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Addressing The Impact Of Gavins Point Dam On The Lowermost~1400 Kilometers Of The Missouri River

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ADDRESSING THE IMPACT OF GAVINS POINT DAM ON THE LOWERMOST ~1400 KILOMETERS OF THE MISSOURI RIVER

by

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ABSTRACT

The Missouri River originates in the Rocky Mountains in western Montana and joins the Mississippi River near St. Louis, Missouri. Beginning in the early 1900s, engineering efforts, such as dam construction, channel narrowing, and river alignment, were performed for flood control, navigational purposes, to use of water for agricultural and industrial needs, to produce hydroelectric power and the impounded lakes for recreation. These projects permanently altered the flow and sediment transport regimes in the river and the exchange of sediment with the surrounding floodplain. We focus on the long term effects of dam construction and channel narrowing on approximately the 1400 kilometer long reach of the Missouri River from Gavins Point Dam, located near Yankton, South Dakota, and the confluence of the Missouri and Mississippi Rivers near St. Louis, Missouri. It has been shown that two downstream migrating waves, one of channel bed degradation and another of channel bed aggradation, formed in this reach in response to the changes in the flow and sediment transport regimes, sediment load, and channel geometry. Using a zeroed one dimensional morphodynamic model for large, low slope sand bed rivers we 1) predicted the magnitude and migration rate of the waves of degradation at engineering time scales, approximately 150 years into the future, and 2) quantified the changes in sand load delivered to the Mississippi River.

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CHAPTER 1

INTRODUCTION

The Missouri River is the longest in the United States. The main channel is approximately 2,341 miles long, and is one of the major tributaries of the Mississippi River. The Missouri River drains an area of approximately 500,000 square miles (mi^2), which corresponds approximately to 43 percent of the Mississippi River basin. Brower's Spring, located in the Centennial Mountains of Montana, first marked in 1888, is identified as the ultimate headwater of the Missouri-Mississippi River system and the river is formed by the confluence of the Jefferson, Madison, and Gallatin Rivers. The Missouri River travels through North Dakota, South Dakota, Nebraska, Iowa, Kansas, and Missouri where it enters the Mississippi River. The river travels through major cities including Great Falls, Montana, Bismarck, North Dakota, Pierre, South Dakota, Sioux City, Iowa, Omaha, Nebraska, Kansas City, Missouri, and St. Louis Missouri. There are over 10 major tributaries along the river notably the James River located in Yankton, South Dakota, the Platte River located near Omaha, Nebraska, and the Kansas River located near Kansas City, Missouri. Figure 1.1 shows the Missouri River Basin catchment area including major cities, tributaries, and dams.

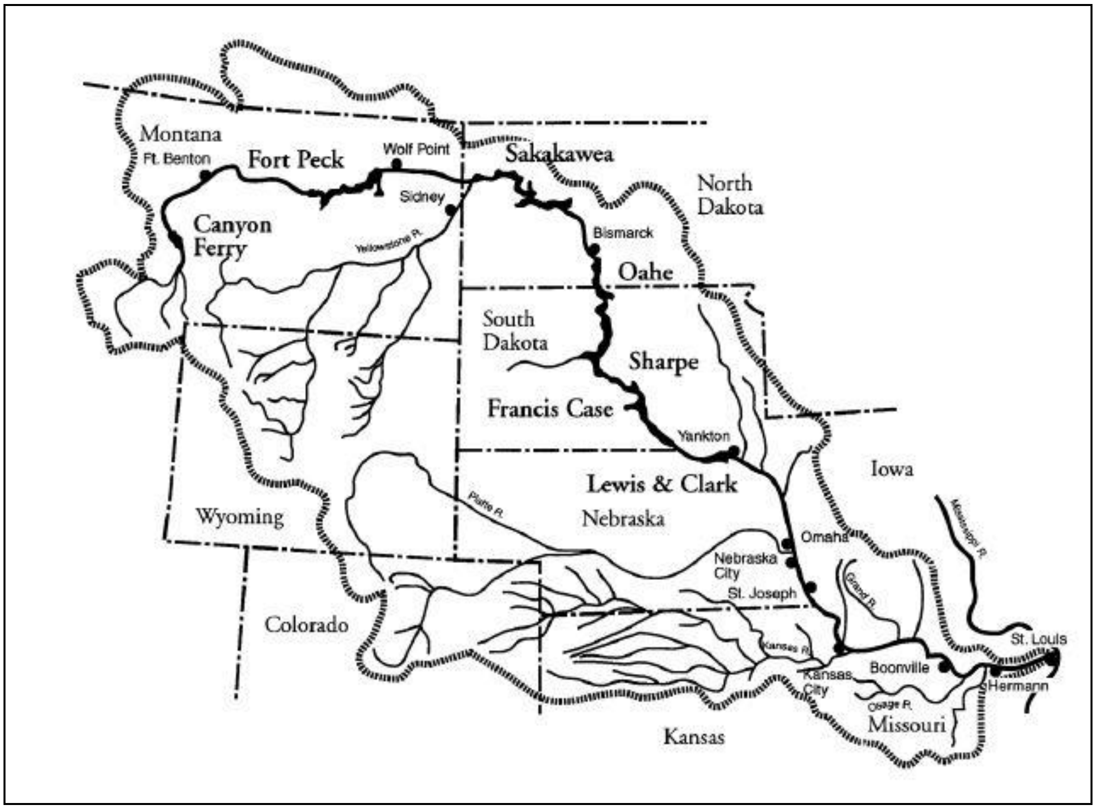

Figure 1.1 Missouri River Basin Catchment Area

The area surrounding the Missouri River has been inhabited for over 2,500 years as evidenced by numerous village sites that have been discovered. However, significant changes to the river and surrounding area largely began just within the last two centuries with the beginning of exploration and settlement.

