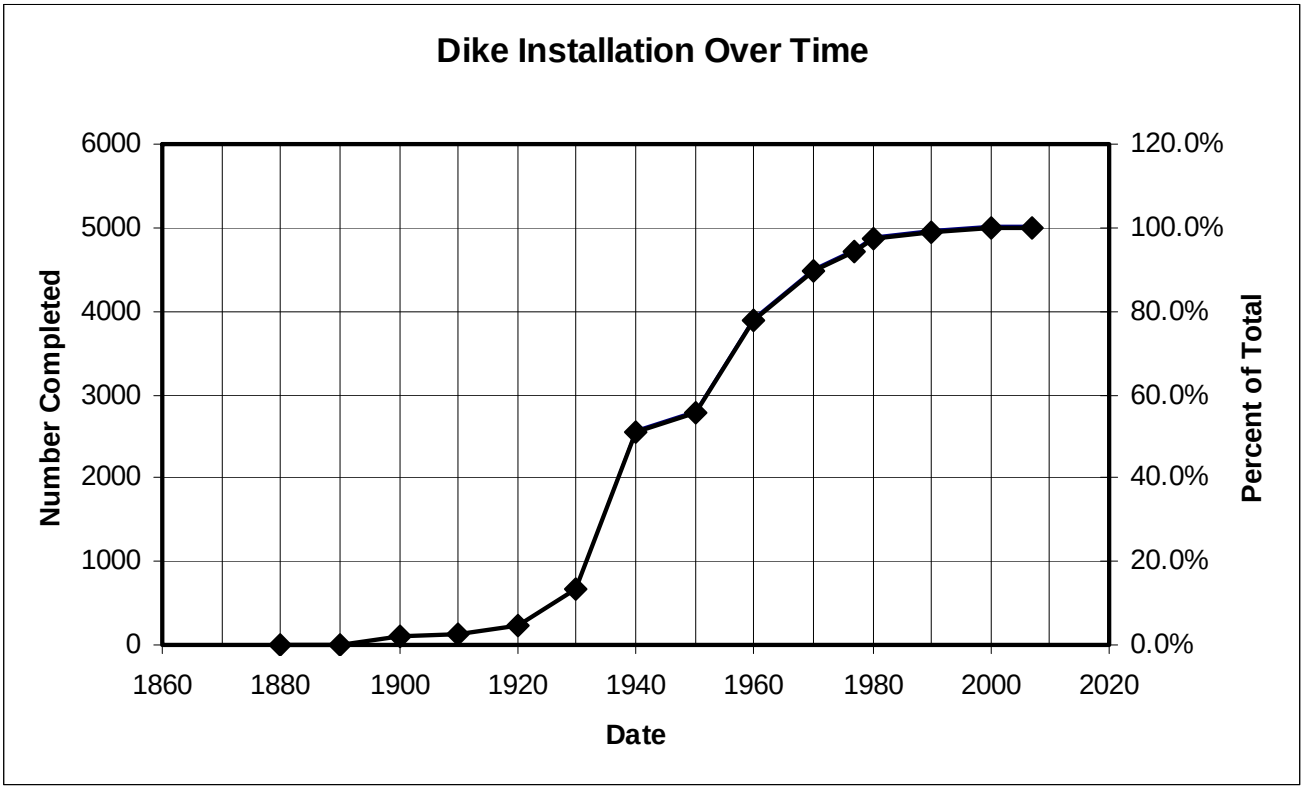


Figure 3.4-4 Number of Dikes Constructed below Rulo, Nebraska and Cumulative Percent of Total

Source: USACE 2009c.

Table 3.4-3 Revetments and Dikes in the Lower Missouri River

Feature	St. Joseph	Kansas City	Waverly	Jefferson City	St. Charles
Revetments (miles)					
Left bank	60	21.6	59.2	61.5	73
Right bank	60.6	22.9	51.5	65.5	54.5
Average miles of revetment per river mile for segment (both banks)	*1.13*	*1.30*	*1.03*	*1.06*	*0.98*
Dikes (count)					
Left bank	523	141	422	545	584
Right bank	599	130	453	556	595
Average number of dikes per river mile for segment (both banks)	*10.49*	*7.92*	*8.18*	*9.18*	*9.08*
Dikes (length in miles)					
Left bank	78.2	21.2	65.1	88	93.7
Right bank	91.9	20.6	69.4	78.4	101.4
Average miles of dikes per river mile for segment (both banks)	*1.59*	*1.22*	*1.26*	*1.39*	*1.50*

Figure 3.4-5 shows a time series of photos taken at the same point over a period of 69 years. The photos were taken upriver of the Project area at Indian Cave Bend (RM 517). The first photo was taken in 1934 and shows initial dike construction. The second photo from 1935 shows the finished dikes on the right side of the photo and sediment starting to fill in. The sand bars in the main part of the river are already gone. The third and fourth photos from 1935 and 1936 show the dike fields rapidly filling with sediment and vegetation establishing on the filled area. The fifth photo, taken 10 years later, shows the dike fields almost completely filled in and forested. The final photo in 2003 shows farm fields and a levee constructed across the edge of the accreted dike fields. This series of photos illustrates how the first phase of dikes (1930–1950) defined the modern river channel.

Revetments

Revetments were one of the first methods used in the early 1900s to protect river banks from erosion and to stabilize the channel location.

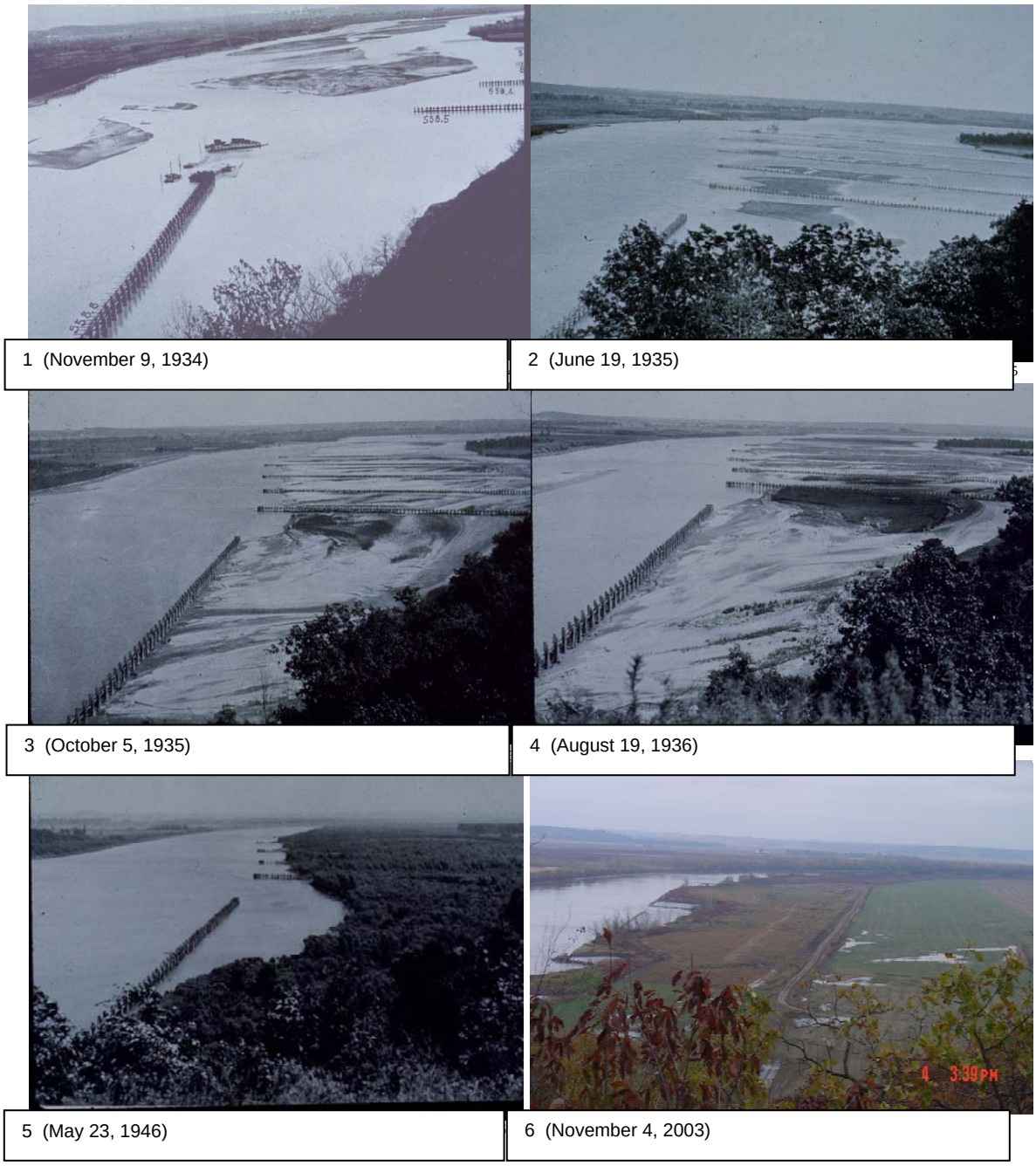


Figure 3.4-5 Time Series of Photos from RM 517 Showing Construction and Filling of Dike Field

Revetments typically consisted of woven willow or beam mats covered with rock. Table 3.4-3 shows the length of revetments for each segment. The Kansas City segment has the highest average number of miles of revetment, and the St. Charles segment has the least.

Figure 3.4-2 shows the locations of dikes and revetments on the river in each segment. At many locations (RM 380, for example, Figure 3.4-2, Sheet 2) long dikes extend from the river's edge into adjacent agricultural fields. These are the areas where the original river channel was narrowed using dike fields. Sediment filled in the area between the dikes, and the area was ultimately converted to agricultural use. The extensive use of revetments on the outside of river bends to prevent erosion and confine the river channel is also illustrated in this figure.

Cutoffs

Since 1890, the length of the Missouri River between Sioux City and the confluence with the Mississippi River has been shortened by approximately 75 miles, or 10 percent. Two-thirds of this shortening was concentrated in two reaches: between Sioux City to Omaha and between Kansas City and Waverly. The overall reduction in river length between 1890 and 1960, primarily by cutting off oxbow bends, is shown in Table 3.4-4. Cutoffs, constructed since 1941, were primarily installed to improve ease of navigation (Figure 3.4-2). Shortening the river increases the local slope of the river because the river bed elevation drops essentially the same amount over a much shorter distance. This typically results in headcuts moving upriver from the cutoff and aggradation occurring downriver from the cutoff as the river adjusts to a new slope.

Table 3.4-4 Changes in Distances between Locations on the Lower Missouri River

	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

Source: USACE 2007c.

Table 3.4-5 lists significant cutoffs between St. Joseph and Waverly. The Liberty Bend cutoff (Figure 3.4-2, Sheet 2) at RM 352 is indicative of riverbed morphology changes associated with river

shortening. Prior to the cutoff, the slope through the oxbow was 0.77 foot per mile (0.0146 percent); a survey of the channel 7 years after the cutoff was opened indicated that the slope had almost doubled to 1.3 feet per mile (0.0246 percent). After 7 years, the channel bottom was 1.3 feet lower at the cutoff, and river bed degradation decreased upriver to a point 8.3 miles above the cutoff where the channel bed elevation had not changed. River bed aggradation occurred for 21.3 miles downriver and reached a maximum bed elevation increase of 2 feet 10.5 miles downriver (USACE 1980).

Table 3.4-5 Significant Cutoffs between St. Joseph and Waverly

Cutoff	River Mile	Decrease in River Length (miles)	Year Completed
Napoleon Bend	324	8.2	1915 (natural)
Big Blue Bend	357–358	0.8	1941
Liberty Bend	350–354	4.3	1949
Jackass Bend	337–339	2.5	1957
St. Joseph	450	6.2	1956

Levees

Levees restrict the river's access to floodplain flow buffering and sediment recruitment. When waters rise, flows are routed between the levees, thus increasing the height of the floodwaters and eliminating floodplain energy dissipation. Figure 3.4-2 shows federal and non-federal levees for each segment. Levees are frequently built away from the mainstem LOMR along tributaries to protect against floodwater from the LOMR flowing up the tributaries, particularly within the valley bottom. Virtually all of the LOMR from the mouth to Rulo has a federal or non-federal levee along its banks (Figure 3.4-2).

Federal levees on the LOMR (Table 3.4-6) are primarily located between Kansas City and Rulo, although two are downstream of Kansas City. Five urban levees are located in the Kansas City metropolitan area, and the rest are between Kansas City and Rulo. These levees, constructed since 1950, protect approximately 153,000 acres; in St. Joseph, Kansas City, and St. Charles, they constrict the floodway to less than 0.5 mile wide (USACE 2004).

Almost 100 non-federal agricultural levees along the LOMR protect approximately 476,000 acres of primarily agricultural land (USACE 2004). These levees are managed by private levee districts and often extend up tributaries or away from the LOMR to protect agricultural lands from moderate floods, with 5- to 25-year return intervals. Three non-federal levees protect urban areas below RM 45 in the St. Charles area (USACE 2004). The non-federal levees below RM 535 on the Missouri River failed during the 1993 flood, except for several in the St. Louis area (USACE 2004).

Table 3.4-6 Federal Levees on the Lower Missouri River

Levee Unit	Location along the Missouri River
R-513	RM 497.5 – RM 495
R-500	RM 484.4 – RM 480
L-497	RM 482.4 – RM 476.7
L-488	RM 475.3 – RM 465.2
R-482	RM 468.4 – RM 458
L-476	RM 461.0 – RM 454.0
R-471-460	RM 456.5 – RM 441.8
L-455	RM 445.6 – RM 437.6
L-448-443	RM 437.6 – RM 428
R-440	RM 431 – RM 424.3
L-408	RM 401.3 – RM 391.5
L-400	RM 391 – RM 385
Fairfax-Jersey Creek	RM 374 – RM 367.5
North Kansas City	RM 370.5 – RM 363.5
Central Industrial District (CID)	RM 367.4 – RM 365.7
East Bottoms	RM 365.7 – RM 357.5
Birmingham	RM 360.3 – RM 354.0
R-351	RM 350 – RM 339.7
L-246	RM 250 – RM 239
Chariton River Mainstem	RM 238.8 – RM 227.3
New Haven	RM 81.7 – RM 81.4

Note: RM = River mile.

Source: USACE 2004.

Current Channel Configuration of the Lower Missouri River

The BSNP created a navigation channel on the LOMR that is a minimum of 300 feet wide and 9 feet deep during a typical navigation season (Table 3.4-7). The BSNP, in combination with the levee system and controlled releases from the upstream reservoirs, has fundamentally changed the geomorphic nature of the river. Prior to the BSNP, the river would deposit sediment on the floodplain during flood events, erode and deposit extensive in-river bars and islands, and erode river banks as the channel moved back and forth across the valley. The pre-BSNP river (Figure 3.4-6) had multiple side

channels, a deeper center channel, oxbow lakes, islands, sand bars and dunes, and backwater habitats with areas of higher ground (NRC 2002).

Table 3.4-7 Design Widths for the Missouri River Bank Stabilization and Navigation Project

Reach	Channel Width (feet)	Channel Width to Sills (feet)
Rulo to Kansas River (RM 498 – RM 367)	800	550
Kansas River to Grand River (RM 367 – RM 250)	900	600
Grand River to Osage River (RM 250 – RM 130)	1000	650
Osage River to mouth (RM 130 – RM 0)	1,100	750

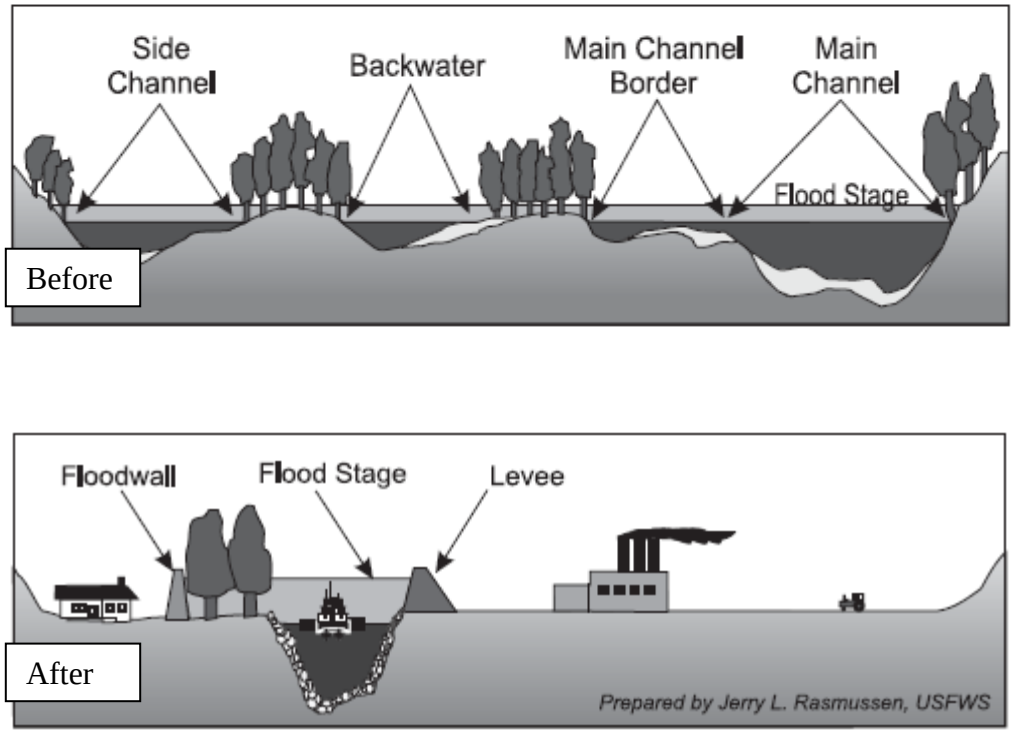


Figure 3.4-6 Typical Cross Section before and after the Missouri River Bank Stabilization and Navigation Project

Source: NRC 2002; Original source: Rasmussen 1999.

Since construction of the BSNP and other infrastructure along the river, flows are constrained to a designed channel that efficiently routes sediment through the system to maintain a clear navigation

channel. Bank erosion and river channel migration have largely been eliminated. Levees constrain flood flows along most of the river to the floodway channel, resulting in increased stages at higher flows at most gage locations along the river.

3.4.4 Hydrology

Flows in the LOMR drive the geomorphic processes that shape the river. Water flow volume and velocity are the main factors in sediment movement through the system. Flows are driven by a combination of natural and human-induced factors and vary by season and year. Dams built over 50 years ago upriver from the Project area have affected the magnitude and timing of flows, and levees and dikes have constrained flows and altered flood peaks.

3.4.4.1 Lower Missouri River Basin and Tributaries

The Missouri River is the longest river in the continental United States (2,315 miles) with a drainage area of 524,110 square miles. Its basin comprises 74 percent of the total upper Mississippi River basin. The Missouri River contributes approximately 42 percent of the long-term average annual flow of the Mississippi River at St. Louis (USACE 2004). Approximately 109,200 square miles of the Missouri River basin occurs within the Project area, and its river bed elevation drops 451 feet—with an average slope of 0.8–1.0 feet per mile.

Flow measurements and other data have been collected at multiple sites along the mainstem Missouri River (Table 3.4-8, Figure 3.4-2) and at sites on most of its major tributaries.

The flow contribution to the mainstem LOMR from each tributary (Table 3.4-9) cannot be estimated because there are no gaging stations at the confluence of the tributaries with the mainstem of the Missouri River. However, the drainage area for each tributary provides a relative measure of the flow it contributes to the LOMR. Figure 3.4-7 shows the percent increase in flow on the mainstem Missouri River at gage locations moving down the river as a function of the additional drainage areas contributed by major tributaries. For example, the drainage area increases significantly (by 15 percent) between the St. Joseph and Kansas City gages where the Kansas and Platte Rivers join the Missouri River, resulting in a 19.9-percent increase in mean annual flow. Between the Boonville and Hermann gages, the drainage area increases 4 percent with the contributions of the Gasconade and Osage Rivers, resulting in a 28.4-percent increase in mean annual flow. This illustrates the differences in annual

precipitation in the Missouri River basin, with much less to the west where the Kansas and Platte Rivers flow, compared to tributaries flowing from the wetter south and east (see Section 3.4.4.2 for details).

Table 3.4-8 Flow Data on the Lower Missouri River

Gage Name	USGS Gage Number	River Mile	Number of Years of Record			
			Discharge	Stage	Annual Peak	Field Measurements
Missouri River at St. Charles, MO	6935965	28	9	25	8	16
Missouri River at Hermann, MO	6934500	97.9	81	22	82	81
Missouri River at Jefferson City, MO	6910450	143.9	0	15	0	0
Missouri River at Boonville, MO	6909000	197.1	84	17	85	84
Missouri River at Glasgow, MO	6906500	226.3	9	9	9	60
Missouri River at Waverly, MO	6895500	293.2	81	19	79	81
Missouri River at Kansas City, MO	6893000	366.1	81	19	81	81
Missouri River at St. Joseph, MO	6818000	448.1	81	18	89	81
Missouri River at Rulo, NE	6813500	498	59	24	61	59

Notes:

MO = Missouri.
NE = Nebraska.
USGS = U.S. Geological Survey.

Sediment sampling data in addition to flow data are available for the highlighted gages and were used in the sediment load analysis.

The flows from major tributaries are nearly equally distributed between the right and left river banks of the LOMR (USACE 2006). The Platte, Kansas, Little Blue, Chariton, Little Chariton, and Osage Rivers—along with some of their tributaries—are regulated by dams (USACE 2008) (Figure 3.4-2). Water releases from some of the USACE and U.S. Bureau of Reclamation (USBR) dams are coordinated with dam releases on the mainstem Missouri River to reduce flooding and maintain navigation depths.

Table 3.4-9 Significant Tributaries to the Lower Missouri River

Tributary Name	River Mile/Side of River (Facing Downstream)	Drainage Area (square miles)	Dams or Flow-Regulating Structures?
Big Nemaha	494.9 Right	1,926	No
Nodaway	462.3 Left	1,935	No
Platte (Missouri)	391.1 Left	2,503	Smithville Lake on Little Platte
Kansas	367.5 Right	60,580	Seven USACE reservoirs and 11 USBR reservoirs
Big Blue	356.9 Right	307	No
Little Blue	339.5 Right	409	Two USACE reservoirs and a county lake
Grand	249.9 Left	7,883	No
Chariton	238.8 Left	2,566	USACE reservoir 140 miles upstream
Little Chariton	227.2 Left	761	One USACE reservoir, one private
Lamine	202.5 Right	2,783	No
Osage	129.9 Right	15,088	Seven major impoundments, the lowest 80 miles from mouth
Gasconade	104.4 Right	3,582	No

Notes:

USACE = U.S. Army Corps of Engineers.
USBR = U.S. Bureau of Reclamation.

Source: USACE 2004.

3.4.4.2 Precipitation Patterns

Drainage basin precipitation and releases from upstream reservoirs determine the amount of water flowing in the LOMR. Precipitation patterns vary in three ways:

- Spatial distribution across the LOMR basin;
- Year to year variation; and
- Monthly variations in precipitation within the annual cycle.

Each is important to define the overall hydrology of the LOMR.

Average annual precipitation patterns vary spatially across the Missouri River basin. Precipitation is lowest near the headwaters in the upper basin and is highest in the lower basin near the confluence with the Mississippi River. The average annual precipitation throughout most of the LOMR basin is between 30 and 40 inches, while the average annual precipitation within the basin south of Kansas City

and Jefferson City, Missouri is between 40 and 50 inches (USACE 2006). Typically, weather systems bring moist air and precipitation from the Gulf of Mexico. Precipitation trends in the Kansas City and St. Louis areas show increases from approximately 35 inches per year at both locations to 40 inches per year from 1948 to 2005 (Figure 3.4-8). Precipitation in the LOMR basin is quite variable and subject to multiple-year droughts, with frequent periods of dry conditions interspersed with periods of abundant or excessive precipitation (USACE 2006) (Figure 3.4-8).

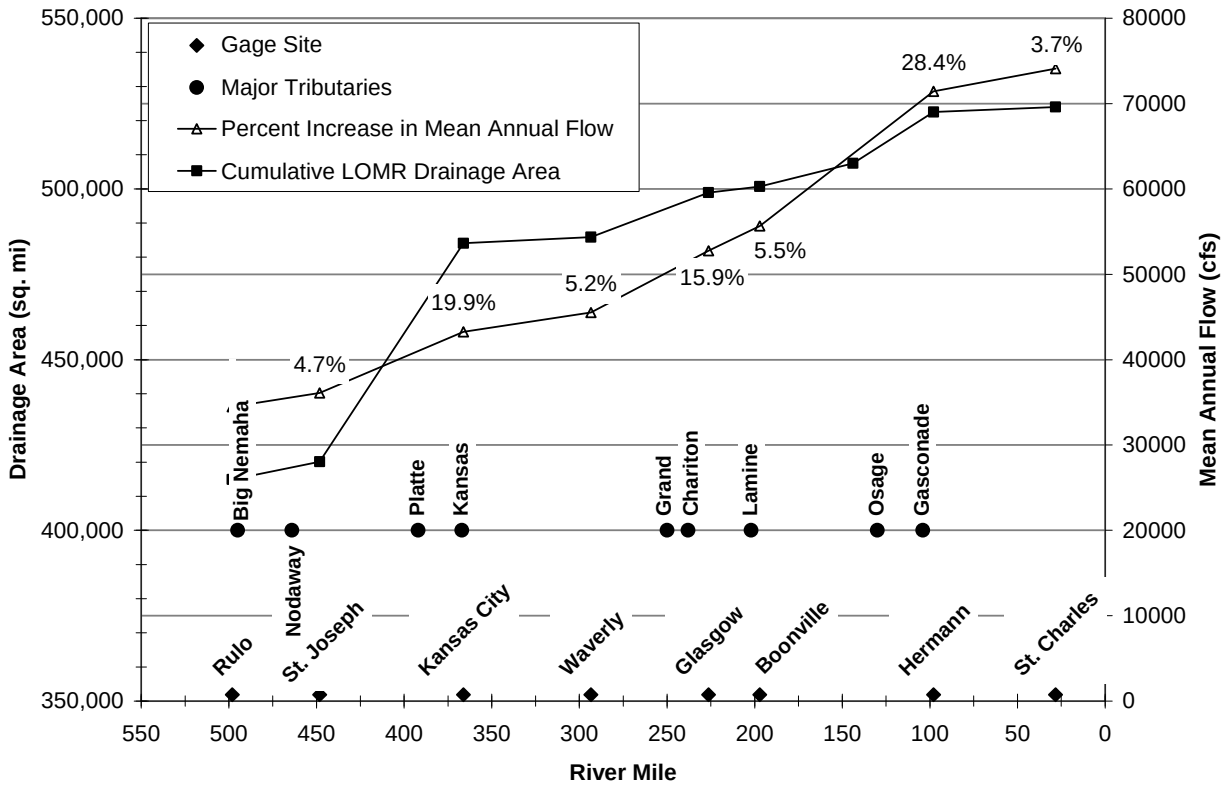


Figure 3.4-7 Cumulative Drainage Area and Mean Annual Flows for the Lower Missouri River

The monthly distribution of rainfall between Kansas City and St. Louis differs even though the average annual precipitation is similar (Figure 3.4-9). St. Louis typically has drier summers and wetter winters than Kansas City and less variability between summer and winter precipitation levels. Precipitation during winter typically falls as snow in both cities. Precipitation is typically greatest in late spring and early summer, with June typically being the wettest month of the year (USACE 2006).

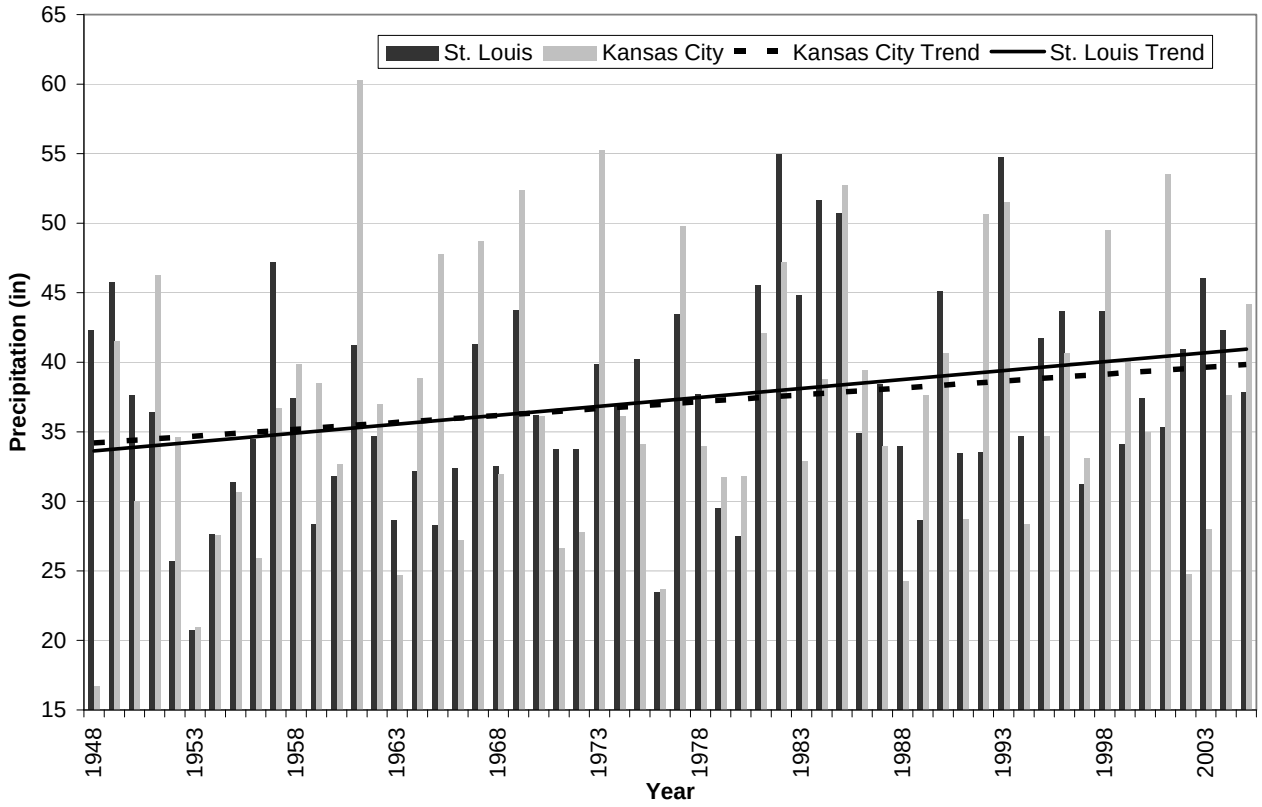


Figure 3.4-8 Annual Precipitation and Long-Term Trends for Kansas City and St. Louis, Missouri (1948–2005)

3.4.4.3 Flow Modifications

As described in Section 3.2.4, the LOMR is a highly regulated system with multiple dams upstream of the proposed Project area that alters the natural flow regime (USACE 2006, Pegg, Pierce, and Roy 2003). The lowest mainstem dam (Gavin's Point at RM 811) was completed in 1955 and has regulated downstream LOMR flows since that time. Flow regulation has primarily changed the timing and quantity of flows immediately downriver of the dam. Further downstream however, these changes are reduced due to inflows from major tributaries (Pegg, Pierce, and Roy 2003; Jemberie, Pintner, and Reno 2008). Figure 3.4-10 shows how the annual hydrograph for the Kansas City and Hermann gages changed from before the dam was completed to after the dam was completed.

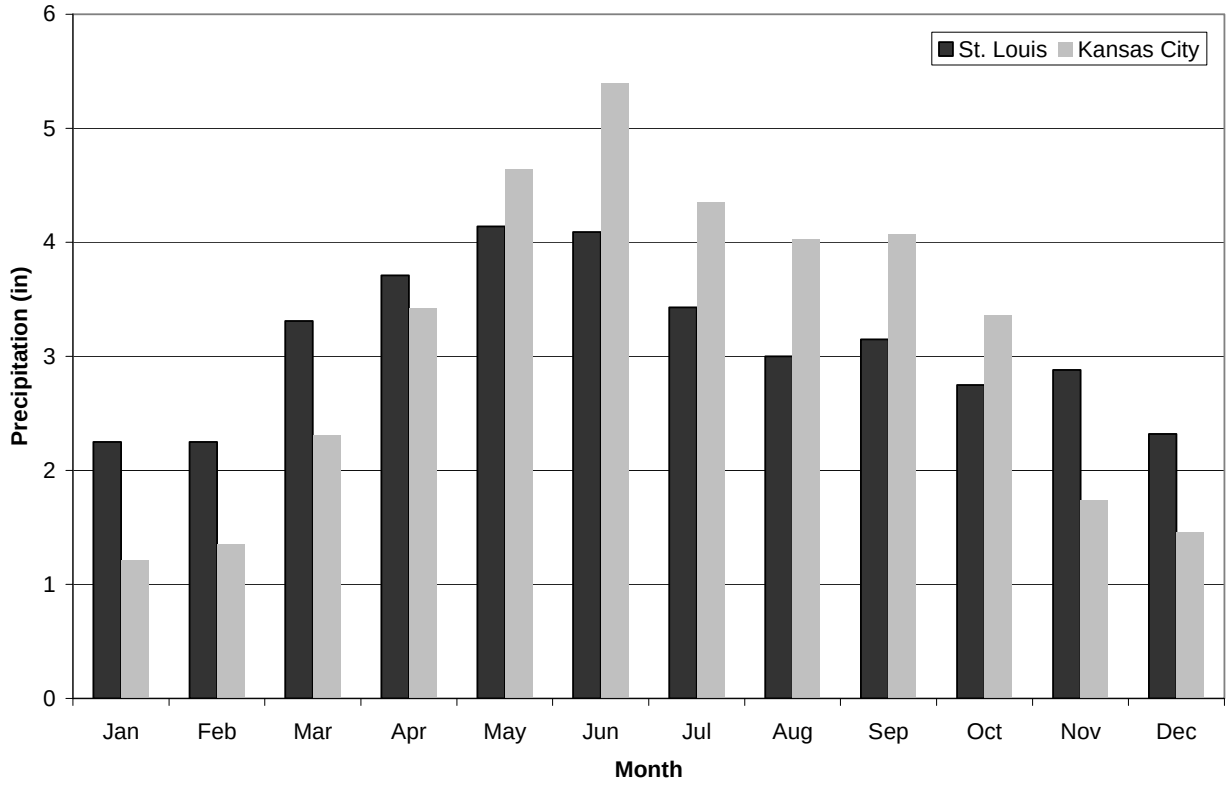
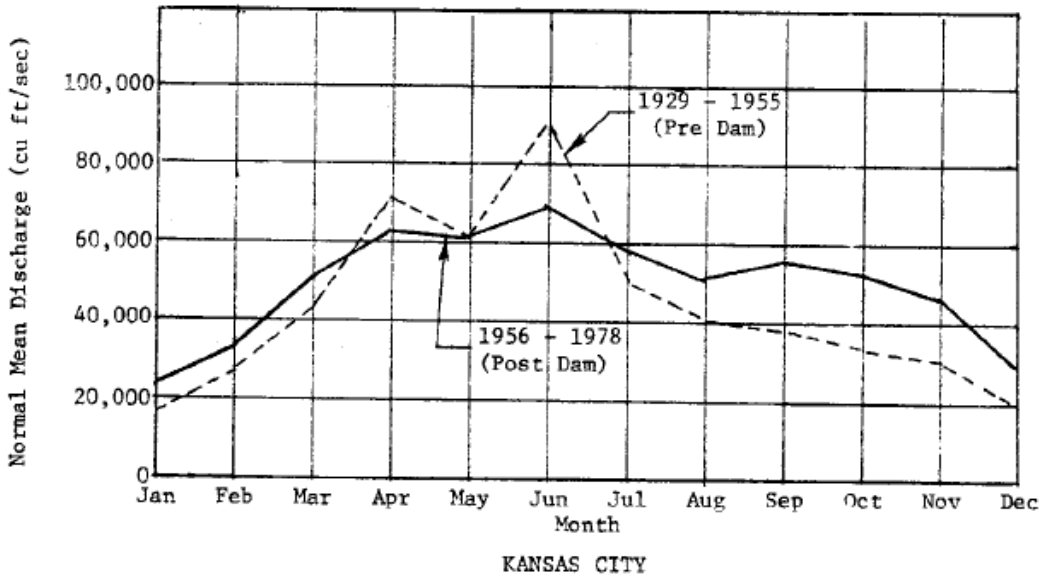


Figure 3.4-9 Mean Monthly Precipitation for Kansas City and St. Louis, Missouri (1948–2005)

Under current regulation, peak runoff from the spring melt and summer peaks from rainstorms in the upper portions of the Missouri River basin are captured behind the dams and discharged to supplement low flows in the late summer, fall, and winter (USACE 2006). Flow duration curves for four different time periods at the Kansas City gage on the mainstem Missouri River illustrate the effects of the implementation of flow regulations on the LOMR system (Figure 3.4-11). Two of the periods (1928–1946 and 1947–1964) are prior to complete implementation of flow regulation, and two are after full flow regulation implementation. Since full flow regulation, high flows have been reduced in frequency, and periods of low flows have been reduced compared to historical conditions. Moderate flows have increased substantially, as peak flows stored in reservoirs behind the dams are released during the rest of the year. Because flow is a key variable in sediment transport, long-term changes in flow regime can result in significant changes in sediment loads, particle sizes, and channel shape.



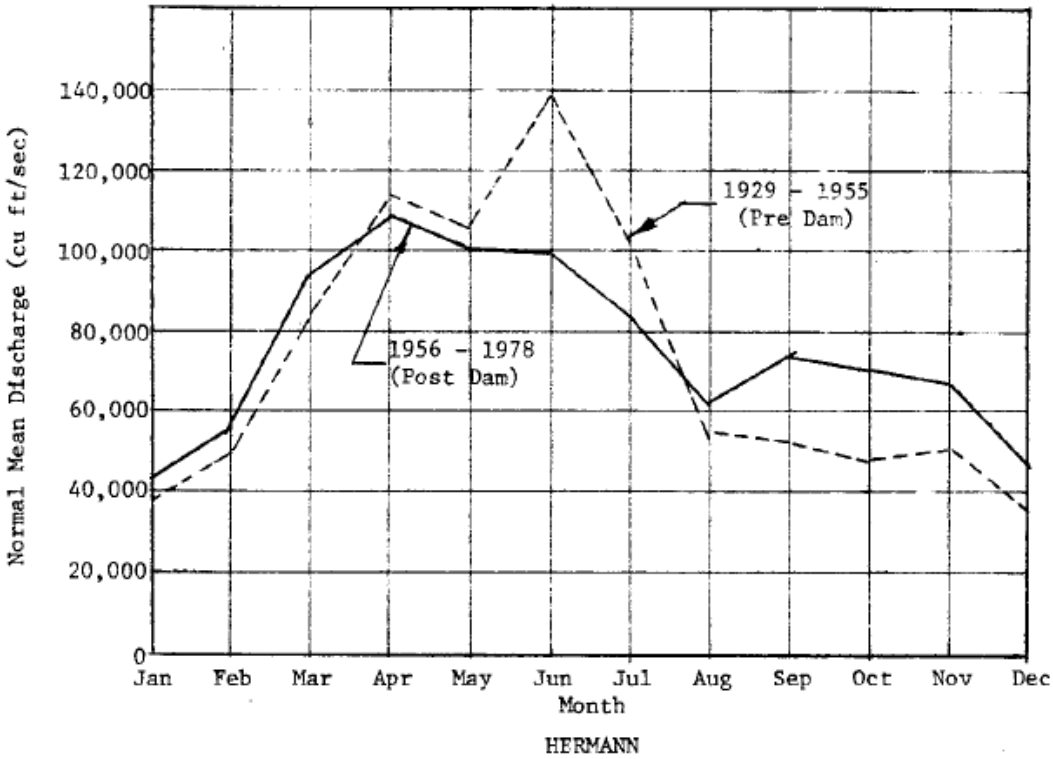


Figure 3.4-10 Mean Monthly Discharge for 1929–1955 and 1956–1978 on the Missouri River at Kansas City and Hermann, Missouri

Source: USACE 1980.

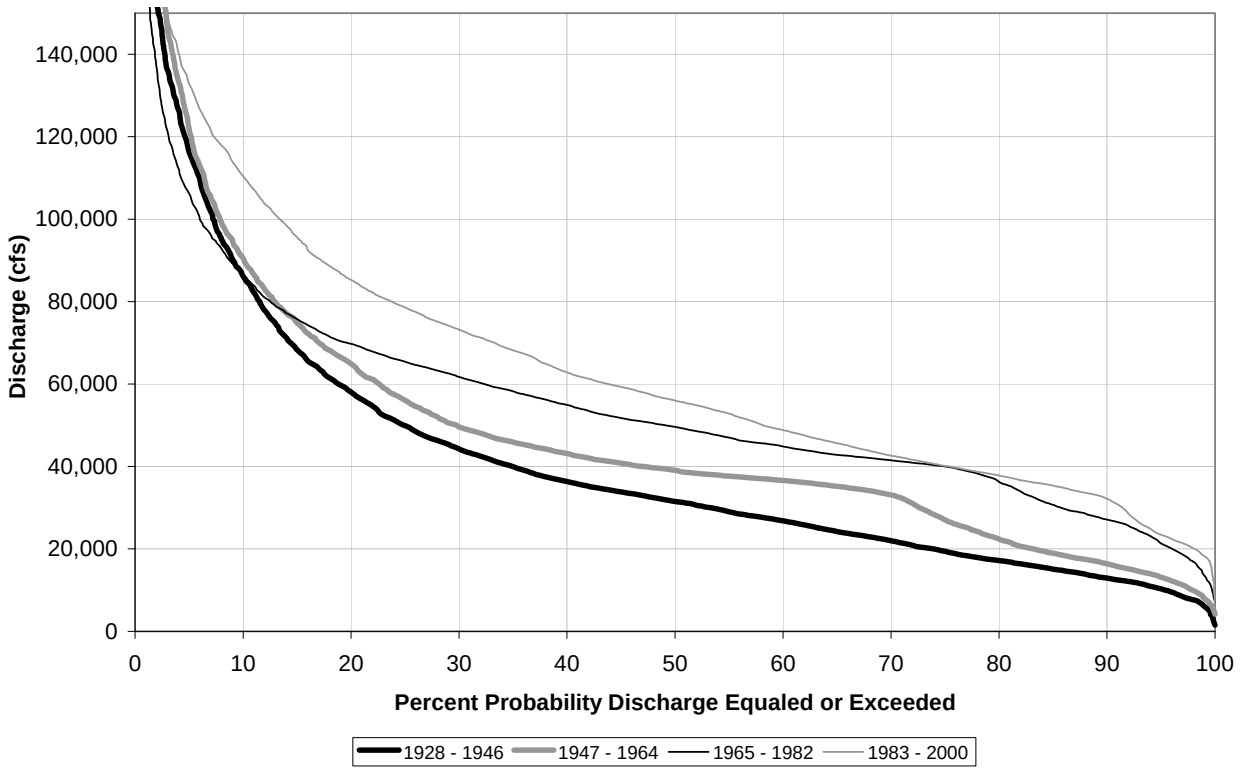
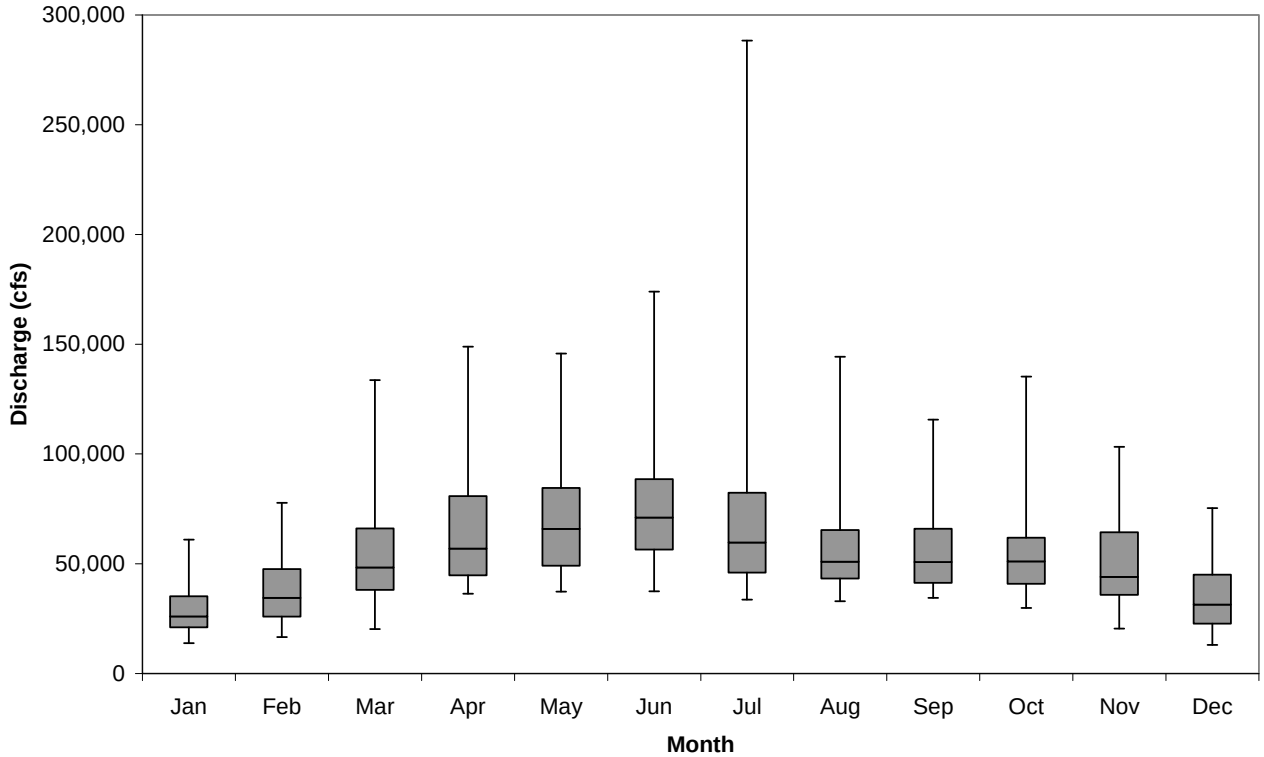


Figure 3.4-11 Flow Duration Curves on the Missouri River Measured at Kansas City, Missouri

Source: USACE spreadsheet "FlowDuration_MoRgages_Qdur.xls.

3.4.4.4 Flow Regime

Typically, during March and April, the accumulated ice and snow in the upper Missouri River basin melts, resulting in an early spring rise (Figure 3.4-12). The highest peak discharges between the headwaters and the Kansas River during the spring rise result from the spring break-up of ice jams in the upper basin (USACE 2006). Snowmelt from the plains and subsequent rainfall in the lower basin also contribute a substantial quantity of spring flow to the LOMR. Summer and fall are typically characterized by diminished rainfall and runoff, but severe storms during this period have caused severe flooding along the LOMR and its tributaries (USACE 2006). Winter flows are typically low due to the general lack of precipitation (Figure 3.4-9), although occasional large precipitation events have resulted in occasional winter flooding (USACE 2006).



Boxes represent the upper and lower quartile [25% and 75%] above and below the median, displayed as the line in the box. Lines above and below represent the whole range of recorded values.

Figure 3.4-12 Monthly Flow Statistics Measured on the Missouri River at Kansas City, Missouri (1929–2008).

The two largest peak flow events recorded at the Missouri River Kansas City gage occurred in 1951 and 1993 (Figure 3.4-13). Periods of low flow occurred during the 1950s, the 1980s and early 1990s, and the 2000s. Although mean flows are typically less than 100,000 cubic feet per second (cfs), flows above 200,000 cfs are not uncommon.

Mean annual flows at the gages on the Missouri River at St. Joseph, Kansas City, and Hermann, Missouri (Figure 3.4-14) demonstrate how inputs from tributaries and precipitation variability (Figure 3.4-8) influence downriver annual mean flows. All three gage locations show increasing flows over the period of record, with the Hermann gage showing the greatest increase.

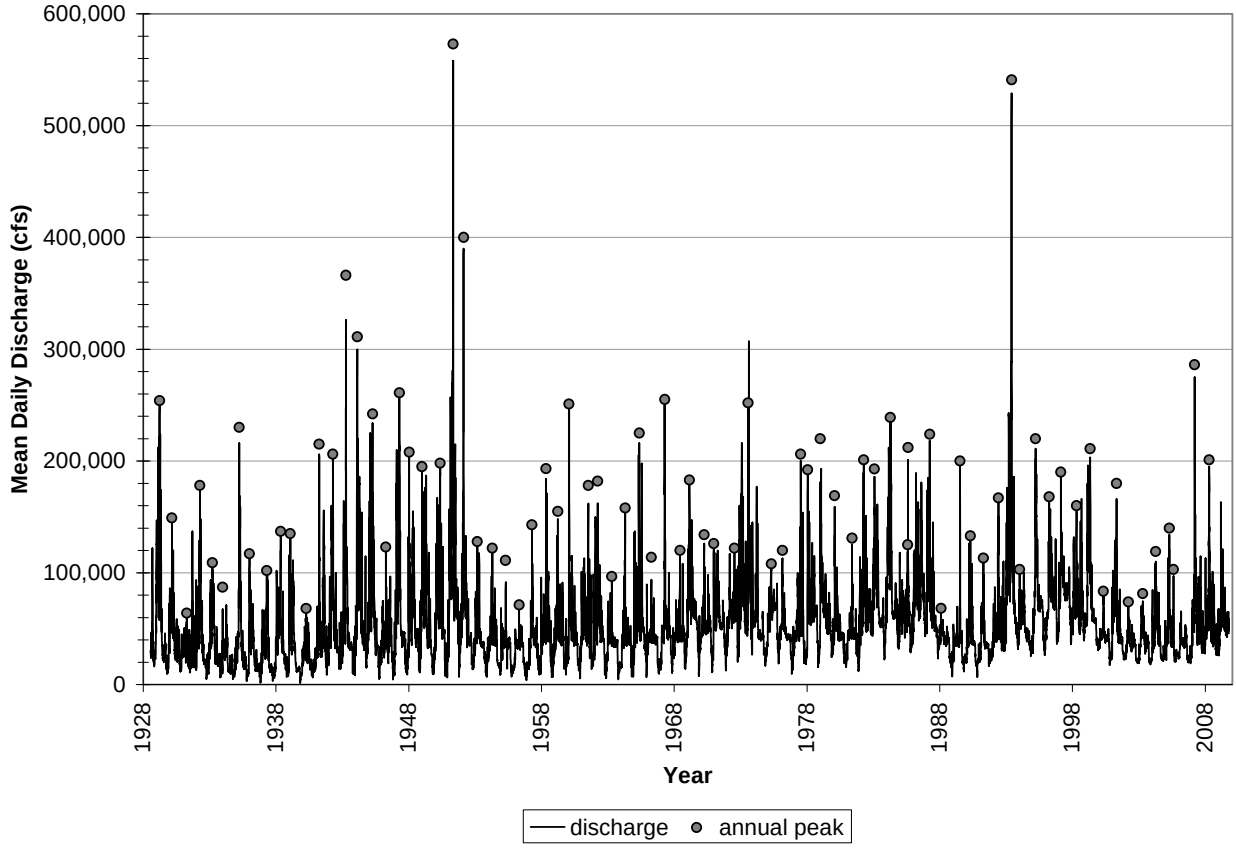


Figure 3.4-13 Mean Daily Discharge and Annual Flow Peaks Measured on the Missouri River at Kansas City, Missouri (1929–2008)

The variability of flows on the LOMR is shown by the range of annual (Table 3.4-10) and seasonal (Table 3.4-11) minimum, maximum, and average daily flows. The table shows that maximum discharges vary from approximately 287,000 cfs at Rulo to approximately 739,000 cfs at Hermann, a more than two-fold difference. Average daily flows approximately double from Rulo to Hermann, illustrating the significant difference in hydrologic conditions between the upper portion of the LOMR in the St. Joseph and Kansas City segments and the lower portion of the LOMR in the Hermann and St. Charles segments.

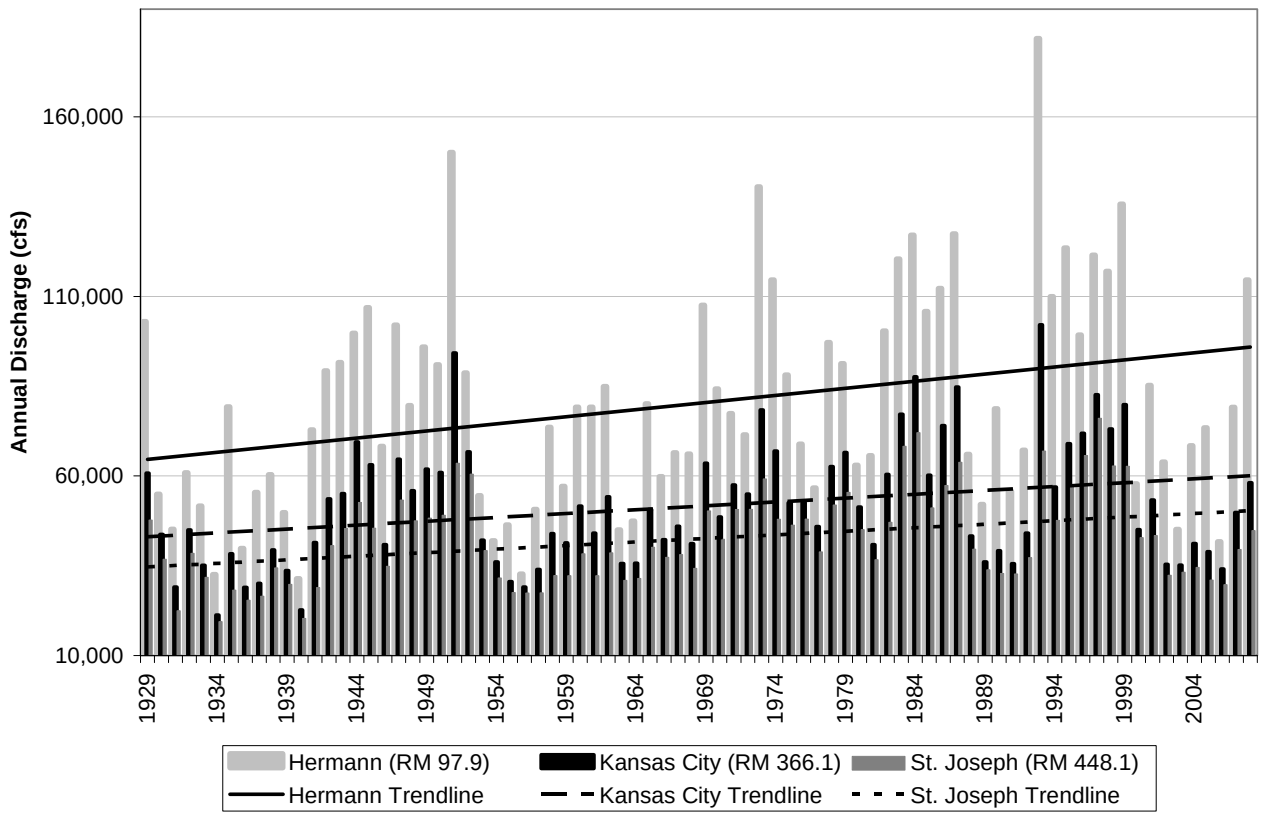


Figure 3.4-14 Mean Annual Flow and Long-Term Trends Measured on the Missouri River at St. Joseph, Kansas City, and Hermann, Missouri (1929–2008)

Navigation Flows

The USACE regulates releases from upstream dams to support navigation in the LOMR, one of the congressionally authorized purposes of the upstream dams. The Missouri River navigation channel extends for approximately 735 miles from Sioux City, Iowa to the Missouri River confluence with the Mississippi River (USACE 2007b). The normal navigation period typically extends from the spring rise through an average 8-month ice-free season that can run (depending on the river segment) from late March/early April to late November/early December (USACE 2006). During this 8-month period water is released from upstream dams and combined with tributary inflows to meet target downstream flows (USACE 2006). Due to the evolving nature of the LOMR channel (see Section 3.4.2), navigation levels are determined based on flow targets instead of river stage. Downstream target navigation flow volume and duration are based on the actual quantity of water in storage in the reservoir system.

Table 3.4-10 Minimum Daily, Maximum Daily, and Average Daily Discharge on the Lower Missouri River

Monitoring Station	Maximum Daily Discharge (cfs)	Minimum Daily Discharge (cfs)	Average Daily Discharge (cfs)
Missouri River at Rulo, NE [a]	289,000	4,420	42,470
Missouri River at Kansas City, MO [b]	529,000	4,730	57,000
Missouri River at Waverly, MO [b]	611,000	5,000	58,720
Missouri River at Boonville, MO [b]	721,000	5,000	69,200
Missouri River at Hermann, MO [b]	739,000	6,210	87,950

Notes:

cfs = Cubic feet per second.
MO = Missouri.
NE = Nebraska.

[a] Period of record between 1953 and 2001.
[b] Period of record between 1958 and 2001.

Source: USACE 2006.

Target flows at four downstream locations are used to plan the quantity of water to be released in order to provide full or minimal navigation services in a particular year (USACE 2006). Target navigation flow discharges at Kansas City (one of the four downstream control locations) are 41,000 cfs during full-service years and 35,000 cfs during minimum service years. Navigation targets are generally exceeded during flood periods, when system releases are based on appropriate floodwater evacuation from the dam/reservoir systems (USACE 2000).

In 2003, the USFWS issued an amended biological opinion for the operation of the Missouri River mainstem reservoir system operations (USFWS 2003, USACE 2008). Under the amended biological opinion, USFWS called for a bi-modal spring flow release from the Missouri River dams to benefit pallid sturgeon. These pulses are timed with the commencement of navigation flows and include downstream flow limits to minimize the risk of flood damage (USACE 2009b). To manage the bi-modal spring flow releases, the USACE has implemented adaptive management techniques that include system storage, downstream flows, and regulated tributary releases in order to achieve desired flow levels in an initial pulse in March and a secondary pulse in May (USACE 2008). Spring pulse releases are estimated to increase river stage as far downstream as Hermann, Missouri (USACE 2009b).

Table 3.4-11 Minimum Daily, Maximum Daily, and Average Daily Seasonal Discharges on the Lower Missouri River

	Winter Runoff (December, January, February)			Plains Snowmelt and Rainfall (March, April, May)			High Mountain Snowmelt and Rainfall (June, July, August)			Fall Runoff (September, October, November)		
Monitoring Station	Maximum Daily Discharge (cfs)	Minimum Daily Discharge (cfs)	Average Daily Discharge (cfs)	Maximum Daily Discharge (cfs)	Minimum Daily Discharge (cfs)	Average Daily Discharge (cfs)	Maximum Daily Discharge (cfs)	Minimum Daily Discharge (cfs)	Average Daily Discharge (cfs)	Maximum Daily Discharge (cfs)	Minimum Daily Discharge (cfs)	Average Daily Discharge (cfs)
Missouri River at Rulo, NE [a]	57,400	10,000	26,300	106,000	15,400	48,500	165,000	29,800	51,100	83,900	17,000	43,800
Missouri River at Kansas City, MO [b]	77,700	13,000	35,200	149,000	20,200	67,200	288,000	33,800	69,100	135,000	20,600	56,100
Missouri River at Waverly, MO [b]	79,800	13,000	36,500	168,000	19,200	69,400	306,000	34,400	71,600	142,000	21,600	56,700
Missouri River at Boonville, MO [b]	106,000	13,800	43,900	235,000	19,500	85,700	375,000	36,600	82,000	188,000	24,600	65,200
Missouri River at Hermann, MO [b]	179,000	17,100	61,500	333,000	22,800	115,000	376,000	39,500	99,900	287,000	29,400	79,200

Notes:

cfs = Cubic feet per second.
MO = Missouri.
NE = Nebraska.

[a] Period of record between 1953 and 2001.
[b] Period of record between 1958 and 2001.

Source: USACE 2006.

3.4.4.5 Droughts and Floods

Droughts and floods are significant because they affect flows that govern sediment transport and storage.

Significant Droughts

Detailed basin runoff records extending back to 1898 document four significant periods of drought (USACE 2006). The 12-year-duration Depression-era drought (1930–1941) is the longest on record and included the three lowest runoff years on record. A second significant drought that extended the reservoir filling time of newly constructed dams occurred from 1954 to 1961. Both of these droughts occurred prior to completion of construction of all of the Missouri River dams and reservoirs. Two additional droughts have been documented since the dams were completed in 1967. The shortest recorded drought from 1987 to 1992 had the fourth lowest recorded runoff year (1988). In 1989, the navigation season was shortened, and service levels were 3,000 cfs below full service, resulting in numerous groundings of ships on the LOMR. Subsequent years saw further shortening of the navigation season and lowering of service levels. The 1989 drought triggered revisions to the Master Water Control Manual to improve the implementation and timing of water conservation measures. During the recent drought (2000–2007), similar water conservation actions were implemented, with record low river levels from October through December and a 30-day shorter navigation season (USACE 2006).

Significant Floods

Due to flow regulation by mainstem dams, annual flooding on the Missouri River between Gavins Point Dam and the Platte River in Nebraska (RM 590) has been essentially eliminated (USACE 2006); however, portions of the LOMR downstream of the Platte River in Nebraska have sufficient tributary inflow to result in over-bank events (USACE 2006). The USACE Kansas City District manages 18 flood control reservoirs on tributaries to the Missouri River, and the USBR operates 11 lake projects primarily for irrigation purposes that also provide flood control on the Kansas River (USACE 2004).

The 10 largest floods recorded at gage stations along the LOMR from 1898 to 1997 are listed in Table 3.4-12. The earliest recorded flood on the Missouri River with sufficient information for analysis occurred in 1844. This largest known flood within the LOMR system set river stage records throughout the river basin. The early spring floods of 1881 resulted in major flooding in the upper basin. Heavy

snows during the winter of 1880–1881 combined with an early spring thaw in the upper basin to produce multiple ice jams. Severe floods from prolonged heavy rainfall occurred in 1903, 1908, and 1927. Severe floods in 1943 and 1947 resulted primarily from melting snow and ice jam formation in the upper basin (USACE 2006).

The magnitude of the 1951 flood on the lower basin was similar to the 1844 flood. Above-average late spring rain followed by heavy rains during summer resulted in record flood levels at many locations on the LOMR (USACE 2006). The following year, a broad area of the upper basin was covered in deep snow and sustained a prolonged period of sub-freezing temperatures. In late March 1952, a rapid warm-up resulted in severe flood conditions throughout the upper basin of the Missouri River and its tributaries. This flood resulted in the most extensive (both the upper and lower basins) flooding to affect the entire Missouri River basin (USACE 2006).

After completion of the upper basin dams in 1967, the snowmelt- and precipitation-driven floods originating in the upper basin could be dampened or eliminated. Floods originating in the upper basin in 1967, 1975, 1978, 1984, 1986, and 1987 were suppressed by reservoir storage (USACE 2006). In 1993, following 6 years of drought, late spring and persistent summer rains resulted in major flooding on the LOMR. Although most of the precipitation and runoff occurred in downstream reaches, the dams were instrumental in flow controls that prevented overtopping of the federal levees in Kansas City and St. Louis. The 1993 flood breached the non-federal levees between Brownsville, Nebraska (RM 535) and the confluence with the Mississippi River (USACE 2004), except for several in the St. Louis metropolitan area. Subsequent upstream floods in 1995, 1996, 1997, and 1999 were successfully suppressed by the dams reducing downstream flooding impacts.

Although flooding in the LOMR typically occurs during the March to July flood season, flooding outside of this season has occurred due to excessive rains within the tributary basins (USACE 2006). Based on past, current, and forecasted hydrometeorological conditions, minimum- and full-target flows can be modified and system releases can be decreased to provide greater flood control during the flood runoff season (USACE 2006). When significant runoff could result in the loss of life or property, the flood control capability of the upstream regulation system becomes the highest system management priority (USACE 2006).

Table 3.4-12 Ten Largest Floods Recorded at Gage Locations on the Lower Missouri River (1898–1997)

	Gaging Station					
Rank	Rulo	St. Joseph	Kansas City	Waverly	Boonville	Hermann
1	1952	1952	1951	1993	1993	1993
2	1993	1993	1903	1951	1903	1903
3	1984	1903	1993	1952	1951	1951
4	1947	1908	1952	1944	1944	1995
5	1949	1917	1908	1943	1947	1944
6	1944	1909	1943	1965	1909	1943
7	1950	1912	1915	1947	1908	1986
8	1943	1987	1974	1915	1927	1973
9	1960	1920	1944	1995	1943	1947
10	1951	1929	1909	1929	1995	1935

Source: NRC 2002.

3.4.5 Sediment Transport and Loads on the Lower Missouri River

3.4.5.1 Introduction

Water flow and sediment transport are the primary variables that govern river bed aggradation and degradation, as well as the volume of sediment that may be available for commercial sand and gravel dredging. The type and distribution of sediment in the river is also important for analyzing changes in river geomorphology and channel configuration over time. Key variables on the LOMR analyzed relative to potential dredging impacts include:

- Historical sediment loads;
- Sources and classification of river sediment;
- Sediment transport mechanisms;
- Particle size distribution of suspended and deposited sediment;
- Suspended sediment (including sand) loads on the mainstem and tributaries; and
- Bed material load estimates.

3.4.5.2 Historical Sediment Loads

Prior to dam construction and flow regulation, the Missouri River existed in a dynamic equilibrium with its floodplain, frequently redistributing sediment between its channel and floodplain (NRC 2002, pg 56). Sediment transport loads were substantially higher; and sediment recruitment through erosion tended to be most severe as flood waters were rising, with substantial deposition of sediment occurring as flood waters receded. Comparatively little data exist relative to historical bed load or bed load transport in the Missouri River; however, measurements of turbidity and suspended sediment have been collected in recent decades, and these variables have changed dramatically as a result of construction of dams and the BSNP.

Information on the range of suspended sediment loads in the Missouri River prior to dams and the BSNP is available from some late 19th century and early 20th century data collection. For example, samples collected by the USACE in 1879 from the River at St. Charles, Missouri yielded 4,100 milligrams per liter (mg/l) of suspended sediment. Samples collected from the same location in 1900 and 1907 had median concentrations of suspended sediment ranging from approximately 1,600 to approximately 2,320 mg/l for lower and higher flows, respectively. In contrast, median suspended sediment concentrations for samples collected from 1973 to 2002 (after construction of upstream dams and the BSNP) from Hermann, Missouri were less than 10 percent of the median concentration in the 1879 measurements and less than 25 percent of the median concentration in 1907. The reduction in suspended sediment and turbidity is attributed to the mainstem dams and later bank stabilization efforts. After the dams were completed, "…almost immediately turbidity decreased by more than 50 percent… later dams and further bank stabilization likely decreased turbidity even more" (Blevins 2006).

Changes in average annual suspended sediment load measured at four gages on the LOMR are shown on Table 3.4-13. These measurements are based on a recent study by Jacobson et al. (2009) that included historical sediment load estimates.

Table 3.4-13 Annual Suspended Sediment Loads at Four Locations on the Lower Missouri River (tons/year)

Gaging Station	Nebraska City	St. Joseph	Kansas City	Hermann
River Mile	562.6	448.2	366.1	97.9
1949–1952	N/A	297,844,432	308,867,542	359,794,310
1968–1980	32,407,943	70,106,980	67,240,971	84,877,947
1981–1993	45,304,982	85,539,334	58,422,483	80,358,472
Percent change (from 1949–1952 to 1981–1993)	N/A	-76%	-78%	-76%
Percent change (from 1968-–1980 to 1981–1993)	40%	22%	-13%	-5%

Note: N/A = Not available.

Source: Jacobson et al. 2009.

The first filling of the six Missouri River mainstem reservoirs occurred between 1937 and 1963 (Jacobson et al. 2009). The BSNP was being constructed during the same period. Jacobson et al. consider the 1949–1952 period representative of the pre-dam suspended sediment loads but not prior to the influence of the BSNP. The two 12-year periods after the upstream dams were completed and filled address post-dam trends[2]. The Missouri River at St. Joseph, Kansas City, and Hermann experienced 76- to 78-percent decreases in suspended sediment loads.

Sediment from upstream is effectively trapped behind the lowermost mainstem dam (Gavin's Point Dam) at RM 811, and degradation and channel coarsening has occurred downriver from the dam as a result of reduced sediment load. Downriver from Gavin's Point, the sediment load increases with recruitment from tributaries and channel/bank erosion. For example, the sediment load at Omaha, Nebraska (RM 616) is less than 15 percent of pre-dam conditions, while further downstream current sediment loads are estimated to range between 16 and 50 percent of historical levels (Jacobson et al. 2009, USACE 2006).

[2] Jacobson et al. (2009) also report average annual sediment loads for the 1994–2006 period. These values are not presented in this report because the USGS recently completed a study to generate new values dating back to 1994 using recently acquired records. The new values are included in Table 3.4-16.

3.4.5.3 Sources of Sediment

Sediment carried by the LOMR comes from a variety of sources and occurs in a variety of sizes. While some fine-grained suspended sediment likely originates upstream of the dams, the majority of the sediment moving within the river erodes from remaining unprotected bank areas along the river or from tributaries eroding the surrounding watersheds. The amount of sediment in the river is influenced by several factors, including:

- Land use practices;
- River bank and floodplain erosion; and
- Geology of surrounding watersheds.

Land use practices play a significant role in the amount of sediment produced by a watershed, and changing land use in the LOMR watershed has affected sediment recruitment. For example, one study estimated that soil erosion on cropland in the Missouri River basin decreased on average 38 percent between 1982 and 2003 due to erosion control practices (Jacobson et al. 2009).

It is unlikely that the river banks or the floodplain of the LOMR supply much sediment to the river due to the extensive engineering structures to prevent erosion and channel the river (Jacobson et al. 2009, pg 9). However, the sandy river bottom likely contributes sediment in degrading reaches, as do tributaries that undergo headcutting as a result of degradation in the main river channel.

The geology and soil characteristics in the surrounding watershed also affect the type and availability of sediment. The LOMR watershed in northern Missouri has extensive deposits of fine-grained, wind-deposited loess soil. These deposits are the source of much of the fine material carried as suspended sediment by the LOMR. Other sources of material include coarser sand and cobbles deposited as glacial outwash in the glacially carved bedrock canyon, and sediment delivered by tributaries such as the Osage River (now blocked by dams) and the Gasconade River that originate in the Ozark plateau to the south (Section 3.4.2 and Table 3.4-14).

Table 3.4-14 Cumulative Frequency Particle Sizes of Bed Material at Four Gage Locations on the Lower Missouri River

Cumulative Frequency Particle Size (mm)	Gaging Station			
	Nebraska City	St. Joseph	Kansas City	Hermann
D_{10}	0.20	0.20	0.19	0.23
D_{16}	0.25	0.23	0.22	0.25
D_{50}	0.45	0.35	0.36	0.55
D_{65}	0.70	0.45	0.50	0.78
D_{84}	1.50	0.75	1.00	1.60
D_{90}	2.00	0.85	2.00	1.90

Notes:

mm = Millimeter.

The cumulative frequency particle size ranges from D_{10} (equals the diameter of a particle where 10 percent of the material in the bed is finer) to D_{90} (the diameter of a particle where 90 percent of the bed is finer). These gradations represent the typical bed material sizes at the locations shown.

Sources: USGS and USACE 2001–2009 data (see Appendix A).

3.4.5.4 Sediment Particle Sizes and Transport Mechanisms

Several terms are used to describe the size, source, and transport mechanism of sediment in the LOMR system. Figure 3.4-15 shows the relationship between sediment particle sizes (silt, sand, and clay), the transport mechanism (bed load or suspended sediment), and the source of the material (wash load or bed material load).

The size of individual sediment particles determines how they are transported by the river and how they interact with the river bed. The Udden-Wentworth scale is used to classify particle sizes into silt-, sand-, and gravel-sized material (Wentworth 1922). Particle sizes smaller than 0.0625 mm are in the silt and clay size category and are generally carried by the river suspended in the water column. Sand-sized particles range from 0.0625 to 2.0 mm and are transported both as suspended sediment and along the river bed as bed material load. Gravel-sized particles larger than 2.0 mm occur in the river bed and are transported as bed load. Sediment dredged for commercial sand and gravel production typically ranges from fine sand- through gravel-sized particles (Figure 3.4-15).

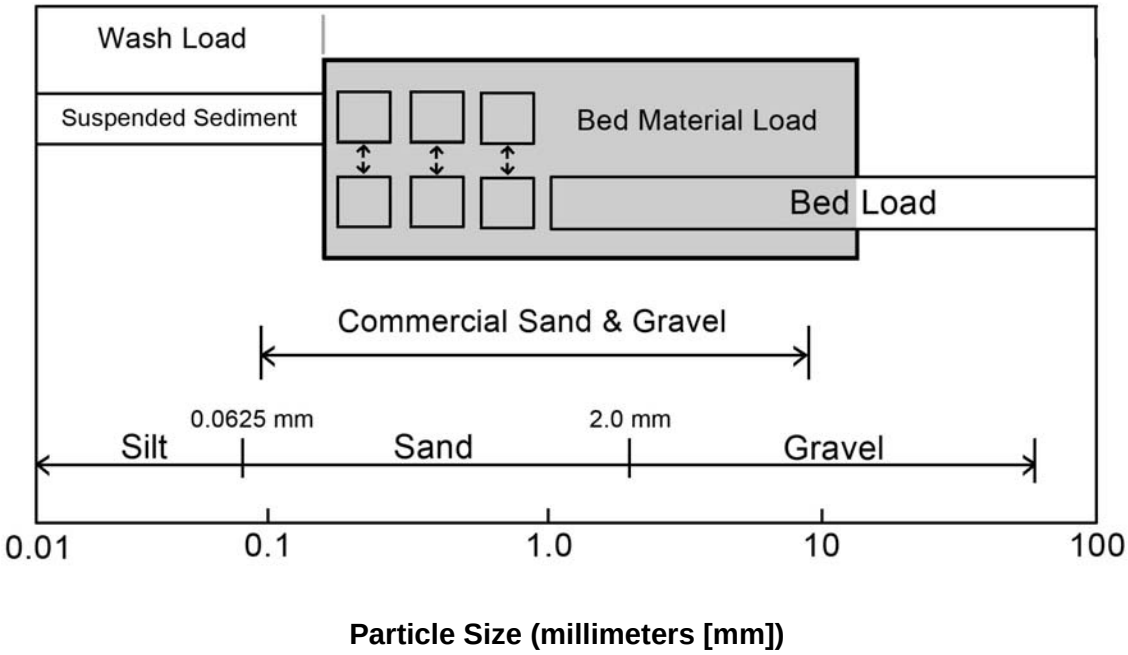


Figure 3.4-15 Sediment Transport Mechanisms and Sediment Sources

Suspended Sediment and Bed Load

Suspended sediment consists of material that is transported by the river in the water column. At low to moderate flows, turbulent eddies may not be sufficiently strong to transport fine- and medium-sized sand in suspension; thus, the sand is deposited on the river bed and transported as bed load. As flow strength increases with higher flow, turbulent eddies bring up the sand from the bed into suspension in the water column, where it is transported. On the LOMR, suspended sediment sizes range from silt and clay to approximately 1-mm sand-sized particles. Particles that may be part of the bed load at a specific flow rate become re-entrained as suspended load if the flow velocity increases (Figure 3.4-15). Because flow velocity constantly changes, the relative proportion of bed load and suspended sediment load also constantly changes.

Medium to coarse sand and gravel particles are generally transported as bed load in migrating dunes on the river bed. Bed load consists of particles moving along or near the bed by rolling, sliding, or saltating (hopping) depending on flow strength and random flow turbulence. Because the source of bed load is scour of the bed material, the same particle sizes moving as bed load comprise the majority of the particle sizes in the bed substrate. Further, because the channel bed is composed of the same

material being transported as bed load, changes in bed load transport rates directly influence channel morphology and channel stability. Imbalance between the capacity of the river to transport sediment (the transport capacity) and the supply of bed material affects the river bed. If the energy available to transport bed material exceeds the sediment supply (for example, at higher flows) the river will scour the bed. Conversely, if the energy for transport is less than the sediment supply, sediment will deposit on the bed.

Wash Load and Bed Material Load

Wash load (Figure 3.4-15) consists predominantly of sediment derived from sources other than the river bed, such as channel bank erosion and runoff from the watershed. Turbulent eddies keep these particles suspended in the flow, with minimal interaction with the active channel bed. The largest wash load particle size has been defined as the grain size at which 10 percent of the bed material (bed substrate) is finer; this is called the "D_{10}" of the bed sediment (Einstein 1950). Although the exact value can differ, wash load particle sizes are found in small amounts in the bed sediment. The volume of wash load transported in the river is principally limited by the supply of material, rather than by the transport capacity. Because wash load is transported in suspension at nearly the same velocity as the river's flow, it can be transported through the system during one runoff event. Importantly, increases or decreases in wash load generally do not affect degradation or changes in the shape of a river (Biedenharn et al. 2006).

Bed material load is the sediment that moves down the river in suspension or as bed load. Unlike wash load, the bed material load does not remain in suspension at lower flows. Bed material load (Figure 3.4-15) includes both the portion of the suspended load that interacts with the river bed and the bed load itself. The bed material load is a key parameter because its size distribution closely approximates the size distribution of the material extracted for commercial sand and gravel production by dredging in the LOMR (Section 2.2). The sum of the bed material load and wash load is the total sediment load.

Determining the Boundary between Wash Load and Bed Material Load

The relative proportion of wash load and bed material load in sediment transport is a key factor in sediment supply analysis. The majority of the LOMR total sediment load is silt- and clay-sized wash load that is transported in continuous suspension. To quantify the percentage of the total sediment

load that is bed material load, and thus important to the channel shape and potential degradation, it is necessary to determine more specific boundaries between wash load and bed material load.

An index called the "Rouse number" indicates whether a particle of a certain size will remain in suspension as wash load or settle out of the water column. Rouse number calculations were performed at four locations on the Missouri River. Details on the calculations are presented in Appendix A. The Rouse number analysis found that, at the Nebraska City (upriver of the Project area), St. Joseph, and Kansas City gages, sand particles finer than approximately 0.25 mm (and 0.2 mm at the Hermann gage) remain in suspension at all discharges and should be considered wash load.

Bed Material Particle Size

The USGS and USACE have an established record of sampling bed material sediment (see Appendix A for a description). Select particle sizes are available from three gage sites in the Project area, as well as the upriver Nebraska gage, ranging from the D_{10} (the diameter of a particle where 10 percent of the material in the bed is finer) to the D_{90} (the diameter of a particle where 90 percent of the bed is finer). Table 3.4-14 lists the particle sizes of the river bed at four gages at various percent of size fractions (referred to as "cumulative frequencies" or "cumulative percent finer than"). For example, the D_{10} for the Nebraska City gage means that 10 percent of the material in the river bed is finer than 0.20 mm, and the D_{90} means that 90 percent is finer than 2.00 mm. This is illustrated in Figure 3.4-14, with the cumulative percent finer (D_{10} to D_{90}) on the Y-axis, and the particle size on the X-axis. These gradations represent the typical bed material sizes at these locations and correspond to the average of 10 years of USGS data for the larger size fractions and USACE values at the finest fraction (D_{10}) (the USGS did not sieve any sediment between 0.0625 and 0.125 mm). In general, the particle sizes recorded at the Hermann gage are coarser than the Nebraska City, St. Joseph, and Kansas City gages for all fractions other than the D_{90}.

It is common for the maximum particle size of the wash load to be similar to the D_{10} of the bed material (Einstein 1950). Comparison of the values in Table 3.4-14 with the Rouse number results show a similar result between material that is nearly always in suspension (wash load) and the D_{10} of the bed material. The Rouse number results predicted that particles from 0.2 to 0.25 mm remain in suspension at all discharges throughout the LOMR and should be considered wash load. Particle sizes of 0.2 to 0.25 mm are very similar to the D_{10} of the bed material.

The particle size data from Table 3.4-14 are plotted on a graph in Figure 3.4-16, which also includes the particle size requirements for commercial sand according to Missouri State Concrete specifications. Most commercially dredged material is used to make concrete that must meet various standards and specifications. Although there are several different specifications for concrete sand, the Missouri State specifications for concrete sand are representative. Sand sizes must fall between the minimum and maximum curves to meet the specification. At the St. Joseph and Kansas City gage locations, river bed sediment is generally finer than the Missouri State specifications for concrete sand. River bed sediment size distributions at the Hermann and Nebraska City gages meet the specification but are closer to the minimum specification than the maximum.

Figure 3.4-17 shows the particle sizes for the D_{10} and D_{50} every 10 miles for the LOMR. Except for the upriver Nebraska City location, particle size distributions become slightly coarser moving downriver. Laustrup, Jacobson, and Simpkins (2007) showed a similar trend in spawning gravels and bedrock outcrops increasing toward the confluence with the Mississippi River (Figure 3.4-2). These data are evidence that the bed material of the LOMR is composed primarily of medium-size sand particles, with a slight increase in coarseness downriver within the Project area. In addition, the variability in particle sizes increases below approximately RM 150.

Suspended Sediment Particle Size

The USGS periodically collects and analyzes the particle sizes of suspended sediment while measuring suspended sediment loads at their gage sites. Available data from 1981 to1991 at Nebraska City, from 1994 to 2005 at St. Joseph, from 1994 to 2002 at Kansas City, and from 1994 to 2005 at Hermann were reviewed.

The average suspended sediment gradations for each location (Figure 3.4-18) show the representative particle size cumulative frequency curves for each location (individual plots are included in Appendix A). On all of the average gradation plots, the D_{50} value is finer than the finest particle size analyzed by the USGS (0.063 mm), which is the boundary between silt and very fine sand. Thus, the median grain diameter is in the silt/clay fraction. Because the USGS does not determine particle sizes finer than sand, USACE mechanical analysis curves of suspended sediment samples dating from 1963 to1965 (for which the silt and clay fraction was determined) were reviewed. The D_{50} values were all in the silt size range (0.014 mm at St. Joseph, 0.012 mm at Kansas City, and 0.012 mm at Hermann).

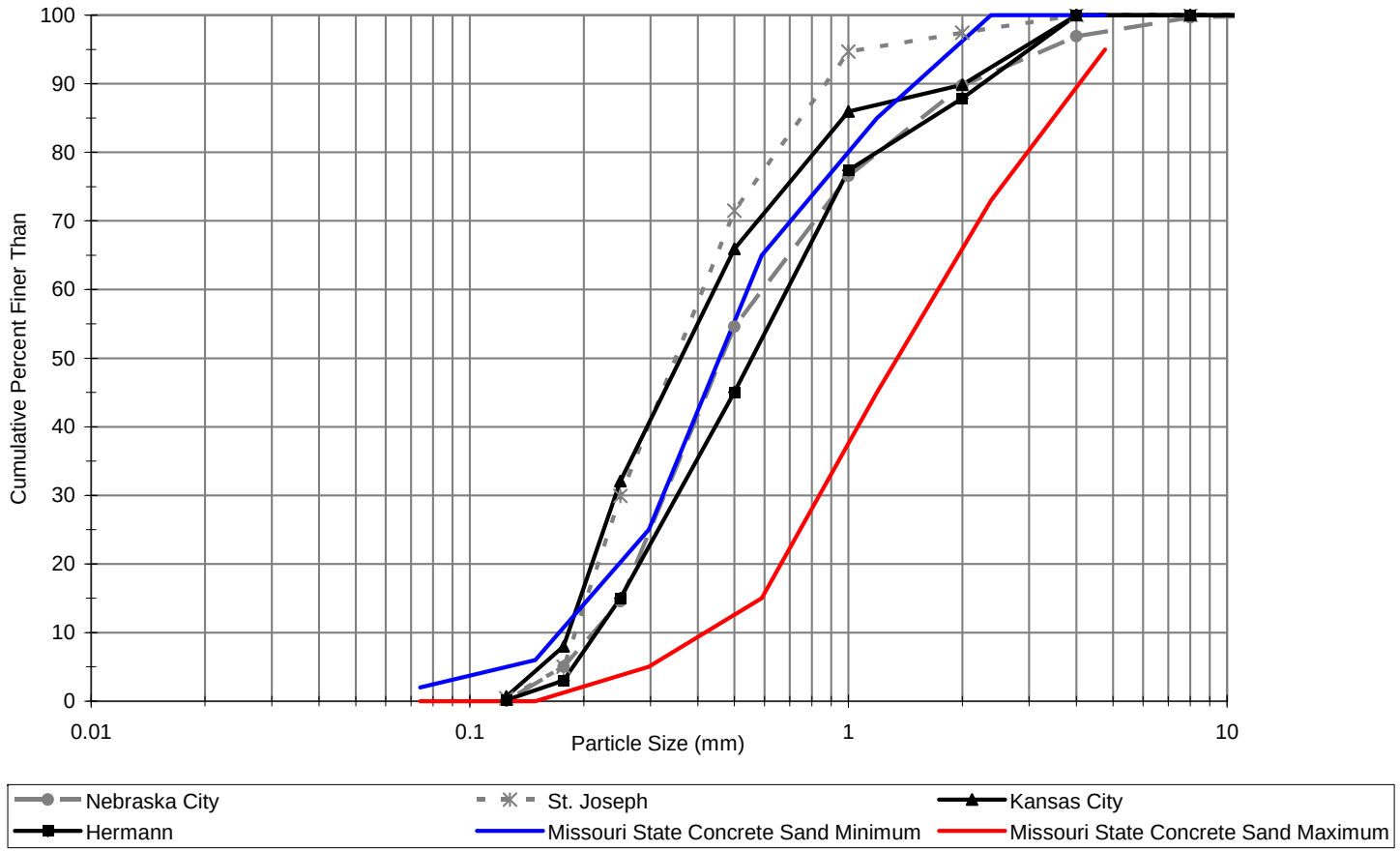


Figure 3.4-16 Cumulative Frequency Particle Sizes in Bed Material at Three Locations on the Lower Missouri River and Nebraska City

Note: The Missouri State specifications for concrete sand also are shown.

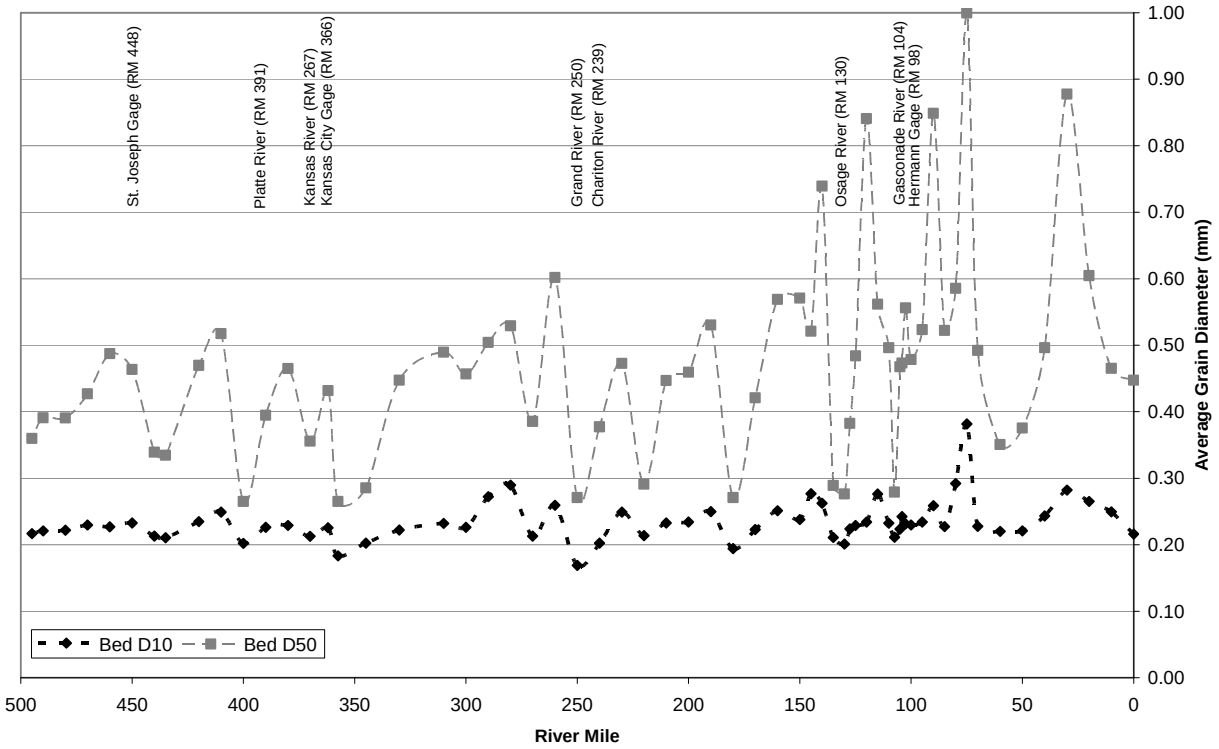


Figure 3.4-17 Particle Sizes of D10 and D50 for the Lower Missouri River (1994)

The percent of sand within the USGS suspended sediment particle size gradations was assessed (Table 3.4-15) for the time periods listed. The sand percentages decrease downstream, from 41 percent at Nebraska City to 24 percent at Hermann. Conversely, the percent of the suspended sediment finer than the D_{10} of the bed material increases downstream, from 87 percent in Nebraska City to 94 percent in Hermann. These results indicate that the percentage of the fine wash load material increases with additional drainage area, which is likely attributable to increased tributary inputs of fine wash load sediment that dilutes the suspended sediment load (Jacobson et al. 2009). When the percent of sand in the measured suspended sediment loads is plotted against the discharge at the time of the measurement, there is no correlation between percent of sand content and discharge (see Appendix A for details). One exception is at Kansas City. When flows exceed approximately 85,000 cfs at Kansas City, the sand content is always less than 30 percent. The lack of any strong correlation for the majority of the locations sampled supports the argument that the vast majority of the suspended sediment load is fine-grained wash load, and indicates that the river's ability to transport the finer suspended sand fraction is likely more dependent on supply than flow strength.

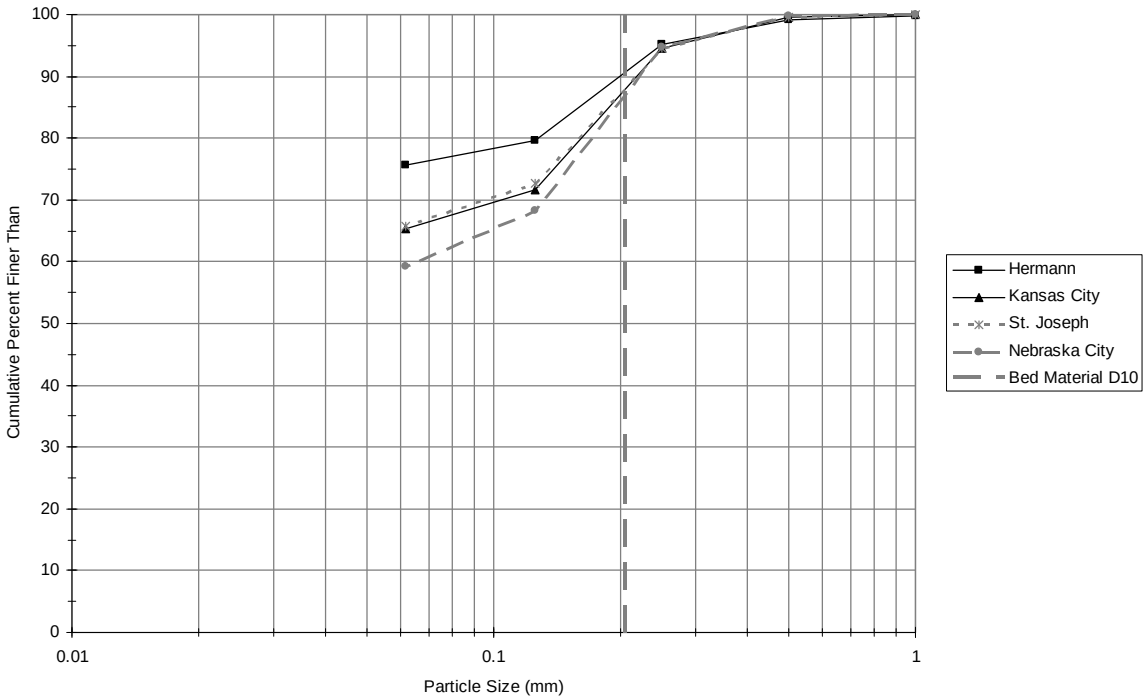


Figure 3.4-18 Representative Suspended Particle Size Gradations at Three Gage Locations on the Lower Missouri River and at Nebraska City

Note: The average bed material D_{10} for the four sites is shown for reference.

Table 3.4-15 Summary Results for Suspended Sediment Particle Size Analysis

Location	Nebraska City	St. Joseph	Kansas City	Hermann
Period of available data	1981–1991	1994–2005	1994–2002	1994–2005
Percent of sand in the total suspended sediment load (%)	41	33	35	24
Percent of total suspended sediment load finer than the bed material D_{10} (%)	87	87	85	94
Percent of total suspended sediment load coarser than the bed material D_{10} (%)	13	13	15	6

The last row in Table 3.4-15 is the percentage of the total suspended sediment load with particle sizes coarser than the D_{10} of the bed material. These percentages represent the amount of the total suspended sediment load that can be considered part of the bed material load instead of the wash load. Thus, depending on the location, less than 6–15 percent of the total suspended sediment load likely interacts with the channel bed and affects the river bed and channel shape.

3.4.5.5 Sediment Load Estimates

Bed material loads for the LOMR were estimated to provide a basis for determining the potential contribution of dredging to river bed degradation and potential impacts on channel stability. As described above, the sediment that composes bed material load is very similar in size to the material dredged to make concrete and asphalt.

To estimate bed material loads, the results of measured suspended sediment loads at four gaging stations were reviewed, and estimates of bed material load were calculated. Estimates included the portion of the sediment not measured by the suspended sediment sampling.

Measurements of Suspended Sediment

The USGS is currently working with the USACE to compile, analyze, and calculate total suspended sediment and suspended sand loads using all available measured data on the LOMR and its major tributaries (USGS 2009). The USGS compiled known suspended sediment measurements, including measurements made by the USACE and the USGS, and other measurements reported in concentrations and daily loads. The effort also included compilation of all information on bed material and suspended sediment particle size gradations.

Using these data, the USGS calculated estimates of annual total suspended sediment and suspended sand loads for the St. Joseph, Kansas City, and Hermann gages; these were the only gages on the LOMR with sufficient measurement records. A 3-year moving average was used to calculate annual loads (see Appendix A for details). The results for the Nebraska City gage are based on published daily suspended loads rather than estimated values. Suspended sand loads include both wash load (fine-grained sand) and bed material load (coarse-grained sand) components.

Preliminary USGS results for total suspended sediment and sand are provided in Table 3.4-16). These results are preliminary values made available by the USGS for use in this analysis and have not yet been published by the USGS. Total suspended sediment loads are displayed for the four gaging stations for water years 1994–2008. The data show the annual variability in both total suspended sediment loads and suspended sand loads. For example, the Kansas City gage shows a greater than 10-fold difference between the lowest recorded suspended sediment load in 2002 (14 million tons) and the highest in 1999 (158 million tons). There is less variability in the suspended sand loads. The average annual suspended sediment load increases farther down river, as expected; unexpectedly, the

average suspended sand loads at the Kansas City gage are lower than those at the St. Joseph gage and those at the Hermann gage.

The percent of the total suspended sediment that is composed of suspended sand (Table 3.4-16) differs somewhat from the suspended sediment particle size analysis (Table 3.4-15) because of different estimating methods. The most significant difference is for the Kansas City gage, with results varying by almost a factor of 2. It should also be noted that the total suspended sand loads listed in Table 3.4-16 include sand that is finer than is typically dredged for commercial sand and gravel production, and is therefore not a good estimate for the amount of material available for dredging. Comparison of Figure 3.4-18 for the average size fractions included in the total suspended sediment measurements (which includes sand) and Figure 3.4-16, which shows the Missouri State specifications for concrete sand illustrates this difference. Bed material load-sized sediment more closely matches commercial sand specifications and is estimated below.

Data for the Hermann gage (Figure 3.4-19) include mean annual flow for reference. The trends are similar between total suspended sediment and suspended sand loads with mean annual flows, but there appears to be less inter-annual variability in the suspended sand loads. The mean annual flow aggregates all of the flow data for a year but averages other factors that influence sediment transport such as peak flows, floods, and where in the watershed peak flows originate. For example, peak flows in 2008 and 1997 were similar, but total suspended sediment loads in 2008 were much lower compared to 1997 and suspended sand loads were similar. Figure 3.4-19 also illustrates the annual variability in the LOMR system for flows and sediment loads, even for the relatively short period from 1994 to 2008.

Suspended Sediment Loads from Tributaries

Limited sediment data are available for some of the tributaries to the LOMR. Total suspended sediment and suspended sand load data were compiled for six gage locations on tributaries to the LOMR (Table 3.4-17). The data provide some indication of the relative contributions of suspended sediment by tributaries, but the data are limited to drawing general comparisons for the following reasons:

- Gage locations are located upstream from the mouth of the tributary and may not represent loads at the mouth. The gage location on the Gasconade River is 104 miles from the mouth, and the data do not include sediment inputs from the lower portion of the river.

Table 3.4-16 Preliminary Estimates of Annual Total Suspended Sediment and Total Suspended Sand Loads (1994–2008)

	Nebraska City Gage			St. Joseph Gage			Kansas City Gage			Hermann Gage		
Water Year	Total Suspended Sediment Load (tons)	Total Suspended Sand Load (tons)	Percent of Total Sediment Load as Sand	Total Suspended Sediment Load (tons)	Total Suspended Sand Load (tons)	Percent of Total Sediment Load as Sand	Total Suspended Sediment Load (tons)	Total Suspended Sand Load (tons)	Percent of Total Sediment Load as Sand	Total Suspended Sediment Load (tons)	Total Suspended Sand Load (tons)	Percent of Total Sediment Load as Sand
1994	26,211,430	--	--	23,690,291	9,538,417	40%	30,071,383	7,562,101	25%	52,906,783	22,815,078	43%
1995	29,085,000	--	--	41,501,678	11,635,319	28%	60,883,646	9,204,014	15%	108,788,187	27,800,344	26%
1996	51,447,590	--	--	42,722,155	16,176,130	38%	51,833,151	11,496,452	22%	71,316,053	16,648,097	23%
1997	41,179,300	--	--	62,776,097	23,959,685	38%	89,916,705	15,586,251	17%	100,818,569	30,546,649	30%
1998	38,692,400	--	--	50,433,838	16,697,396	33%	64,962,777	11,182,991	17%	77,723,362	22,896,373	29%
1999	31,539,700	--	--	74,486,708	16,006,959	21%	158,825,288	11,311,009	7%	110,341,112	29,901,720	27%
2000	14,220,600	--	--	16,607,801	7,709,083	46%	18,582,887	4,234,603	23%	14,698,826	4,380,979	30%
2001	22,966,140	--	--	39,802,233	9,051,823	23%	47,313,068	6,941,695	15%	72,344,565	15,456,483	21%
2002	11,192,140	--	--	14,293,862	4,607,988	32%	14,382,525	3,482,254	24%	45,960,346	8,007,942	17%
2003	14,685,110	--	--	20,472,436	4,768,702	23%	18,059,993	3,545,394	20%	10,677,631	2,885,998	27%
2004	16,315,440	--	--	37,872,119	5,198,606	14%	30,676,860	5,396,230	18%	42,544,685	9,704,181	23%
2005	14,343,880	--	--	19,666,152	2,847,506	14%	27,488,343	4,301,219	16%	58,036,214	11,506,182	20%
2006	9,329,500	--	--	11,453,830	--	--	15,044,932	--	--	8,175,245	2,408,194	29%
2007	22,087,110	--	--	26,905,009	--	--	56,276,239	--	--	36,822,836	13,975,437	38%
2008	33,751,800	--	--	35,652,160	--	--	46,550,446	--	--	55,505,753	26,694,551	48%
Average	25,136,476			34,555,758			48,724,550			57,777,344		
Sand Average		--	--		*10,683,135*	*29%*		*7,853,684*	*18%*		*16,879,169*	*27%*

Notes:

-- = No data.

These results are preliminary values made available by the U.S. Geological Survey (USGS 2009) for use in this analysis and have not yet been published. See Appendix A for additional details.

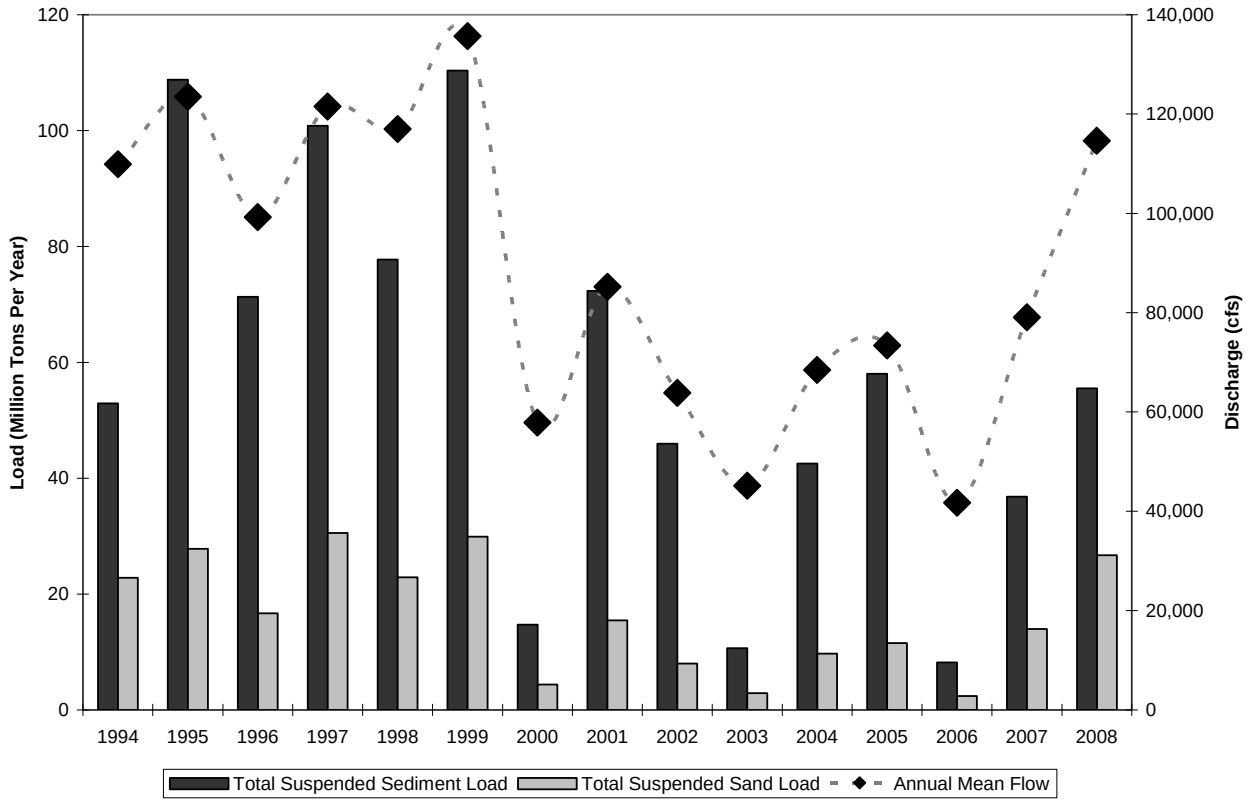


Figure 3.4-19 Total Suspended Sediment Load, Suspended Sand Load, and Annual Mean Flow at Hermann, Missouri (1994–2008)

- The time periods covered by the tributary gage data are limited and do not fully overlap with the time periods covered by gage data from the sites on the mainstem Missouri River. Because measured sediment load is a function of flows and flows vary over time, comparisons of these data sets must consider the effects of flow variations over time.
- Based on the sand fraction of the suspended sediment load, most of the suspended sediment loads and sand loads within the tributaries would translate to wash load in the LOMR and therefore would neither contribute to LOMR bed material load nor contribute sediment-size fractions to the LOMR suitable for commercial dredging.
- The Grand River at RM 250 is undammed and contributes more suspended sediment and suspended sand to the LOMR than most of the other tributaries, including the Kansas River.

Table 3.4-17 Estimated Average Annual Suspended Sediment Loads and Suspended Sand Loads for Tributaries to the Lower Missouri River with Comparisons to the Nearest Gage on the Mainstem

Location	Missouri River Mile	Location of Gage on Tributary[a]	Period of Record	Average Annual Suspended Sediment Load (tons)	Average Annual Suspended Sand Load	Suspended Sand / Suspended Load (%)	Nearest Gage on the Mainstem	Tributary Percentage of Suspended Sediment Load of Nearest Gage on the Mainstem[b]	Tributary Percentage of Suspended Sand Load of Nearest Gage on the Mainstem[b]
Missouri River at St. Joseph	448	N/A	1981–1993	85,539,358	18,298,368	21%	N/A	N/A	N/A
Platte River at Sharp Station	391	24	1980–1992	6,033,055	281,983	5%	Kansas City 25 miles downstream	10%	2%
Kansas River at Desoto	367	31	1976–1981	11,481,626	2,017,780	18%	Kansas City 1 mile downstream	20%	11%
Missouri River at Kansas City	366	N/A	1981–1993	58,422,500	18,408,599	32%	N/A	N/A	N/A
Grand River at Sumner	250	36	1974–1992[c]	18,631,934	2,470,225	13%	Kansas City 116 miles upstream	32%	13%
Chariton River at Prairie Hill	239	20	1979–1985	4,340,040	2,348,597	54%	Kansas City 127 miles upstream	7%	13%
Osage River at St. Thomas	130	34	1975–1993	803,035	335,330	42%	Hermann 32 miles downstream	1%	1%
Gasconade River at Jerome	104	104[d]	1978–1992	240,762	74,024	31%	Hermann 6 miles downstream	0.3%	0.2%
Missouri River at Hermann	98	N/A	1981–1993	80,358,495	47,178,924	59%	N/A	N/A	N/A

Notes:

N/A = Not available.

[a] River miles on the tributary from confluence with the Missouri River.

[b] Calculated by dividing the tributary suspended load or suspended sand load by corresponding values at the nearest U.S. Geological Survey gage on the lower Missouri River.

[c] Data from 1993 were excluded from the average due to the extreme values reported from the 1993 flood, which were as much as 200 times the annual average for other years in the series.

[d] This gage is much farther upriver than the other gages and does not represent the majority of the watershed.

Sources: U.S Geological Survey gage data for tributaries and Jacobson et al. 2009 for data on the lower Missouri River.

While the Kansas River has a much larger drainage, two primary factors inhibit its sediment contribution to the LOMR: numerous impoundments on its tributaries and dredging in the lower portions.

Most of the other tributaries, except for the Gasconade River, have impoundments or other sediment-trapping structures (Table 3.4-9). The available data suggest that the Osage River and Gasconade River are not contributing much sediment to the LOMR. The lack of substantial sediment contribution from the Osage River is consistent with the major impoundments that exist along its channel. The Gasconade River, however, is likely contributing more sediment to the LOMR than the data indicate because the gage location is a considerable distance upstream from its confluence with the LOMR.

Bed Material Load Estimates for This Analysis

The amount of bed material load transported by the LOMR is equivalent to the sum of the bed load and bed material load component of the suspended load. The LOMR bed material load was estimated using five different equations appropriate for large sand-bed rivers like the Missouri River (García 2008, Molinas and Wu 2000), including:

- Yang (1973);
- Ackers and White (1973) with adjusted coefficients according to H. R. Wallingford (1990);
- Molinas and Wu (2001);
- Engelund and Hansen (1967); and
- Series Expansion of the Modified Einstein Procedure (SEMEP) (Shah-Fairbank 2009).

The Yang, Ackers and White, and Engelund and Hansen equations were used in fractional form to estimate the transport for each particle size fraction of the bed material (Molinas and Wu 2000). The transport rates for each particle fraction were summed to obtain the total bed material load. The Molinas and Wu, and SEMEP equations are based on the median particle diameter (D_{50}) of the bed material.

The bed material equation calculations were performed using data from the Nebraska City, St. Joseph, Kansas City, and Hermann gaging locations. The bed material particle size gradations (Figure 3.4-18) and average hydraulic output (including channel depths, velocities, shear stresses, and widths) for the several cross sections that comprise the HEC-RAS modeling for each reach were used in the calculations. Because hydraulics and bed material load estimates can vary between nearby cross

sections, the average of several cross sections was used to best represent the typical hydraulic conditions within each reach (see Appendix A for details).

Four of the five bed material load equations are largely based on the hydraulic parameters of the river channel that define the energy available to transport the river bed material particle sizes. These empirically based equations represent an estimate of the transport capacity at that location in that they calculate the amount of sediment that would be transported given an adequate supply of sediment.

The SEMEP equation, however, calculates the amount of bed material in transport using a relationship between the material in the bed substrate and the particle size and concentration of material measured in suspension. It is designed to estimate the actual amount of sediment in transport rather than an equilibrium sediment load, or the maximum amount of sediment that could be transported at a particular location on the river if the sediment was available. The SEMEP equation uses measured total suspended sediment concentrations, bed sediment (D_{10}, D_{50}, and D_{65}) and suspended sediment (D_{50}) particle sizes, and channel hydraulics to determine the amount of sediment being transported in the unmeasured zone. The unmeasured zone includes bed load and suspended sediment in transport near the channel bottom beneath the maximum depth a suspended sediment sampler can sample (typically less than 0.5 foot). The bed material portion of the total suspended load is based on the percent of the total suspended load that is coarser than the D_{10} of the bed material. The Modified Einstein method, on which the SEMEP is based, is well-established and a recommended approach where restrictions on the sand supply may exist (Hicks and Gomez 2003). It was used in the only other study to estimate bed material loads on the LOMR, the 1999 L-385 study by West Consultants (1999).

Although each of the five equations uses different methods and makes different assumptions, each can be used to estimate the total amount of bed material transported by the Missouri River at the four gage locations. Estimates of bed material transport resulting from each of the five equations were similar at three of the four gaging stations. For the Hermann gage location, however, the SEMEP equation yielded an estimate that is slightly more than half of the average of the other four equations (Table 3.4-18). The SEMEP equation incorporates measured suspended sediment data and represents an actual estimate of bed material load rather than transport capacity. The SEMEP bed material transport estimate was therefore given equal weight to the average of the other four equations in order to yield a single estimate of bed material load for each gage location (see Appendix A for details). It should be noted that although a single averaged result is provided in Tables 3.4-18 and 3.4-19, and in the Environmental Consequences Section 4.2, it represents a range of results averaged

from five equations that use data with underlying variability (see Appendix A for details). The standard deviation of the unweighted average of the five equations is listed in Table 3.4-18.

Bed material loads were estimated for two time ranges, 2000–2009 and 1994–2009. The period from 2000 to 2009 was calculated so that the results could be compared to the amount of material dredged during the same period. On average, this period experienced below-average annual flows when compared to the overall period of record. Because bed load transport is correlated to mean annual flows, the estimated bed material load for this period would be lower, representing bed material loads under below-average flow conditions. (See Figure 3.4-19 for an illustration of sediment loads relative to flows and Figure 3.4-14 for mean annual flows and the long-term trend.) The mean annual flow for the Kansas City gage is 51,588 cfs for the entire period of record from 1929 to 2008, 54,974 cfs for the period from 1994 to 2008, and 43,465 cfs for the period from 2000 to 2008. Data were available for analysis for the period from 1994 to 2009, and this period was selected as representative of average conditions because the mean annual flows were slightly higher than the long-term mean for the period and lower than the long-term trend line flow for 2009 (see the trend line for the Kansas City gage in Figure 3.4-14).

The estimated bed material loads (Table 3.4-19) show similar trends to the measured total suspended loads (Table 3.4-14). Both parameters increase between Nebraska City and St. Joseph and between St. Joseph and Kansas City. Between Kansas City and Hermann, however, the bed material load estimate decreases by approximately 32 percent. Although the cause of the decrease in bed material load between the Kansas City gage and the Hermann gage is unclear, it may partially result from the contribution of flows from the Osage and Gasconade Rivers without an equivalent contribution of sediment, or a difference in sediment sizes from sites upriver and their allocation between wash load and bed material load.

Table 3.4-18 Total Bed Material Loads Estimated from Bed Material Load Equations (tons/year)

Location	Ackers & White (1973)	Engelund & Hansen (1967)	Molinas & Wu (2001)	Yang (1973)	Average (AVG) of Four Bed-Material Equations (no SEMEP)	SEMEP (2009)	Weighted AVG – AVG of SEMEP and AVG of Four Bed-Material Equations	Standard Deviation of the Unweighted Average of the Five Bed Material Equations
2000–2009								
Nebraska City	3,858,310	3,345,360	3,735,295	4,289,933	3,807,225	2,442,765	3,124,995	623,460
St. Joseph	4,342,438	3,316,504	4,141,181	3,030,405	3,707,632	3,308,508	3,508,070	515,752
Kansas City	7,147,775	5,032,985	5,991,383	5,834,135	6,001,569	4,702,736	5,352,153	852,016
Hermann	5,303,880	3,726,159	5,187,083	5,301,546	4,879,667	2,517,785	3,698,726	1,117,659
1994–2009								
Nebraska City	5,956,510	5,092,627	5,507,685	6,508,525	5,766,337	5,365,748	5,566,042	497,227
St. Joseph	7,144,192	5,455,947	6,467,546	5,020,173	6,021,965	5,410,855	5,716,410	784,941
Kansas City	10,584,323	7,305,296	8,550,699	8,576,194	8,754,128	7,650,806	8,202,467	1,139,792
Hermann	7,912,424	5,553,251	7,561,138	7,969,907	7,249,180	3,956,009	5,602,594	1,588,006

Table 3.4-19 Comparison of Estimated Average Annual Bed Material Loads at Four Gaging Stations on the Lower Missouri River

		Average Annual Bed Material Load Estimate (tons/year)			
Source	Period	Nebraska City	St. Joseph	Kansas City	Hermann
This analysis	2000–2009	3,124,995	3,508,070	5,352,153	3,698,726
	1994–2009	5,566,042	5,716,410	8,202,467	5,602,594
Missouri River Levee Unit L-385 Sediment Analysis (West Consultants 1999)	1967–1997	N/A	8,954,994	10,881,367	N/A

Note: N/A = Not available.

Comparison with Other Bed Material Load Estimates

The 1999 Missouri River Levee Unit L-385 Sediment Analysis (West Consultants 1999) estimated bed material loads to determine the impact of dredging up to 3.5 million cubic yards of sediment from the Missouri River for use in levee construction upstream of the confluence with the Kansas River. The 1999 study used the Modified Einstein Method (Appendix A) to calculate the total bed material load. A particle size of 0.125 mm (the boundary of very fine to fine sand) was specified as the cutoff between wash load and bed material load. The report did not explain how this was determined other than,

> …Based on a comparison of size characteristics from suspended sediment samples and bed material samples, suspended bed material load is assumed to be the portion of the suspended sediment load that is coarser than 0.125 mm (fine sand sizes and coarser). The finer material is assumed to be wash load. (West Consultants 1999)

For the 1967–1997 period, which had higher than average mean annual flows at 59,837 cfs (the mean annual flow for the period of record is 51,588 cfs), the report estimated an average bed material load of 10,881,367 tons/year at Kansas City, and 8,954,994 tons/year at St. Joseph (Table 3.4-18). The estimates from the current study for the 1994–2009 period for Kansas City and St. Joseph are 8,202,467 and 5,716,410 tons/year, respectively. Given the difference in analysis periods, flow variations within those periods, differences in the lower range of bed material load grain size (0.125 mm in the L-385 study and 0.2 mm in the current study) for calculation purposes, and the resultant variability in estimated bed material loads, the results from the L-385 study and the results from the current study lie within a reasonable range of each other.

Influence of Dredging on Estimated Bed Material Loads

In each case, the gage locations used for bed material load estimations and measurements of suspended sediment loads are downriver from commercial dredging operations that occurred during the period used for analysis. Although commercial dredging represents a removal of bed material load-sized sediment from the system, the amount dredged upriver from the gage locations was not added back into the calculations estimating bed material loads. There is a dynamic equilibrium between the bed material load and the transport capacity of the river (Lane 1955). As sediment is removed from active transport (for example, as a previously dredged area refills), the river erodes material from the river bed downriver from the dredged area to replace the material removed from active transport (Kondolf 1997; Simons, Li, and Associates 1985). Therefore, the transported sediment that is removed from active transport above the gage location because it fills in a dredged area is replaced by sediment recruited from the bed between the dredged area and the gage, causing river bed degradation (Simons, Li, and Associates 1985). For recruitment of sediment from the river bed into active transport to occur, bed material load-sized sediment in the river bed must be readily available. Because the banks of the LOMR are largely protected by revetments and vegetation and are generally stable, evidence of river bed degradation at locations near dredging operations indicates that dredged material is primarily being replaced by sediment recruited from the bed.

Bed material load-sized sediment appears to be available based on samples of bed material along the river and at the gage sites (see Figures 3.4-16 and 3.4-17). In addition, the four bed material load equations (excluding the SEMEP) calculate sediment transport capacity based on the geomorphic and hydraulic characteristics of the river rather than measured bed material loads; results therefore represent the amount of sediment that can be transported by the river assuming a readily available supply of sediment. The SEMEP calculation is based on measured suspended sediment loads and, with the possible exception of the Hermann gage, shows similar levels of bed material load transport as the four transport capacity equations. This similarity in levels of bed material transport indicates that the river is likely recruiting new bed material from the river bed upstream of the gage in response to the loss of supply in dredged areas.

Other Estimates of Bed Load

An acoustic Doppler current profiler (ADCP) was used to quantify the bed load sediment transport rate on the Missouri River approximately 9.3 miles downstream from Booneville (RM 197). Assuming an active bed width of 656 feet, the authors calculated an annual bed load rate of approximately 6,300,000

tons, or approximately 8 percent of the total annual Missouri River suspended sediment load (Gaeuman and Jacobson 2007). The authors do not state the time period over which the annual load was computed. They define the bed load as the portion of the sediment load captured in a bed load sediment sampler. Assuming that a typical Helley-Smith bed load sampler collects anything transported within 3 inches from the bed, the estimated bed load from this analysis would include suspended sediment moving in the unmeasured zone.

The USACE Engineer Research and Development Center (ERDC)[3] also is using ADCP technology to track sand dune movement in order to estimate bed load transport on the LOMR. Preliminary bed load estimates have been made at two sites on the LOMR, the Kansas City reach above the Kansas River (~RM 370) and at Washington, Missouri at RM 67. The study is in the preliminary stages, but additional results at different flows are expected for the two locations in 2010 (Abraham pers. comm.). The measured bed load in the Kansas City reach was 5,174 tons/day at a flow of 47,507 cfs; at the Washington site, 6,458 tons/day was measured at a flow of 140,425 cfs. For the same discharge of 47,507 cfs at Kansas City, the bed material load estimate (based on the average of the SEMEP and the other four equations) would be 12,823 tons/day. For the same discharge of 140,425 cfs at the Hermann gage, the bed material load estimate would be 26,784 tons/day.

The ADCP bed load measurements are lower than the total bed material load equation results. This is expected, given that the ADCP study is reporting bed load measurements that include sediment particles moving on or very near the bed in dune formations and does not include suspended sediment. Unlike the bed material load estimates, which do not distinguish between the percent of the total bed material load that is bed load or suspended sediment load, the ADCP measurements aim to exclude the bed material load moving in suspension during the time of measurement. It is not known how much of the sediment moving in suspension near the bed is included in the ADCP measurements.

3.4.6 River Bed Degradation

3.4.6.1 Methods of Measuring River Bed Changes

The LOMR is a dynamic system altered by the completion of flow-regulating dams and instream structures to create and maintain the navigation channel. The USGS and the USACE are primarily responsible for collecting data along the LOMR. In the past 20–30 years, the USACE has collected

[3] David Abraham of the USACE Engineer Research Development Center is leading this study.

data to assess the potential impacts of the mainstem dams and the BSNP on the LOMR. As technology and interest in monitoring environmental impacts has changed over time, so has the type and quantity of data collected.

While different types of records and measurements are available for different aspects of the LOMR system, the parameter of primary interest for this assessment is river bed elevation over time. Bed degradation and the potential for continued degradation pose risks to a variety of resources. Measuring the extent and rate of bed degradation is challenging on the LOMR because elevations of the river bed can change over time scales ranging from hours, weeks, years, and decades. Various sets of data are available, but few data sets directly measure river bed degradation. Changes in river bed elevation are therefore estimated using other studies.

The most useful data sets for river bed degradation assessment fall into two broad categories—data collected over time at one location and data collected over time within a wide area. Time series data can reveal long-term trends as well as short-term variability. Time series data can also provide insights on river system responses to the many management changes that have occurred over the past century, including flow regulation and the BSNP.

The USGS gages at Rulo, St. Joseph, Kansas City, Waverly, Boonville, and Hermann provide long-term records of flow, channel characteristics, and other parameters (see Table 3.4-8 for details on the location and period of record for the gages). Based on channel top width and flow, an average river bed elevation can be calculated based on the depth of the flow relative to the stage and the elevation of the gage. This method was used to calculate average annual river bed elevations for the time series at the USGS gages; it represents an average bed elevation across the channel and throughout the year for given flows rather than an exact measurement of the bed elevation at any given time or position on the cross section. Since this method averages the depth across time and the cross section at the gage, it is useful for representing long-term trends. Stage heights for the time series also were plotted to show trends and gross changes in channel geometry. Applying the results from USGS gage sites to other locations on the river must be done carefully given the changes in channel geometry and flows at different locations.

Other time series data include river hydrographic surveys collected for many years between 1942 and the late 1980s. These surveys include navigational aid maps of the LOMR that provide depths at various locations along the river. The usefulness of these data for this analysis was limited because of

limitations in the format of the data (only hard-copy maps) and the difficulty of reliably relating measurements shown on the maps to a specific location and benchmark elevation.

To evaluate changes in river bed elevation and low-flow water surfaces, data with a common datum is required. One such dataset is the low-flow water surface elevation data collected in 1990 and 2005 adjusted to the Construction Reference Plane (CRP) established by the USACE. The CRP is an imaginary sloping plane that extends the length of the LOMR and is used by the USACE as a benchmark for building and maintaining structures in the river (USACE 2005). The CRP has been revised periodically due to changing conditions on the river, the most recent change occurring in 2005. Recent revisions have based the CRP on the 75-percent exceedance flow, or a flow determined from flow records over the past approximately 30 years that is likely to be exceeded approximately 75 percent of the time during the navigation season. The CRP is calculated by measuring the low-flow water elevation of the river at various points along the river, adjusting them to nearby gage benchmarks, and then interpolating water surface elevations between measured locations at 0.1-mile increments (USACE 2005).

Low-flow water surface elevations from different years are not directly comparable due to differences in flows at the time the data were collected. However, they can be compared by adjusting to common flows for both profiles. This was done in the current study by adjusting both profiles to the flow values determined for the 2005 CRP. Figure 3.4-20 shows the difference in CRP water surface elevations from approximately RM 750 to Rulo between 1990 and 2005 and the net change in CRP-adjusted low-flow water surface elevation between 1990 and 2005 between Rulo and the mouth.

Water surface elevations do not exactly parallel river bed elevations because water surface elevations result from a combination of factors, including discharge, slope, velocity, and channel roughness. The water surface tends to smooth out the highly variable and changing river bed surface.

In addition to the analyses described above, a third set of longitudinal data collected by the USACE was analyzed for this EIS. In 1998 and 1999, hydroacoustic bed elevation data (HBED) were collected along the LOMR in a “serpentine” manner with approximately 50 feet between survey points. In 2007, 2008, and 2009, the USACE collected hydroacoustic survey data at cross sections established every 250 feet at most locations in the river and every 87 feet at Habitat Monitoring Assessment Program locations, with river bed elevation points collected every 0.5 feet. 2008 data were collected only at locations with active dredging. The 2009 data set had not been finalized by the USACE at the time of

this analysis, but the draft 2009 data were processed to obtain results that are comparable to the data from 1999, 2007, and 2008 (see Appendix A for details).

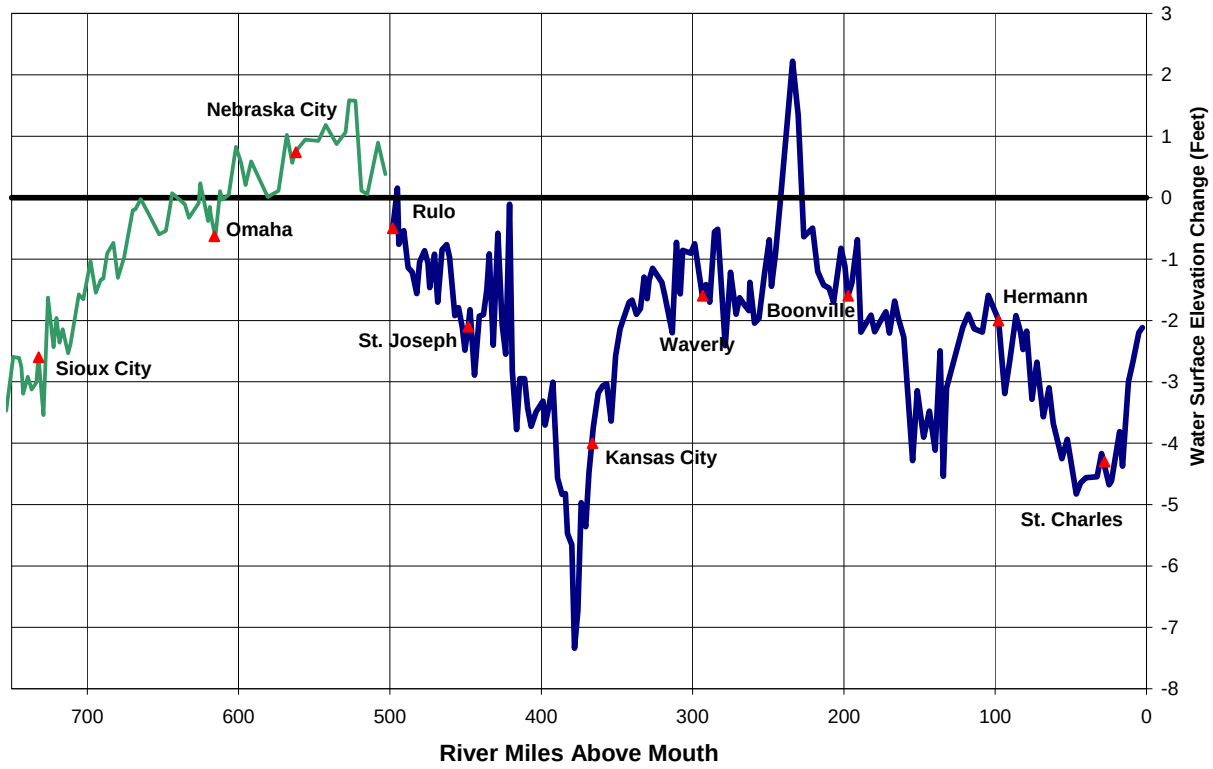


Figure 3.4-20 Change in CRP Water Surface Elevations between 1990 and 2005 (RM 750 to Rulo – shown in green) and Change in CRP-Adjusted Low-Flow Water Surface Profiles between 1990 and 2005 (Rulo, NE to the mouth – shown in blue)

Note: The water profile estimate above Rulo uses a different data set.

Source: USACE spreadsheet "Public_mtg_posters_6_2_2009.xls" and USACE spreadsheet "2002 to 2005 CRP Comparison vs Dredging.xls."

All points on each transect within 200 feet of the "sailing line" were selected and averaged to obtain an average river bed elevation for each transect and for each year. The sailing line follows the navigation channel and tracks the outside portion of the channel where flow strength is greatest and the channel is usually the deepest. The average river bed elevation for each transect was then averaged by river mile and compared by river mile to the survey results from the other years. The results from any given survey year can therefore be compared to other survey years by river mile to determine changes in average river bed elevation within 200 feet of the sailing line. Figure 3.4-21 displays the change in river

bed elevation between 1998 and 2007, 2008, and 2009. The data were smoothed using a 5-mile moving average.

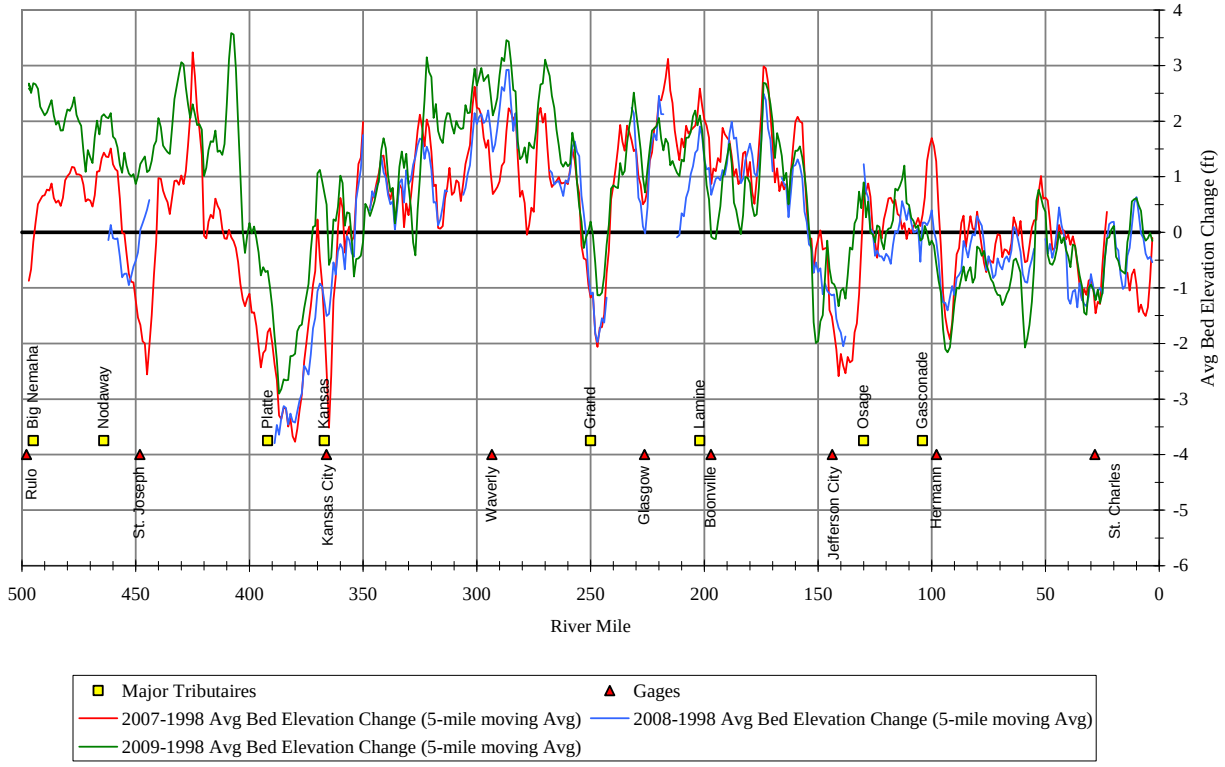


Figure 3.4-21 Change in Average River Bed Elevation between 1998 and 2007–2009 Using a 5-Mile Moving Average

The results using the HBED are not directly comparable to the CRP-adjusted low-flow water surface elevation data because of the difference in data collection methods and time periods analyzed. For issues such as water levels dropping below water intakes along the LOMR and tributary degradation, changes in low-flow water surface elevations are the key factor for assessing change and potential impacts. The HBED, in contrast, directly measures river bed elevations at known locations over time and is useful for assessing potential impacts on infrastructure such as bridge pilings, pipeline crossings, revetments, and levees.

The analysis period for the low-flow water surface elevation data spans 15 years from 1990 to 2005 and includes the 1993 flood event and several years of above-average flows during the 1990s. The 1998–2009 HBED analysis period is shorter and includes several years of below-average mean annual

flows during the early 2000s (see Figure 3.4-14 for mean annual flows). The period of overlap between the two datasets is 7 years between 1998 and 2005, which corresponds to a period with below-average flows and above-average dredging rates (Figure 3.2-2).

3.4.6.2 Changes in River Bed Elevations and Surface Water Profiles

Upriver Conditions

Upriver of the Project area, from Rulo, Nebraska (RM 498) to the Gavins Point Dam (RM 811), the river is managed by the USACE Omaha District. The BSNP continues upstream from Rulo, Nebraska to near Sioux City, Iowa at RM 732. Here, the BSNP ends; but structures continue to stabilize the channel until approximately RM 750. The upstream river is unconstrained until it reaches Gavins Point Dam (USACE 2001). Construction of Gavins Point Dam and other upstream dams changed both the flow regime and sediment transport for this segment of the Missouri River.

When Gavins Point Dam was completed in 1955, the estimated average annual sediment load immediately below the dam changed from approximately 135,000,000 tons per year to essentially zero (USACE 2001). A 1949 report projected that approximately 15 feet of river bed degradation would occur just below the dam. As of 2007, the channel had degraded approximately 11 feet, with lower rates of degradation occurring during the period of comparatively low flows from 1987 to 1993 and from 2000 to 2006 (USACE 2007c). A reduction in sediment load while flow and channel geometry remain constant results in increased erosive power, as exhibited by the channel degradation below the dam.

For segments of the river farther downstream from the dam (beginning with the BSNP at RM 735), changes in flow regime, channel cutoffs, changes in sediment inputs, channel stabilization, and construction of levees have contributed to degradation since the dam was completed (USACE 2001). Dredging is not permitted above Rulo, Nebraska at RM 498. Sioux City, Iowa has experienced approximately 11 feet of degradation since completion of Gavins Point Dam, similar to the level experienced at the dam itself. Rates of degradation have tended to stabilize during periods of lower flow and to increase during periods of higher flow. The amount of degradation has stabilized since 1999 (USACE 2007c). Figure 3.4-20 shows changes in low-flow water surfaces between 1990 and 2005 from RM 750 to the mouth.

At Omaha, Nebraska (RM 616), river bed degradation (as indicated by lower flow stage at 10,000 cfs) occurred from approximately the mid-1930s until the 1950s, and from the early 1970s until the present.

The 1950s saw stable or aggrading channels. Between Sioux City and Omaha, the river channel was shortened over 31 miles (21 percent) as a result of cutting off river bends between 1890 and 1960 (USACE 2007c).

Nebraska City, Nebraska (RM 562) lies below the confluence of the Missouri River and the undammed Platte River (RM 590). Here, the Missouri River receives an input of flow and sediment load in the form of coarse and fine sand (NRC 2002). Approximately 1–3 feet of degradation (based on 20,000-cfs flows and calculated average river bed elevations) occurred from approximately 1930 until the late 1970s. The channel then began to stabilize or slightly aggrade until approximately 2000, when the river bed dropped approximately 2 feet. Higher flows have increased in stage due to a reduction in channel width, increasing the likelihood of flooding (USACE 2007c). Changes in low-water profiles between the 1990 CRP and the 2005 CRP indicate that aggradation has occurred between RM 600 and RM 500 (Figure 3.4-20).

St. Joseph Segment

The St. Joseph segment extends from Rulo, Nebraska (RM 498) to the confluence of the Platte River (in Missouri at RM 391.1) just above Kansas City.

Average river bed elevation estimates available for the USGS gage at Rulo from 1949 to 2009 (Figure 3.4-22) indicate declining river bed elevations from 1952 to 1965 and stable to slightly aggrading conditions until 1997. Between 1997 and 1998, the USGS changed the method it used to collect data at this and most of the other LOMR sites, resulting in a potential shift in average bed elevations. These data are shown on the subsequent graphs as points rather than a continuous line, and likely explain the sharp increase in bed elevation at the Rulo gage between 1997 and 1998. The average bed elevation was relatively stable between 1998 and 2009.

Average river bed elevations and stage trends at the St. Joseph gage (RM 448) from 1928 to 2008 (Figure 3.4-23) indicate that river bed elevations were stable from approximately 1930 to the 1952 flood. The bed then rises several feet and stabilizes until the early 1960s. It then drops below the previous level until the early 1980s, when it rises several feet and stabilizes until the present. The measurement in 2008 is the same as the first measurement in 1928. Lower flows (20,000 cfs), however, have been declining on average since soon after the 1952 flood and have dropped approximately 4.3 feet from 1956 to 2006 and approximately 2.6 feet since 1951. Flows at 40,000 cfs have remained approximately the same, and flows at 70,000 cfs and 100,000 cfs experienced stage increases since the 1940s. The increases seem to have stabilized since the 1960s for 70,000-cfs flows

and since the 1980s for 100,000-cfs flows. The divergence in stages between high flows and low flows is moderately pronounced at this gage. It results from the narrowing of the top width of the channel over time as a result of the BSNP stabilization structures and levees, along with vegetation establishing on the former floodplain.

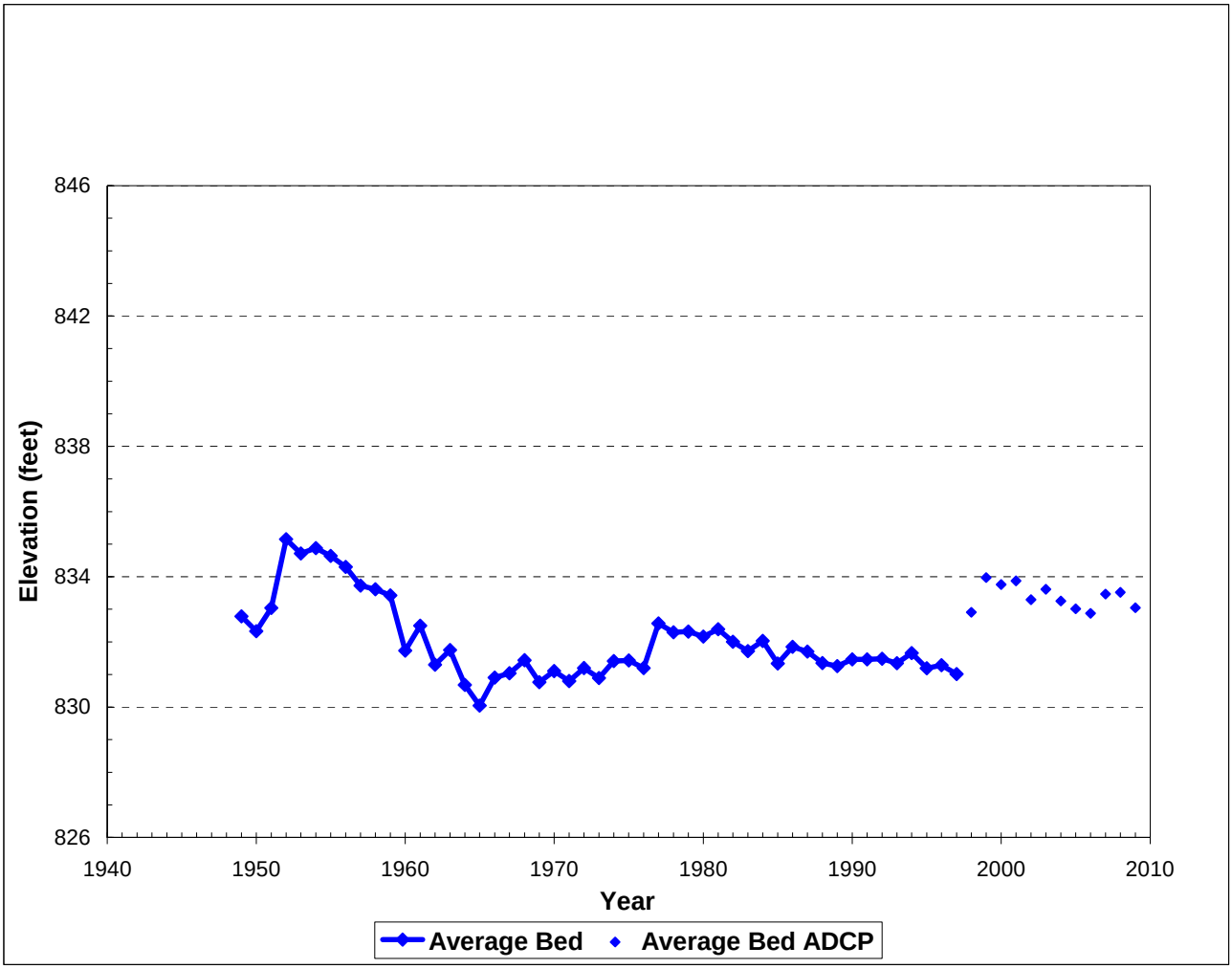


Figure 3.4-22 Missouri River Stage and Average Bed Trends at Rulo, Nebraska (RM 498.1)

Source: USACE spreadsheet "AveBed all gages upto Dec 5 2008.xls" updated with USGS gage data through 2009.

Changes in CRP-adjusted low-flow water surface elevations between 1990 and 2005 indicate an approximate 2-foot drop in water surface elevation over that period at the St. Joseph gage, a small drop near Rulo and at approximately RM 422, and a 2- to 3-foot drop in the St. Joseph area and also in the reach from approximately RM 420 to RM 390 near Kansas City (Figure 3.4-20).

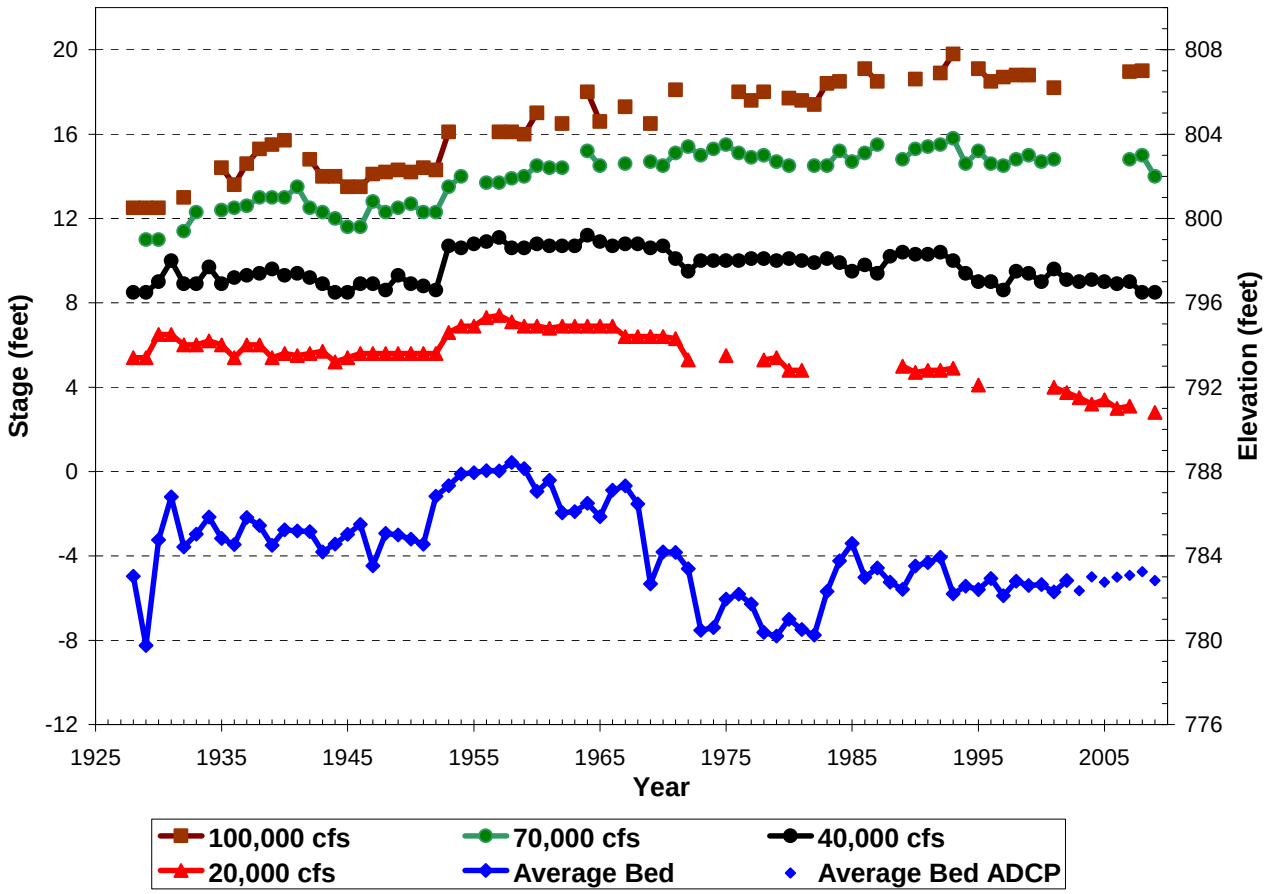


Figure 3.4-23 Missouri River Stage and Average River Bed Trends at St. Joseph, Missouri (RM 448.2)

Source: USACE spreadsheet "AveBed all gages upto Dec 5 2008.xls" updated with USGS gage data through 2009.

Analysis of average river bed elevations based on the HBED shows a 2.5-foot drop in the river bed elevation between 1998 and 2007 at St. Joseph, but a 1-foot increase between 1990 and 2009 (Figure 3.4-20). The river bed also shows approximately 2 feet of degradation near Kansas City at RM 390. Average river bed elevations appear to have increased approximately 1–2 feet through most of the segment between 2007 and 2009.

Boring logs from 1978 for the Route 36 Bridge in St. Joseph (RM 447.9) were compared to river bed elevations collected from underwater surveys conducted in 2009. The results show very little change at the downstream side of the in-channel bridge pier and a 5- to 10-foot lowering of the river bed elevation on the upstream side of the pier, where the effects of local scour from the bridge pier are likely to be greatest.

Kansas City Segment

The Kansas City segment extends from the Platte River in Missouri at RM 391.1 through Kansas City to the Big Blue River at RM 356.9. This segment of the river has experienced more degradation than anywhere else in the Project area. It is also one of the most developed segments of the river and consequently has been studied extensively due to potential risks and costs to infrastructure in the Kansas City metropolitan area.

Average annual river bed elevations have been declining at the Kansas City gage since approximately 1940 and have dropped approximately 12 feet since that time, although elevation increased in 2008 and 2009 (Figure 3.4-24). The rate of decline in average river bed elevation appears to have been relatively steady from 1955 until the 1993 flood event. At that time, the river bed dropped 4 feet, then recovered 2 feet, and then stabilized for a few years before continuing its downward trend after 2000.

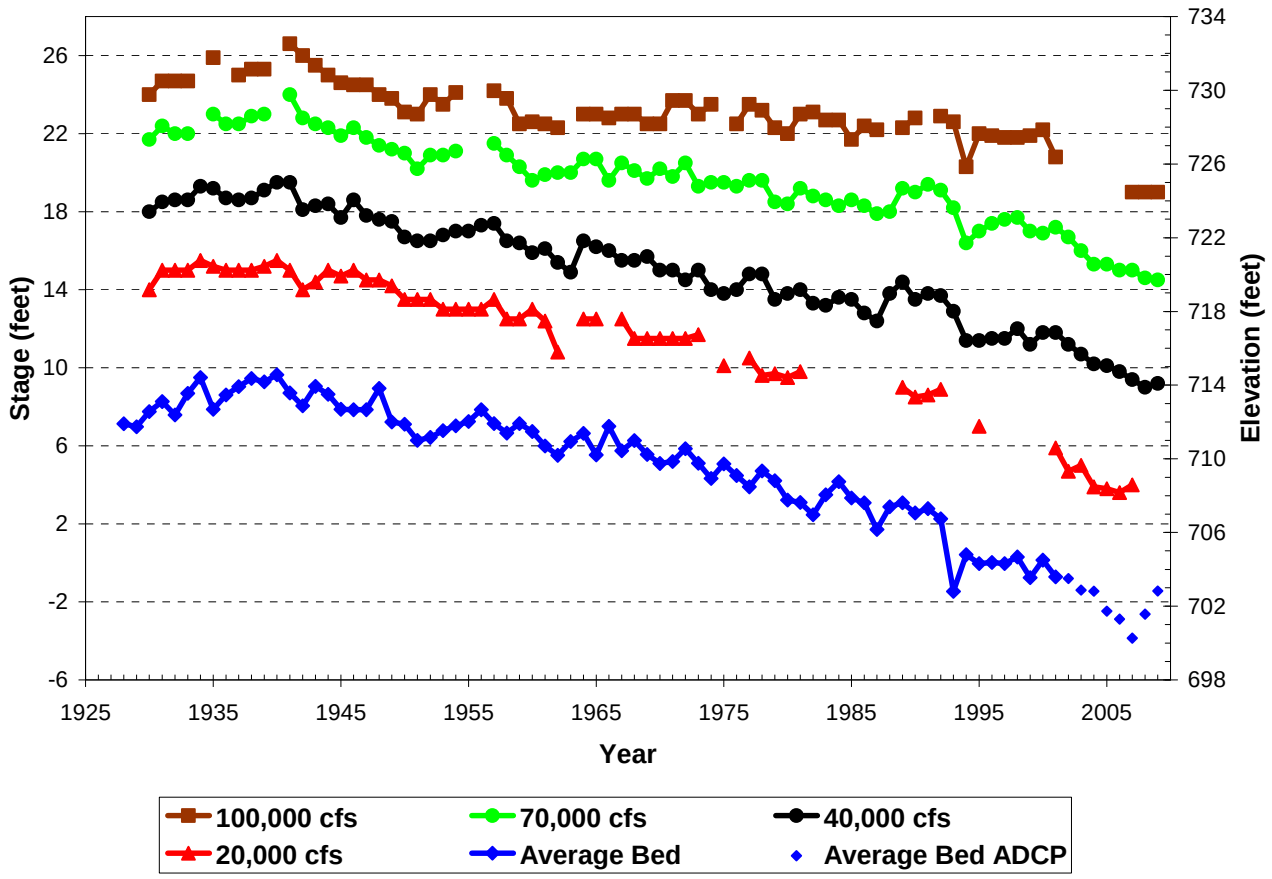


Figure 3.4-24 Missouri River Stage and Average River Bed Trends at Kansas City, Missouri (RM 366.1)

Source: USACE spreadsheet "AveBed all gages upto Dec 5 2008.xls" updated with USGS gage data through 2009.

The Missouri River stage trend at Kansas City also has been consistently downward for all discharge levels up through 100,000 cfs (Figure 3.4-24). This trend began in approximately 1940, in contrast to trends at nearby upstream and downstream stations. Generally, stages average 8–12 feet lower than those experienced in the 1930s for 20,000 and 40,000 cfs, and 6–9 feet lower at 70,000 and 100,000 cfs. Kansas City stages for 40,000 and 70,000 cfs recovered 1 to 2 feet during the drought years of 1987 to early 1993 and then declined dramatically following the 1993 flood, with little recovery since. Stage estimates for 2006 indicate a 2- to 4-foot drop from the 1993 pre-flood stages in the 20,000- to 70,000-cfs range. Stage observations in 1995 indicated only a partial recovery to the pre-1993 level following the dramatic shift after the 1993 flood.

The CRP-adjusted low-flow water surface elevations (Figure 3.4-20) between 1990 and 2005 show a drop of approximately 4 feet at the gage, similar to the drop in river bed elevation over the same period (-5.36 feet) and similar to the drop in the 20,000-cfs-flow water level (-4.7 feet) at the same location. The low-flow water profile graph shows the greatest amount of change in the longitudinal profile of the water surface elevation (over 7 feet) occurring at approximately RM 378 upriver from the gage and from the mouth of the Kansas River. Moving upriver from the point of greatest decline in the low-flow water surface elevation (RM 378), it is approximately 14 miles until the water surface decline is 3 feet (RM 392), and approximately 43 miles until the decline is 2 feet (RM 421). Moving downriver from the point of greatest decline in the low-flow water surface elevation (RM 378), it is approximately 18 miles until the surface decline is 3 feet (RM 360), and approximately 33 miles until the decline is 2 feet (RM 345) (Figure 3.4-20).

Analysis of average river bed elevations based on the HBED shows a drop of approximately 3.5 feet just downriver from the gage (RM 365) between 1998 and 2007, but only a 0.5-foot drop between 1990 and 2009 (Figure 3.4-21). The maximum drop in river bed elevation of approximately 3.8 feet occurs at RM 381 between 1998 and 2007, and at RM 387 with a drop of approximately 2.9 feet between 1998 and 2009. Between approximately RM 350 and RM 370, the HBED analysis indicates areas of both aggradation and degradation, although the change is generally less than 1 foot. The river bed aggraded between 2007 and 2009 for most of the segment, which is consistent with what was observed at the Kansas City gage between 2007 and 2009 (Figure 3.4-24).

An approximate 15- to 30-foot drop in river bed elevation at the center pier of the Broadway Bridge (RM 366) between 1954 and 2009 is indicated by a comparison between the construction boring logs from 1954 and a 2009 underwater bridge survey. This drop in river bed elevation is likely influenced by localized scouring around the bridge pier. Even though the water surface elevations were within a few

feet of each other at the time of the original borings and at the time of the survey in 2009, the piers on both sides of the channel that were in the water in 1954 are now both dry. The left bank pier, which was under approximately 6 feet of water in 1954, is now 40 feet from the water's edge. This illustrates the extent of channel degradation and changes in channel geometry over the past 50 years at this location.

Tributaries to the LOMR in the Kansas City segment also have experienced degradation, although the extent of the problem has not been documented. In the USACE (2009a) Degradation Reconnaissance Study, the USACE stated:

> Head cuts are occurring on several of the tributaries. These head cuts are affecting bank stability, causing scour and exposure of bridge piers, and causing potential loss of habitat as banks of tributary streams erode. An example is a bridge at Line Creek, located near RM 385 in the Kansas City reach. In this location, a traffic bridge located just upstream of the tributary mouth was shut down temporarily for safety concerns while temporary measures were implemented to ensure the bridge's safety. This incident occurred in FY 2009 and is an indication of the active nature of the river bed degradation and its impacts. The head cut on this tributary has now migrated to the point that a railroad bridge further upstream is also at risk. (USACE 2009a)

Waverly Segment

The Waverly segment extends from the Big Blue River at RM 356.9 to the Grand River at RM 249.9. This segment has no major metropolitan areas and no major tributaries.

There is one USGS gage in this segment at Waverly, Missouri (RM 293.1). This gage has been collecting data from 1928 until the present. The average annual river bed elevation has been steady to slightly declining over the period of record, with periods of relative stability before and after the flood event in 1993. That event caused a drop in river bed elevation of approximately 1 foot. Most recent data points are within 1 foot of the first measurements collected in the late 1920s (Figure 3.4-25).

Water surface elevations during low-flow stages (20,000 cfs) have been stable to slightly increasing over the period of record. Water surface elevations during higher flows have been increasing over the period of record, with the flows equal to or greater than 70,000 cfs recording stages 3–5 feet higher than during the 1930s (USACE 2007c).

The difference in CRP-adjusted low-flow water surface elevations between 1990 and 2005 (Figure 3.4-20) indicate that most of the Waverly segment has experienced moderate declines in the

0.5- to 2-foot range, except for the most upriver portion near Kansas City where the surface has dropped approximately 3.5 feet around RM 354.

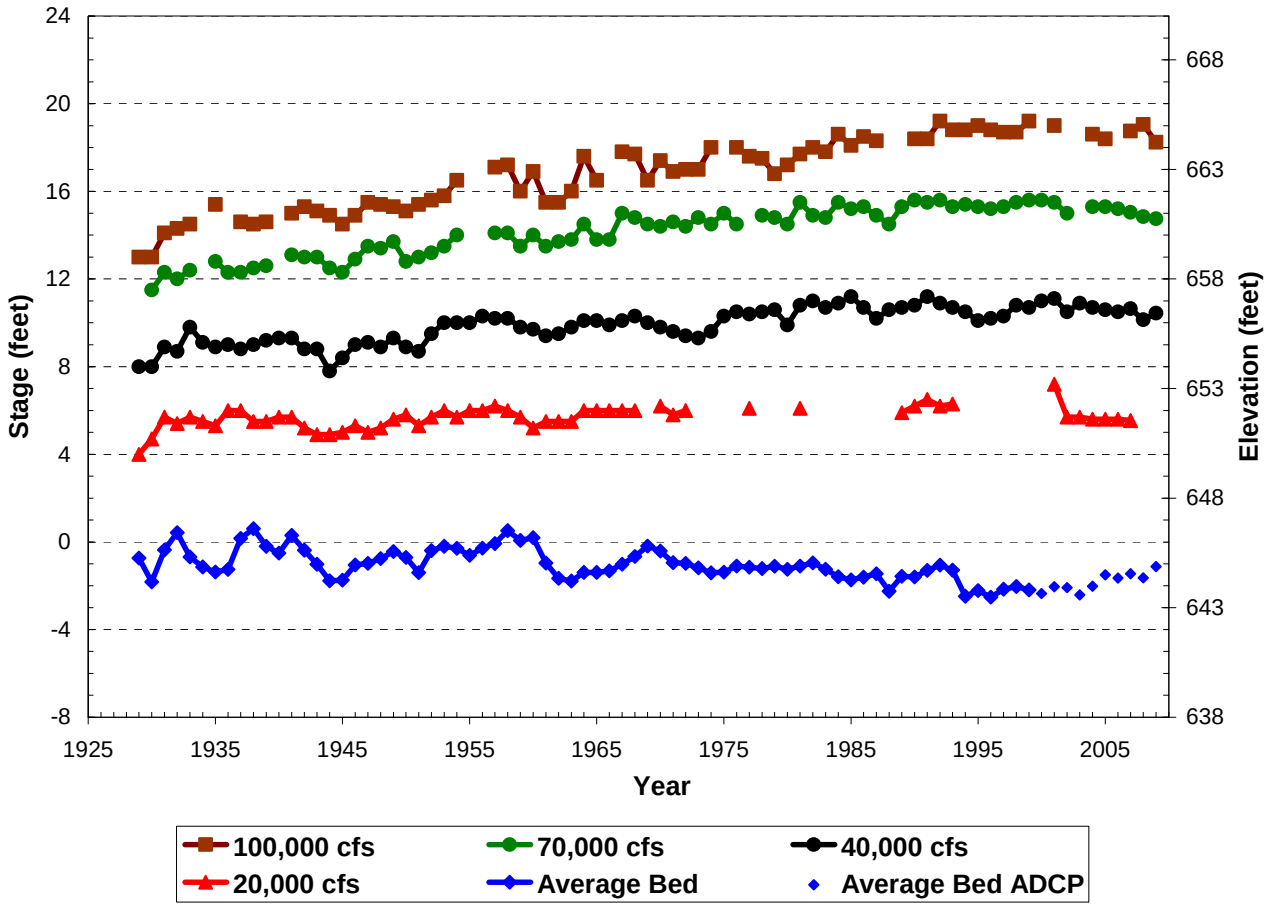


Figure 3.4-25 Missouri River Stage and Average Bed Trends at Waverly, Missouri (RM 293.4)

Source: USACE spreadsheet "AveBed all gages upto Dec 5 2008.xls" updated with USGS gage data through 2009.

Analysis of average river bed elevations based on the HBED shows an average of approximately 1 foot of aggradation between 1998 and 2007, and 1.7 feet of aggradation between 1998 and 2009 for the Waverly segment (Figure 3.4-21).

Jefferson City Segment

The Jefferson City segment extends from the Grand River at RM 249.9 to the Osage River at RM 129.9. This segment includes Jefferson City, where dredging occurs to provide sand for Jefferson City and the surrounding area.

There are two USGS gages in this analysis segment. The Glasgow gage located at RM 226.3 has limited data. A small number of average river bed elevation measurements were taken around 1950, and approximately 10 data points have been collected over the past 10 years. The average river bed elevations from the past 10 years are within 1–2 feet of the 1950s values, showing no discernible trend.

The difference in CRP-adjusted low-flow water surface elevations between 1990 and 2005 (Figure 3.4-20) shows a decline of approximately 0.5 foot at the Glasgow gage, but it is immediately downriver from the only point on the graph that shows aggradation. The aggradation occurs below the confluence with the Grand and the Chariton Rivers, which appear to contribute a considerable amount of sand compared to other tributaries to the LOMR (see Table 3.4-17).

Records at the Boonville gage (RM 197.1) date back to 1930, and provide stage and average river bed elevation trends (Figure 3.4-26). The average river bed elevations are variable but do not exhibit a trend until approximately 1970, when a downward trend begins, with an uptick in the last couple years of data (2007 and 2008). The maximum difference is approximately 5 feet between 1970 and 2006, and the difference is approximately 2.8 feet between 1990 and 2005. Lower flow stages (20,000 cfs) also show some decline, even though stages for 40,000–100,000 cfs have remained fairly constant. Flows greater than 100,000 cfs show an upward trend of 2–4 feet (USACE 2007c).

The difference in CRP-adjusted low-flow water surface elevations between 1990 and 2005 (Figure 3.4-20) is approximately 1.5 feet at the Boonville gage.

No rated gage is in the vicinity of Jefferson City, but water surface elevations between 1990 and 2005 show a decline of approximately 3.0–4.5 feet between RM 160 and RM 130.

Analysis of average river bed elevations based on the HBED shows aggradation between approximately RM 155 and RM 240 for the period from 1998 to 2007–2009 (Figure 3.4-21). Unlike the Waverly segment, however, slight degradation was present between 2007 and 2009 for most of the segment. Approximately 1–2 feet of degradation was present at RM 250 near the confluence with the Grand River, and 2–2.5 feet of degradation in the Jefferson City area (RM 135 to RM 150).

A comparison of boring logs taken in 1954 from the US 54W Bridge in Jefferson City (approximately RM 144) to recent underwater surveys conducted in 2009 indicates a drop in the river bed elevation of 20–30 feet around the bridge pier located in the active flow channel, although this drop is likely influenced by local scour surrounding the bridge pier. Underwater surveys at points surrounding the piers show a general decline in river bed elevation from 2004 to 2009; however, a survey conducted in

December 2008 showed higher bed elevations than did surveys conducted in May, July, and August of the same year.

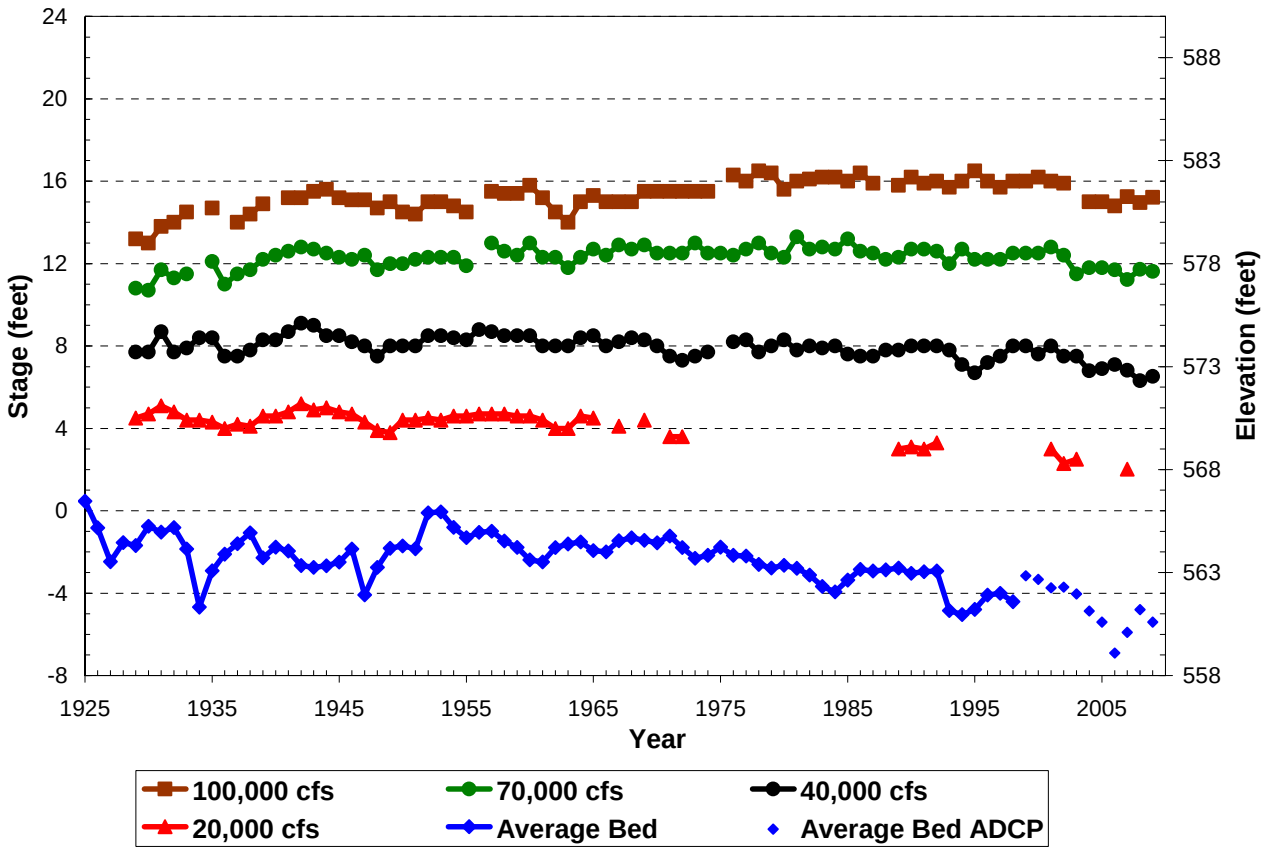


Figure 3.4-26 Missouri River Stage and Average River Bed Trends at Boonville, Missouri (RM 197.1)

Source: USACE spreadsheet "AveBed all gages upto Dec 5 2008.xls" updated with USGS gage data through 2009.

St. Charles Segment

The St. Charles segment extends from the Osage River (RM 129.9) to the confluence with the Mississippi River (RM 0). This segment includes a major tributary (the Osage River) at RM 104.4, and the city of St. Charles within the St. Louis metropolitan area, approximately 30 miles upriver from the confluence with the Mississippi River.

There are two USGS gages in this segment. Records for the Hermann, Missouri gage at RM 97.9 date back to approximately 1930, while the St. Charles gage has recorded average bed data since 2000.

The average annual river bed elevations for the Hermann gage (Figure 3.4-27) trend slightly upward from approximately 1930 to approximately 1960 and then begin to trend steadily downward until 2006. In 2007, the river bed elevation rose approximately 2 feet. This increase is not thought to be indicative of recovery of the bed, in light of the long term downward trend. The maximum decline between 1959 and 2006 is approximately 7.5 feet. The change from 1990 to 2005 is approximately 2.8 feet. Stages for flows below 100,000 cfs have been declining slightly since approximately 1970, and higher flows have been declining since the 1993 flood (USACE 2007c).

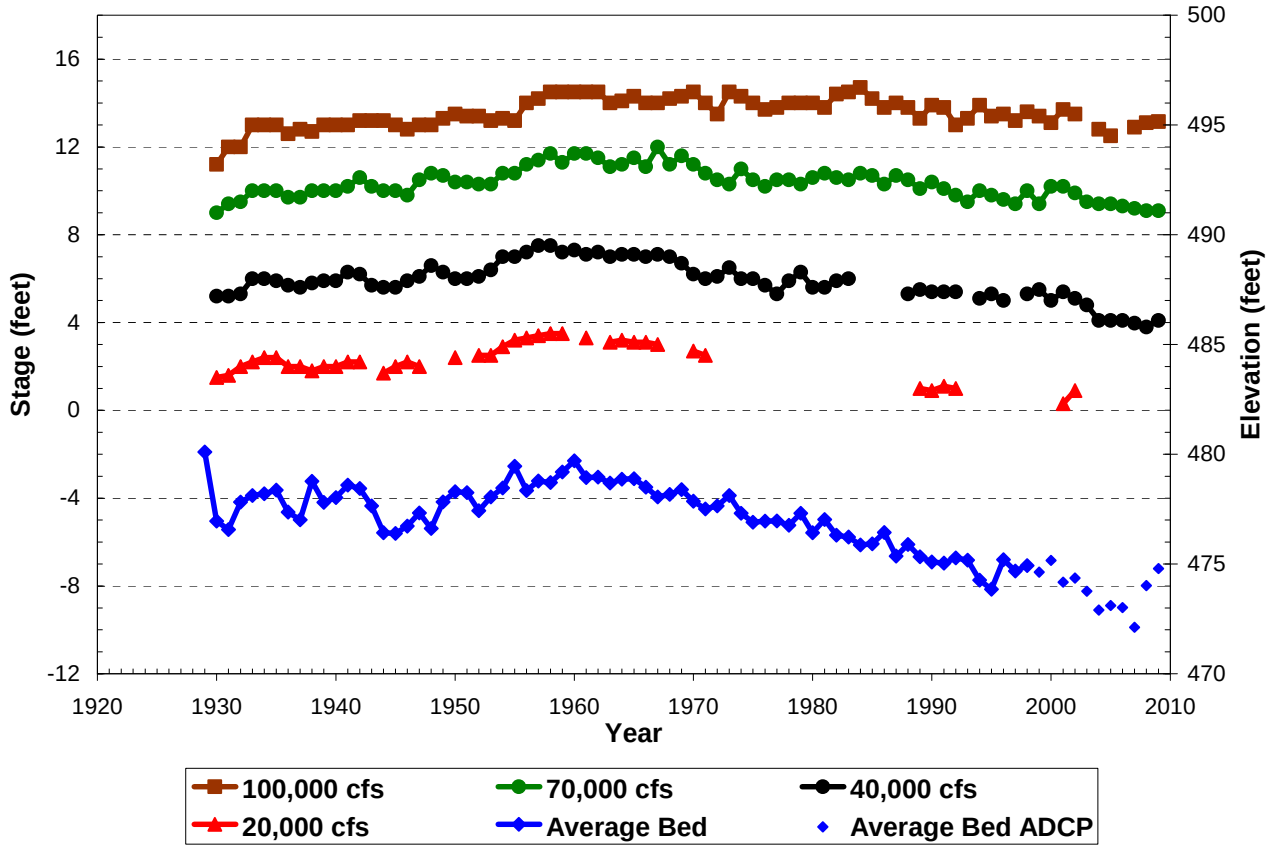


Figure 3.4-27 Missouri River Stage and Average River Bed Trends at Hermann, Missouri (RM 97.9)

Source: USACE spreadsheet "AveBed all gages upto Dec 5 2008.xls" updated with USGS gage data through 2009.

The average river bed elevations for the St. Charles gage have been generally stable over the short period of record (10 data points, no figure), declining approximately 1 foot between 2000 and 2009.

The difference in CRP-adjusted low-flow water surface elevations between 1990 and 2005 (Figure 3.4-20) is approximately 2 feet at the Hermann gage and approximately 4.3 feet for the

St. Charles gage. From 1990 to 2005, the water surface elevation changes approximately 2 feet at RM 85 and almost 5 feet at RM 48. It changes between 4 and 5 feet from RM 52 to RM 20. The lowest 15 miles of the LOMR near the confluence with the Mississippi River are subject to backwater influences from the Mississippi River that affect low-water profile readings, flows, sediment transport, and related parameters.

Analysis of average river bed elevations based on the HBED shows less than 1 foot of aggradation between RM 95 and RM 129, and an average of less than 1 foot of degradation between RM 0 and RM 98. The maximum degradation of approximately 2 feet occurs near the Hermann gage at RM 95 for the 1998 to 2007–2009 period and at RM 60 for the 1998–2009 period. The river bed in the St. Charles area (RM 25 to RM 40) dropped approximately 1.5 feet between 1998 and 2007–2009.

A comparison of river bed elevations from bore hole logs taken in 1996 to river bed elevations from a 2008 underwater survey for the Route 364 bridge (RM 32.6) revealed negligible changes in river bed elevations at most locations and a maximum of approximately 6 feet of bed lowering at the upstream side of one bridge pier. At the Interstate 70W bridge (approximately RM 29), bore logs from 1954 and surveys from 2008 indicate an approximate drop of 7–10 feet in average river bed surface elevation with a maximum drop of approximately 22 feet. The maximum drop was measured at the pier, however, and is likely influenced by localized scouring.

3.4.6.3 Potential Causes of River Bed Degradation

River bed degradation has been identified as an issue for the past 10–15 years on the Missouri River and since the 1970s on the Kansas River. More effort has been focused on the study of the Kansas City segment of the LOMR than on other portions of the river due to the magnitude of the bed degradation occurring in this area and the amount of infrastructure at risk. In addition, the rate of bed degradation in this segment accelerated in recent years (USACE 2007a). A number of studies and summary documents have been produced by the USACE and the USGS documenting the degree of bed degradation and examining its causes (Jacobson et al. 2009; USACE 2009a; USACE 2009b). As a result of these analyses, dredging volumes authorized under recently approved commercial dredging permits for the Kansas City segment have decreased.

As described in earlier sections, the geomorphic character of a river is controlled by interacting variables including slope, sediment grain size, flow regime, flow discharge, flow velocity, sediment loads, flood frequencies, structures in and near the river, and other factors. As a matter of general

principal, river bed degradation occurs when more material is leaving a reach of a river than is entering it. The historical unconstrained Missouri River—prior to construction and operation of the BSNP and the dam-reservoir complex—was a dynamic system that constantly changed bed elevations, channel location, channel sinuosity, and sediment load. The current Missouri River, particularly in the Kansas City segment, is constrained by dikes and revetments, bridge abutments and pilings, levees, and floodwalls. Geomorphic adjustments normally available to unconstrained rivers in the form of bank erosion, sand bar formation, lateral migration, and channel avulsions are not available to the LOMR. Consequently, when geomorphic variables change, such as increased flows or a reduction in sediment loads, the only geomorphic response remaining to the LOMR is adjustment in the river bed elevation.

Several factors have been identified that may be contributing to degradation in the Kansas City and other segments of the LOMR, including:

- Reduction in sediment loads by dams;
- Flow modification by regulation;
- Major flood events;
- Dikes and structures;
- River cutoffs; and
- Commercial dredging for sand and aggregate.

Reduction in Sediment Loads by Dams

All six mainstem dams on the Missouri River were completed and brought into service between 1940 and 1964, with the most downstream dam (Gavins Point Dam) becoming operational in 1955. The most downstream dam is approximately 450 miles upstream of Kansas City, Missouri. Degradation downstream of the dams as a result of sediment trapped in the upstream reservoirs has been well documented (USACE 2001). Sediment trapping occurs in the reservoirs when flow velocities drop as a stream enters the quiet waters of the reservoirs. All but the finest-grained sediments settle to the bottom and are trapped upstream of the dam. Degradation downstream of a dam occurs as a result of sediment-free water released from the reservoir scouring the channel to reestablish the sediment load characteristics of the stream.

Evaluations of USGS gage data and other data collected by the USACE indicate that the degradation caused by mainstem reservoirs does not likely extend below the Rulo, Nebraska gage (Section 4.4.6.2,

St. Joseph segment). In fact, the data reveal a trend of deposition from Rulo, Nebraska (RM 498) upriver to Nebraska City, Nebraska (RM 562) as shown in Figure 3.4-20. The low-flow water surface at Nebraska City, Nebraska, is clearly stable or rising with time. By contrast, Omaha, Nebraska (RM 616) shows a slight drop in stage at low flows; and Sioux City, Iowa (RM 732) shows a steep, downward trend for all discharges.

Data taken at these USGS gaging locations indicate that degradation associated with mainstem dam construction extends through Omaha, Nebraska but ends upstream of Rulo, Nebraska. Because the river is aggrading at that point it can be concluded that recent degradation trends in the portion of the LOMR from RM 0 to RMR 498 are likely not a result of the capture of sediment in the reservoirs in the upper river. It has been more than 50 years since completion of the most downriver dam on the mainstem (Gavins Point Dam) at RM 811.1, and 30 years since the BSNP was completed. Therefore, sediment transport blocked by the upstream dams is not likely affecting riverbed degradation at or downstream of Rulo, Nebraska (USACE 2009a).

The Kansas River has seven reservoirs that control most of the flow from the river's tributaries. The USACE has developed some evidence that these reservoirs have contributed to bed degradation of the Kansas River (USACE 1984), although it has not been determined whether this effect carries downstream to the Missouri River. Approximately 55 percent of the Kansas River watershed has been cut off from sediment delivery; consequently, the post-dam suspended sediment loads are approximately 36 percent of the pre-dam levels (USACE 1981). The Kansas River has seen a decrease in dredging over the last decade but still has been dredged for an average of over 2,120,000 tons of sand and aggregate annually between 1992 and 2007. Other local reservoirs near Kansas City are assumed to be too small to affect the Missouri River (USACE 2009a).

The reduction in sediment delivery from the Kansas River may contribute to the sediment deficiency and river bed degradation on the Missouri River downriver from the confluence with the Kansas River. This effect is likely minor, however, because the upper portion of the Waverly segment (downstream of the confluence with the Kansas River) appears to have aggraded from 1998 to 2007–2009 based on the HBED analysis.

In contrast, bed degradation in the St. Charles segment may be affected by reduced sediment loads from the Osage River (USACE 2009a). The Bagnell Dam, 80 miles upriver from the confluence of the Osage River and the LOMR, traps sediment from 92 percent of the Osage watershed (USACE 2009a). Neither the Osage River nor the Gasconade River contribute much sediment relative to the Missouri

River or other tributaries upriver (Table 3.4-17), but they do contribute a significant amount of flow (Figure 3.4-7). The Hermann gage (RM 97.9), below both the Osage River (RM 129.9) and the undammed Gasconade River (RM 104.4), has experienced long-term bed degradation (Figure 3.4-20). The HBED analysis shows the St. Charles segment below the Hermann gage to have degraded, on the order of 1 foot from 1998 to 2007–2009, with slight degradation continuing between 2007 and 2009 between RM 15 and RM 98.

Flow Modification by Regulation

As described in the hydrology section (Section 3.4.4), the flow regime of the LOMR has been altered by both the mainstem dams and dams on tributaries to the LOMR. Two objectives of the mainstem dams on the Missouri River are to control flooding and to provide navigation flows. Spring and early summer peaks are captured by the reservoirs and released during the late summer and fall, maintaining flows in the river sufficient for barge traffic (Figures 3.4-10 and 3.4-11). The relationship between sediment deposition and erosion and flows is complex; in general, most sediment gets deposited as flows are decreasing. The mainstem dams reduce the variability in flows, thus smoothing out peaks and low flows, which in turn affects sediment transport and deposition in the river. The moderating effects of the dams are reduced moving downriver as tributaries contribute variable flows.

Although the erosive power of peak flows is reduced by the upstream dams, peak flows tend to transport more sediment, thus making more sediment available for deposition on the falling limb of the hydrograph. The higher average low flows caused by the upstream dams, in combination with the design of the BSNP to maintain a self-scouring navigation channel, reduce the amount of sediment deposition that would occur at lower flows.

A feedback loop exists with river bed degradation, navigation flows, and the BSNP structures. In areas with bed degradation, the water surface elevation at navigation flows lowers as the bed degrades; and dike structures designed to have overtopping flows divert more water into the navigation channel, resulting in increased flow velocities that scour the channel more effectively.

Controlled release from the upstream dams is likely affecting the transport and deposition of sediment in the LOMR system. Mean annual flows also have increased over the period of record, with greater increases occurring farther downriver (Figure 3.4-14). Increased mean annual flows and increased low and moderate flows due to controlled releases (Figure 3.4-11) likely increase the overall transport capacity of the river (Figures A-34 through A-37 in Appendix A show the relationship between higher

flows and higher bed material load transport rates). In the Kansas City segment in particular, the constrained nature of the river through the highly urbanized area likely reduces opportunities for deposition even at lower flows.

Major Flood Events

The impact of major flood events on river bed degradation is variable and depends in part on where in the watershed the floodwaters originate. Significant flood events are described in Section 3.4.4.5. The floods of 1951, 1952, and 1993 rank among the top floods for most gages on the LOMR. The floods of 1951 and 1993 had similar genesis in that both were the result of spring and summer precipitation events in the lower Missouri rather than a snowmelt event similar to the one that triggered the floods of 1952. The floods from the 1950s affected river bed elevations differently from the flood event of 1993. Nonetheless, all three flood events caused tremendous amounts of flooding and damage to communities along the river.

The floods of the 1950s caused noticeable aggradation for several years following each flood event at most gage sites on the LOMR. The most pronounced effect was observed at the St. Joseph gage, and minor effects were recorded at Kansas City and Waverly (Figures 3.4-23 to 3.4-25). The 1993 flood, in contrast, caused a noticeable drop in river bed elevations at most of the gage sites, with the most pronounced drop at Kansas City (Figure 3.4-24) and no noticeable impact at the Rulo gage (Figure 3.4-22). Average river bed elevations both before and after the 1993 flood for the Kansas City gage (Figures 3.4-28 and 3.4-24) indicate that the river bed did not recover in the vicinity of the gage after that flood. River bed elevations recovered quickly at the Hermann gage; recovered more slowly at Boonville; and continued their previous downward trends at St. Joseph, Kansas City, and Waverly.

No two floods are the same, even if they are caused by similar meteorological conditions. Although both the 1951 and 1993 floods were caused by spring storm events, the Kansas River contributed 87 percent of the peak flows measured at the Kansas City gage during the 1951 flood but only 31 percent of the peak flows measured at the same gage during the 1993 flood (Niesen 2004). While natural storm variability is important in the river's response to these flood events, of far more significance are the engineering changes that occurred on the river in the intervening years between the two storms. More than one- half of the dams and reservoirs affecting the timing of flows and sediment delivery were completed after the 1951 flood event. By 1951, a reasonably stable channel of 6- to 9-foot depth from St. Louis to Kansas City had been established. By 1993, the BSNP had been completed, which constrained the channel with in-river dikes designed to maintain the 9-foot depth of the navigational

channel without maintenance dredging. Most federal flood protection levees were completed after 1950. By 1993, sediment had accreted between many of the dikes—further narrowing the river channel.

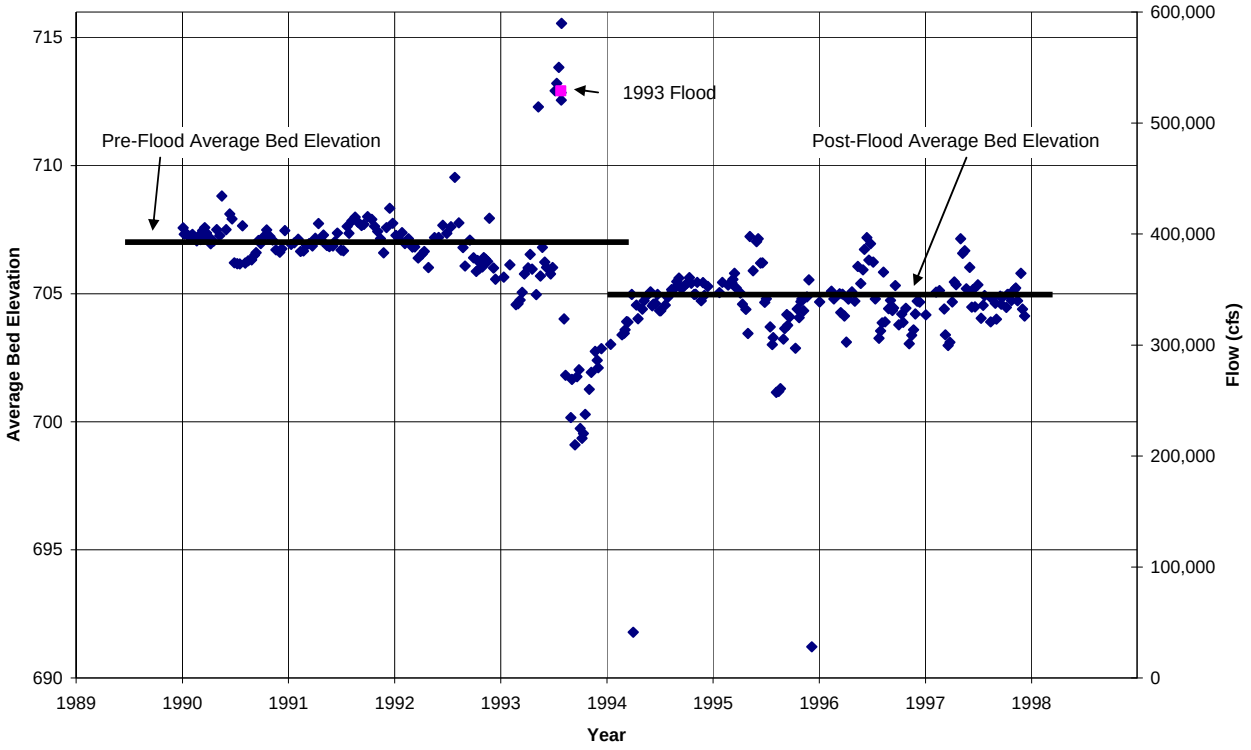


Figure 3.4-28 River Bed Elevations Based on Hydraulic Depth before and after the 1993 Flood at the Kansas City Gage

Source: USACE spreadsheet "KCmeasurements (y3).xls".

Consequently, stages for high-discharge events such as the 1993 flood have increased at all gage sites since the 1950s (USACE 2007c). Higher stages increase the shear stress on the river bed, and these higher stresses can result in river bed degradation and increased sediment transport capacity during storm events.

Dikes and Structures

As described in Section 3.4.5.2, the BSNP has caused major changes to the geomorphic character of the LOMR. The extensive system of dikes and revetments is designed to maintain a self-scouring navigation channel that is 300 feet wide and 9 feet deep, even at lower flows. By design, the structures

reduce sediment deposition at lower flows and reduce the likelihood of recovery from scouring events such as floods and dredging.

Construction of the BSNP occurred at the same time as construction of the dams, cutoffs, and side channel eliminations that changed the length of the river. In some places, navigation channel scouring as a result of BSNP structures may be contributing to ongoing bed degradation.

In particular, the Kansas City segment is more constrained than other segments of the LOMR. This is due to the extensive infrastructure in the Kansas City metropolitan area and the location of the Kansas River confluence. As stated in the 2009 USACE Reconnaissance Study Report:

> This set of river conditions has resulted in the installation of a very constrictive dike system to maintain a navigation channel. The construction of that dike system has resulted in a reach of river that is very efficient at "cleaning" and maintaining the low-flow channel (USACE 2009a).

In the river segments with limited river bed degradation since the BSNP was completed, it appears that the river has stabilized relative to the BSNP, dam-release flows, and modern sediment loads.

River Cutoffs

River cutoffs were an element of the BSNP process of creating a navigation channel. At several locations, sharp bends and loops were cut off to shorten the navigation channel and make curves easier for barges to navigate tight turns. As described in Section 3.4.3.2, most of the cutoffs in the Project area occurred between Kansas City and Waverly. Table 3.4-5 lists some of the significant cutoffs upriver from Waverly.

Rivers normally meander, creating loops and bends to achieve a slope that is in equilibrium with the size and volume of sediment that it is carrying in relation to the velocity and discharge of the flowing water. A river's pattern and form rarely stay unchanged due to constant variation in flows and sediment loads, as well as heterogeneity in the floodplain. With the BSNP in place, the river cannot adjust its length to compensate for changes in sediment loads, flows or, in this case, cutoffs in the river. Cutoffs shorten the river and increase the local slope, increasing flow velocities and sediment transport capacity. Assuming that the sediment size distribution does not change significantly, and with the river banks stabilized with revetments and dikes, the river can adjust its slope only by eroding the river bed upriver from the cutoff and depositing the sediment downriver from the cutoff.

The effects of the cutoff on the channel slope can be estimated based on information collected before and after the cutoff of the Liberty Bend in 1949, and on river slope data collected at various times for the Kansas City to Waverly segment. The Liberty Bend was shortened approximately 4.3 miles, and the slope was increased from 0.77 foot per mile to 1.3 feet per mile (Section 3.4.3.2). Seven years after the cutoff was completed, the channel bottom had dropped 1.3 feet at the cutoff, and the channel had degraded to a point 8.3 miles above the cutoff while aggrading to a point 21.3 miles downriver of the cutoff; the point of maximum aggradation occurred 10.5 miles downstream. Assuming that the headcut kept migrating upriver at the same rate since 1949, the upriver extent of the channel change would be 72 miles from the cutoff and over 50 miles upriver from Kansas City. A review of slope changes over time between Kansas City and Waverly—although a gross-scale estimate—shows that the slope increased substantially after the Liberty and Jackass cutoffs were completed, as expected, and then quickly decreased by 1963 and returned almost to pre-cutoff levels by 1978 as shown in Figure 3.4-29 (USACE 1980). The channel slope increased in response to the sudden change in channel length but stabilized as the channel headcut migrated upriver and re-established an equilibrium slope similar to pre-cutoff conditions.

Slopes also were calculated from the CRP water surfaces for 1990, 2002, and 2005. Although the CRP uses a different method to calculate slopes, the 1990 value is similar to the slopes measured in the 1950s. However, the CRP values show reduced slopes for the 2002 and 2005 water surface elevations. As indicated by the graph, the recent slope changes are unlikely the result of cutoffs completed in the 1950s.

Commercial Dredging

Commercial dredging has occurred to various degrees at different locations along the LOMR for the past 75 years (Figure 3.2-2). It was not until 1958 that levels exceeded 1 million tons per year. In 1965, dredging amounts exceeded 2 million tons per year. Dredging levels generally increased to a peak in 2002, at 8.7 million tons per year. Figure 3.2-3 shows dredging levels by river mile for dredging that has occurred in the last 10 years.

Concerns regarding the effects of river bed degradation on infrastructure and flood control structures have increased in the past 10–15 years. As a result, the USACE has conducted analyses and studies on the extent of river bed degradation and dredging. The methods used to measure river bed degradation and the extent of river bed degradation by segment are described in Sections 3.4.6.1 and 3.4.6.2, respectively.

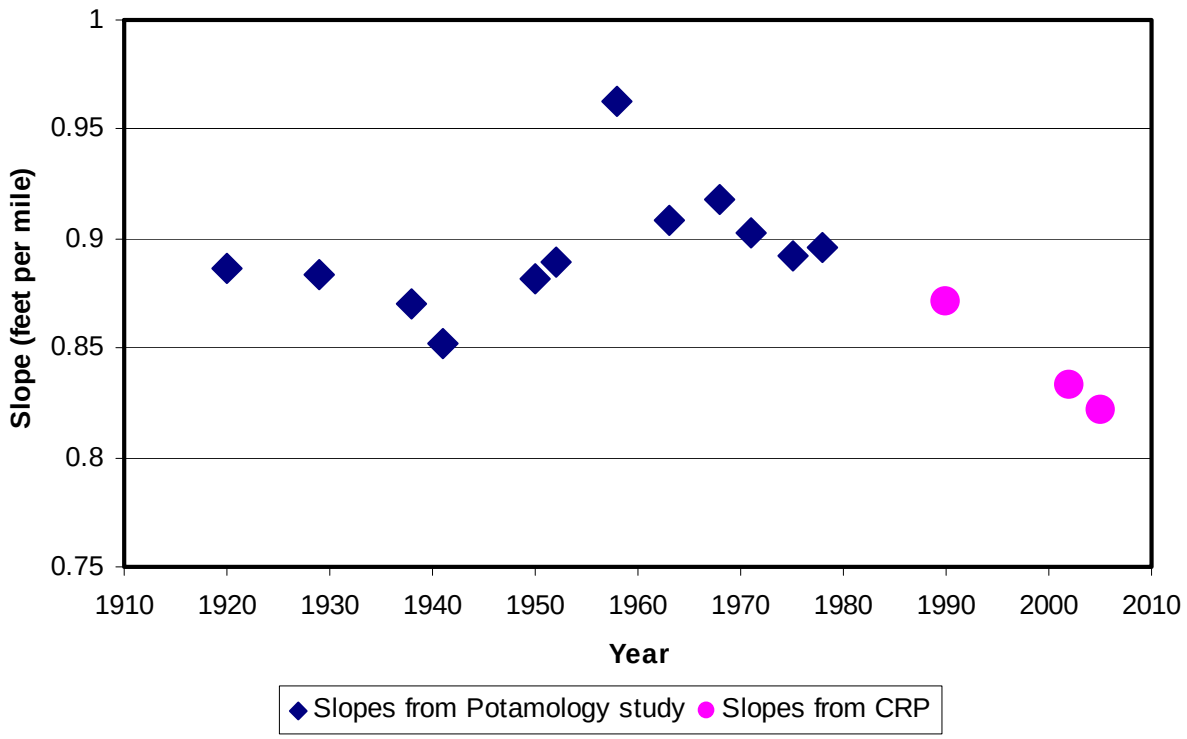


Figure 3.4-29 Water Surface Slope between the Kansas City Gage and the Waverly Gage (1920–2005)

Source: USACE 1980, USACE spreadsheet "2002 to 2005 CRP Camparison vs Dredging.xls."

Evidence of Degradation Caused by Commercial Dredging

The impacts of dredging on river systems have been documented in publications at the local level and worldwide (Jacobson et al. 2009; Kondolf 1997; Simons, Li, and Associates 1985; Rinaldi et al. 2005). There is strong evidence that dredging has contributed to degradation at several locations on the LOMR. The evidence comes from five sources:

- Changes in water surface elevations compared with dredging locations (1990–2005);
- Changes in river bed elevations compared with dredging locations (1998 to 2007–2009);
- Correlation between changes in stage elevation and dredging amounts at USGS gage locations (2000–2005); and
- Comparison of bed material loads with dredging amounts for stable and degrading segments (1999–2008).

CHANGES IN WATER SURFACE ELEVATIONS COMPARED WITH DREDGING LOCATIONS

Figure 3.4-30 shows the change in CRP-adjusted low-flow water surface profiles between 1990 and 2005 overlain with dredging amounts at corresponding locations. Water surface levels have fallen throughout the LOMR except for a small reach in the Jefferson City segment at RM 240. The portions of the LOMR where dredging has been concentrated experienced the greatest change in water surface elevations. This includes locations such as Jefferson City (RM 144) and St. Charles (~RM 28) that do not have the same constricted flow issues found in the Kansas City segment.

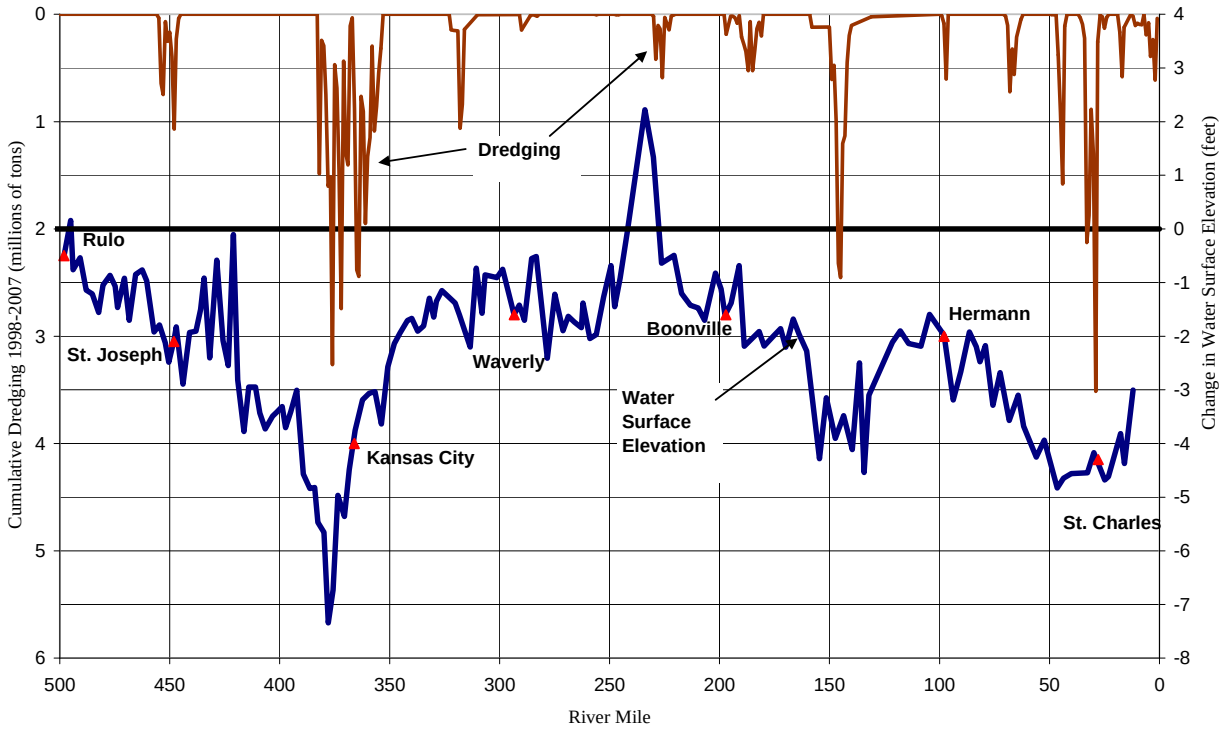


Figure 3.4-30 Cumulative Dredging (1998–2007) and Changes in the CRP-Adjusted Low-Flow Water Profile between 1990 and 2005.

Source: USACE spreadsheet "Public_mtg_posters_6_2_2009.xls" and USACE spreadsheet "MO Dredging Master 1935 to 2009.xls."

CHANGES IN RIVER BED ELEVATIONS COMPARED WITH DREDGING LOCATIONS OR AMOUNTS

Dredging amounts in the Kansas City segment are significant when compared to the volume of the river bed. An analysis conducted by the USACE estimated that dredged materials removed from RM 353 to RM 378 between 1990 and 2005 represent a volume of in-situ material roughly equivalent to a change in river bed elevation over the same distance of approximately 9 feet (USACE 2009a). The low-flow water surface elevation dropped between 3 and 7.5 feet at that location during the same period (Figure

3.4-30). If the volume of dredged material was spread over the reach between RM 290 and RM 440, an equivalent change in river bed elevation of between 1 and 2 feet would result (USACE 2009a).

The HBED analysis measured changes in average river bed elevations between 1998 and 2007–2009 (Figure 3.4-31). Changes between 2007 and 2009 give an indication of the variability of the system while changes between 1998 and 2007–2009 indicate the longer term trend. With the exception of the confluence of the Grand River at RM 250 and the general slight degradation trend through the St. Charles segment, areas with the most dredging evidenced the most degradation between 1998 and 2007–2009. Both the CRP-adjusted low-flow water surface elevation change results and the HBED results show greater degradation in areas with concentrated dredging.

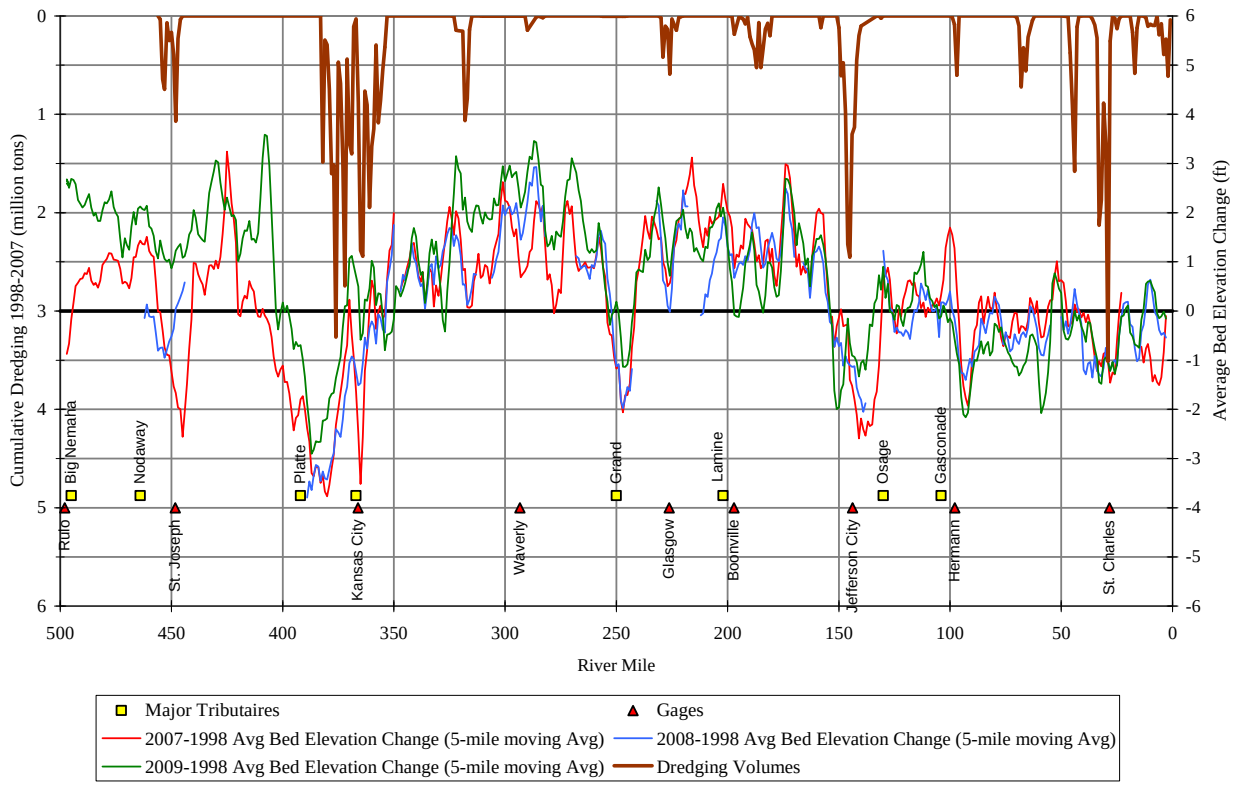


Figure 3.4-31 Cumulative Dredging (1998 to 2007) and Change in Average River Bed Elevation between 1998 and 2007–2009 Using a 5-Mile Moving Average.

Source: For dredging data: USACE spreadsheet "MO Dredging Master 1935 to 2009.xls."

In the Kansas City segment, degradation also has occurred upriver from the area of heaviest dredging, and is likely the result of river bed erosion on the upriver side of a dredging depression in the river bed (Kondolf 1997; Simons, Li, and Associates 1985; Rinaldi et al. 2005).

CORRELATION BETWEEN CHANGES IN STAGE ELEVATION AND DREDGING AMOUNTS

A strong correlation exists between the amount of dredging and change in the 40,000-cfs stage at USGS gage locations on the LOMR. Figure 3.4-32 shows the decrease in stage at 40,000 cfs with increased dredging near that location. The values are measured at a constant discharge to remove flow as a variable from the correlation.

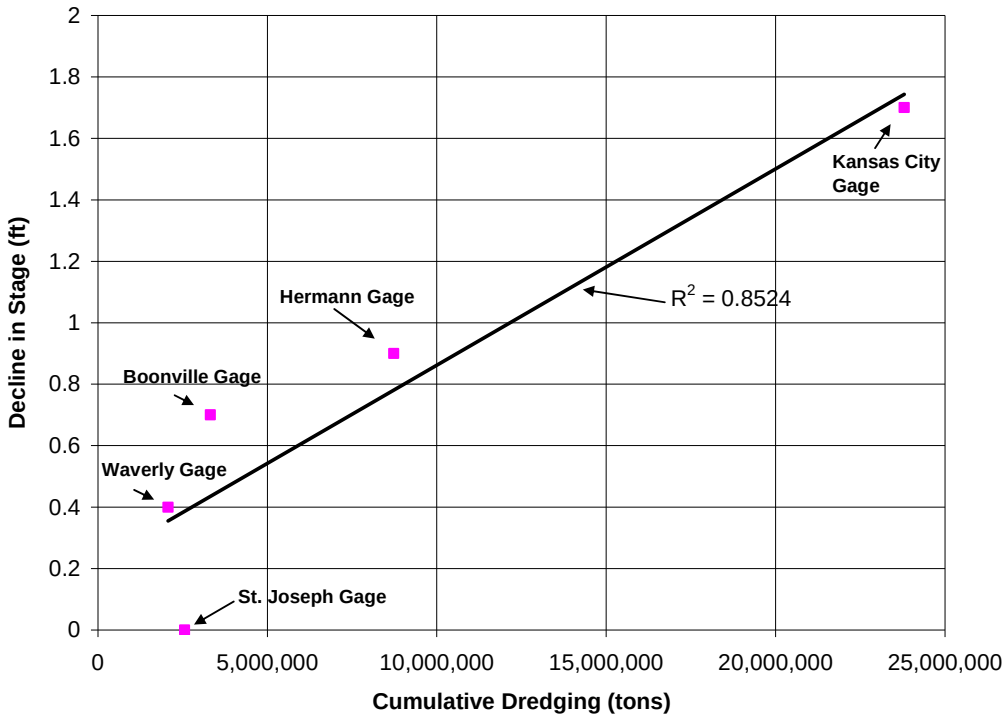


Figure 3.4-32 Correlation between Dredging and Changes in Stage at 40,000 cfs for Gages on the Lower Missouri River (2000–2005)

Source: USACE spreadsheet "Figure y.32 taken from Stage Trend 2007.xls."

COMPARISON OF BED MATERIAL LOADS WITH DREDGING AMOUNTS FOR STABLE AND DEGRADING SEGMENTS

To explore the relationship between dredging amounts, rates of river bed degradation, and bed material loads, dredging amounts were compared with bed material loads for the St. Joseph, Kansas City, Waverly, and St. Charles segments. These segments were selected because they allowed a comparison of relatively stable versus degraded river beds. The bed material load is composed of sediment that is on average smaller in size than the material removed from the river bed by dredging (see the particle size gradation comparison of bed material and concrete sand specification in Figure 3.4-16). The average annual amount of sediment dredged in a segment can be compared to the

amount moving as bed material load at nearby gages at St. Joseph, Kansas City, and Hermann (Table 3.4-20). In addition to the river bed elevation and sediment data available at the three gaging stations, long-term river bed elevation trend data are available for the Waverly gage at RM 293. For analysis purposes, the St. Joseph and Waverly segments, which have experienced minimal bed degradation, were compared with the Kansas City and St. Charles segments, where degradation has occurred. The Jefferson City segment was not analyzed because of the distance from the Kansas City gage; because of the variable amount of bed degradation in the segment; and because the Grand River, which delivers a considerable amount of sediment to the LOMR, joins the LOMR between this segment and the gage at Kansas City.

Table 3.4-20 Comparison of Dredging Amounts to Bed Material Loads for Four Segments on the Lower Missouri River (2000–2009)

Segment	St. Joseph	Kansas City	Waverly	St. Charles
Nearest gage	St. Joseph (RM 448)	Kansas City (RM 366)	Waverly (RM 293)	Hermann (RM 98)
River bed status at gage	Stable	Substantially degraded	Stable	Degraded
Average annual amount dredged (2000–2009) (tons/year)	343,231	2,855,073	500,143	1,716,518
Average annual bed material load (2000–2009) (tons/year)	3,508,070	5,352,153	4,955,740[a]	3,698,726
Dredged percent of bed material load	9.8%	53.3%	10.1%	46.4%

Note:

The Jefferson City segment was not analyzed because of the distance from the Kansas City gage; because of the variable amount of river bed degradation in the segment; and because the Grand River, which delivers a considerable amount of sediment to the Lower Missouri River, joins the Lower Missouri River between this segment and the gage at Kansas City.

[a] The bed material load for the Waverly segment was estimated by interpolating the values between the Kansas City gage and the Hermann gage.

For the St. Joseph segment, which has not degraded between 2000 and 2009 (based on the HBED analysis and river bed elevation records from the gage), the average annual amount dredged from 2000 to 2009 is approximately 9.8 percent of the bed material load estimate at the St. Joseph gage. The Kansas City segment has experienced substantial ongoing degradation, and dredging represents 53.3 percent of the bed material load calculated at the Kansas City gage. Based on a bed material load estimate interpolated between the upriver Kansas City gage and the downriver Hermann gage, sediment removal by dredging represents approximately 10.1 percent of the bed material load in the Waverly segment, which has experienced little or no degradation at the Waverly gage. For the St.

Charles segment, dredging represents approximately 46.4 percent of the bed material load estimate at the Hermann gage, which has experienced long-term degradation.

The results show that the Kansas City and Hermann segments with degrading river bed elevations are also the reaches with the most dredging; dredging amounts equal approximately 46 to 53 percent of the bed material load estimates for nearby gages. In contrast, river bed degradation appears to be minimal in the St. Joseph and Waverly segments, where dredging represents approximately 10 percent of the bed material loads.

Other Effects of Commercial Dredging

MINING GLACIAL DEPOSITS

As described earlier, river bed degradation occurs when more sediment leaves a river reach than enters it. Dredging operates independently from other geomorphic variables such as sediment loads and transport capacity in that it removes bed material directly from the bottom of the river. Limited studies and anecdotal evidence on dredge depression refilling have shown that dredge depressions may take several days to over a week to refill at navigation flows in the main channel, and longer if the dredging occurs off the main channel behind dikes (USACE 2007d).

The dredge depression does not refill with the same material that was extracted. Dredge heads used on the LOMR may be over 50 feet long; depending on the angle that it is deployed and the depth of the water, material can be dredged up to approximately 30 feet below the surface of the river bed. At normal flows, bed load typically moves as dunes that migrate down the river. Depending on flows, dunes may range from 2 to 4 feet high and from 60 to 120 feet long (Abraham pers. comm.). River bed sediment below the dune migration zone is mobilized only during flood events; and even during one of the most extreme events on record (the 1993 flood), the average river bed elevation dropped only approximately 7 to 10 feet (Figure 3.4-28).

The layer of river bed sediment actively transported is likely approximately 10 to 15 feet deep based on boring log records. Boring logs from the 1954 engineering plans for the Broadway Bridge (Kansas City, RM 366) indicate that the top layer of fine brown sand in the center of the river channel is approximately 10 to 15 feet deep, which likely represents the material that has been transported in modern times at that location.

The modern LOMR channel sits in a trench filled with alluvial material deposited from glaciers over 10,000 years ago (see Section 4.4.2). Although the glacial deposits are highly variable, they tend to

consist mainly of coarser and more densely packed sand than is transported by the modern Missouri River; this glacially deposited material tends to get coarser with depth (Kelly 2003). The glacial deposits also include gravels, cobbles, and boulders near the bedrock bottom of the trench, which at the Broadway Bridge is approximately 40 to 45 feet below the river bed at that location.

An active dredging depth of up to 30 feet, the use of cutter-head dredges, and the retention of a coarser fraction of material than typically found in bed surface samples, in combination with the long-term lowering of the river bed indicates that some portion of the dredged material is being mined from glacial deposits. The underlying glacial sediments may provide some erosion resistance to all but the most extreme flood events, and the larger size fraction resists transport and degradation more effectively than finer size fractions. With the removal of the glacial deposits, the river bed is both physically lowered and more prone to scour if the material that refills in the dredge depressions is a finer size fraction.

Reductions in water surface elevations have occurred with dredging in the Jefferson City and St. Charles metropolitan areas as well. Permits authorized by the USACE St. Louis District for the lower St. Charles reach allow only the use of suction-type dredges, not cutter-head dredges. Some Dredgers in Jefferson City use cutter heads, and some use suction heads. In the St. Charles segment, Dredgers can dredge to approximately 30 feet below the river bed surface but stop when they hit the “hardpan,” which can be felt by the dredge operator. The exact nature of the hardpan is unclear, but a review of bridge boring logs for the Interstate 70 bridge (~RM 29), and the Route 364 bridge (RM 32.6) shows that there is a general transition from more heterogeneous sand to sand with clay, gravel, or cobbles at approximately 15 to 30 feet below the river bed surface. The combination of less aggressive dredging techniques with a more resistant geological layer in the St. Charles segment may reduce rates of bed degradation from commercial dredging in that segment.

EFFECTS OF REMOVING COARSER MATERIAL FROM THE RIVERBED

Up to two-thirds of the material dredged in some areas of the Kansas City segment is too fine to meet specifications for making concrete and is discharged back into the river. Consequently, the actual volume of material extracted from the river bed may be up to three times greater than the retained dredging volumes indicate. The practice of retaining the coarser fraction of the dredged material likely increases the effect of dredging on bed degradation for two related reasons: (1) The portion of the dredged material that is returned to the river as a slurry is finer and more likely to remain in suspension and become part of the suspended bed material load than if it remained in the bed; and (2) even if the material discharged from the dredge becomes part of the bed, the process of extracting the coarser

fraction of the bed material decreases the mean sediment size and increases the likelihood that the bed material will be eroded and transported at equivalent flows. The dredging process also deposits material too coarse to meet specifications back onto the river bed, resulting in a river bed that is composed of coarse material in rows near the surface and more fine material than the original bed.

3.4.6.4 Conclusion

This geomorphic assessment relies on a combination of new analyses developed for this Draft EIS; analyses and data supplied by the USACE, the USGS, and other cooperating agencies; and other published literature. The new analyses primarily include estimation of bed material loads at three gage locations in the Project area and compilation and review of the HBED.

Comparison of low-flow water surface elevation changes, average bed elevation changes, HBED cross section changes, and the percent of bed material load extracted by commercial dredging clearly indicate that those areas where river bed degradation is most pronounced are the same areas where commercial dredging has been most active. While other factors such as the BSNP, river bend cutoffs, and flow modification also have contributed to degradation in areas both with and without dredging, they have been in place for decades and the river has largely adjusted to those factors. The 1993 flood was an unusual event that caused widespread degradation and the drop in overall low-flow water surface elevations between 1990 and 2005, as indicated in Figure 3.4-30. However, local declines in river bed elevations near areas of dredging and long-term degradation trends are not the result of the 1993 flood.

For the St. Joseph segment, low-flow water elevations have declined moderately from 1990 to 2005, and the river bed has been stable based on gage data from Rulo and St. Joseph. The HBED analysis shows aggradation throughout the reach from 1998 to 2009. Dredging in the segment has been less than 10 percent of the bed material load during the past decade. Although the river bed at the St. Joseph gage has fluctuated in the past, particularly from approximately 1965 to approximately 1985, it has been stable since the early 1990s based on the average river bed elevation data at the gage locations.

For the Kansas City segment, the river bed and low-flow water surface elevations have dropped 10 to 15 feet over the past 50 years, with approximately half of the degradation occurring in the past 15 years. Multiple factors are likely influencing bed degradation rates. The BSNP structures and more moderate but slightly higher than average river flows from construction of upstream dams are likely

contributing to increased sediment transport capacity, which results in scour in the Kansas City segment. Dredging is likely the key factor in causing bed degradation in the Kansas City segment based on the results of the bed material load estimates, the HBED analysis, and the change in CRP-adjusted low-flow water surface elevations compared with dredging locations. The volume dredged is over one-half of the total bed material load transported by the river over the past 10 years, which is substantially higher than dredging rates in reaches with little or no degradation. Given the extent of ongoing bed degradation, dredging in the Kansas City segment is likely mining from glacial deposits in the river bed.

The Waverly segment has been stable or aggrading based on river bed elevation and water surface profiles. Comparison of water surface profiles between 1990 and 2005 show a moderate decline of 0.5–2 feet, and the HBED analysis shows river bed aggradation from 1998 to 2007–2009. Dredging in this segment has been less than 10 percent of bed material loads estimated for this segment.

The Jefferson City segment has experienced moderate degradation over the past 40 years of approximately 3 to 5 feet at the Boonville gage, which is located approximately 50 miles upriver from Jefferson City. The low-flow water surface elevation data show that the only area of increase in the Project area occurred in this segment below the confluence of the Grand and Chariton Rivers. Based on water surface elevation data and the HBED analysis, the greatest amount of degradation in the segment appears to be occurring at the same location on the river as the highest levels of dredging—in the Jefferson City area. Degradation also is occurring at the confluence with the Grand River, where no dredging has occurred. The Jefferson City portion of the segment is not affected by the additional factors that affect the Kansas City segment, such as a major tributary confluence, flow-restricting infrastructure, or nearby river bend cutoffs. The only factor that appears to differentiate the Jefferson City portion of the segment from the rest of the segment is the amount of dredging.

The St. Charles segment also has experienced degradation near the urban area, although the trend is less certain because of limited gage data in that section of the river. The HBED analysis shows some degradation occurring throughout most of the segment below approximately RM 100, including the St. Charles area. The average river bed elevation at the Hermann gage has shown a long-term downward trend since approximately 1960, even though dredging levels have been moderate around the Hermann gage. The sediment-limited Osage River and the Gasconade River may be contributing flows that increase the sediment transport capacity below their confluence without contributing much sediment, thus initiating bed degradation. Sediment extracted by dredging, primarily in the St. Charles area, represents over 40 percent of the bed material load estimated to be passing the Hermann gage

and is a likely contributor to the degradation indicated by low-flow water level reductions in the St. Charles area.

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