The river and its drainage basin provided live game, accessibility to clean drinking water, fertile soil for agriculture, and timber forests for development. In addition, the river provided a means for transportation and the ability to move natural resources and manufactured goods great distances and the river was a means for developing economic potential in the area.

The French first discovered the river in 1673 while canoeing near what is now the confluence of the Mississippi River. In the early 1700s French fur traders began to travel upstream taking advantage of the abundance of natural game in the surrounding area. Early explorers gave the Missouri River the name “Big Muddy” as a result of the river’s abundance of sediment and turbid waters (Blevins, 2006). In 1804, the Lewis and Clark Expedition set out from St. Louis heading westward seeking to explore the Missouri River, make contact with Native-Americans, and expand the American fur trade. Territorial disputes between the French and the Great British began in the middle 18th century.

Later in the 18th century, the United States claimed the rights to travel on the Missouri and Mississippi Rivers enabling transport of exports to New Orleans. The United States purchased the entirety of Louisiana and the area surrounding the Missouri River from the French in the early 19th century and in doing so doubling the size of the United States. With westward expansion the railroad was built and it diminished transportation occurring on the river.

Despite its abundance in resources and desirable conditions for approximately 150 years after the initial exploration little was done to develop the waterway and use the surrounding area for agriculture. Beginning in the middle of the twentieth century, targeted engineering efforts including dam construction and channelization were carried out by the United States Federal Government in hopes that the river basin would benefit in many different ways. In 1944, the Government set out a wide-sweeping plan to establish flood control, development of a water supply, increase transportation on the river, improve agriculture in the surrounding area, and later the plan was extended to the production of hydroelectricity as well as recreation.

A bank stabilization effort was put in place with the deepening of the river channel along an approximate 760-mile reach of the river spanning from Sioux City, Iowa, to the Mississippi River. Major dams were built on the river between the 1930s and 1960s. While these targeted engineering efforts were carried out in order to improve society, they altered the natural fluvial processes and therefore created changes in the Missouri River's hydrology, sediment load and longitudinal profile.

Spring rains and snowmelt in March and April and the second flood stage in June from snowmelt in remote mountain regions motivated the flood control projects on the Missouri River. The Missouri River is integral in the movement of freight and goods south to ports in the Gulf of Mexico. Approximately 1,500 mi^2 of open water with six main-stem reservoirs make up the Missouri River Main-Stem System. Areas for camping, hiking, and walking are numerous in the area. In recent decades extensive conservation and preservation efforts have been made in the Missouri river basin. Portions of the Missouri River have been designated as a United States National Wild and Scenic River. Fort Peck Lake, one of the six main-stem reservoirs, is conserved and preserved as part of the Charles M. Russell National Wildlife Refuge. Many of the tributaries of the Missouri River are protected as well.

Six major main-stem dams, all located upstream of Yankton, South Dakota, are part of the coordinated, basin-wide, Missouri River Basin Project first executed by United States Congress in 1944. These six major main-stem dams are Fort Peck, Garrison, Oahe, Big Bend, Fort Randall, and Gavins Point. In addition, there are over eighty other dams located on the primary and secondary tributaries of the Missouri River. The six major main-stem dams above impound Lake Fort Peck, Lake Sakawea, Lake Oahe, Lake Sharpe, Lake Francis Case, and Lewis & Clarke Lake respectively.

The northern most main-stem dam, Fort Peck, is located in Glasgow, Montana, approximately 300 miles west of the capital city Helena. Lake Fort Peck has a drainage area of approximately 57,500 mi^2, an average inflow of approximately 10,200 cubic feet per second (cfs), and a maximum-recorded discharge of approximately 137,000 cfs in 1953. Construction began in 1933 and the dam became operational in 1940.

Garrison Dam is located in Garrison, North Dakota, approximately 75 miles north of the capital city Bismark. Lake Sakawea has a drainage area of approximately 123,900 mi^2, an average inflow of approximately 15,400 cfs, and a maximum-recorded discharge of approximately 348,000 cfs in 1952. Construction began in 1946 and the dam became operational in 1955.

Oahe Dam is located in New Pierre, North Dakota, approximately 200 miles south of the capital city Bismark. Lake Oahe has a drainage area of approximately 62,090 mi^2, an average inflow of approximately 3,300 cfs, and a maximum-recorded discharge of approximately 444,000 cfs in 1952. Construction began in 1948 and the dam became operational in 1962.

Big Bend Dam is located in Chamberlain, South Dakota, approximately 85 miles south of the capital city Pierre. Lake Sharpe has a drainage area of approximately 5,840 mi^2, and a maximum-recorded discharge of approximately 444,000 cfs in 1952. Construction began in 1959 and the dam became operational in 1964.

Fort Randall Dam is located in Lake Andes, South Dakota, approximately 170 miles south of the capital city Pierre. Lake Sharpe has a drainage area of approximately

14,150 mi^2, an average inflow of approximately 1,100 cfs, and a maximum-recorded discharge of approximately 447,000 cfs in 1952. Construction began in 1946 and the dam became operational in 1953.

Gavins Point Dam is located in Yankton, South Dakota, approximately 250 miles south of the capital city of Pierre. Lewis & Clarke Lake has a drainage area of approximately 16,000 mi^2, an average inflow of approximately 2,000 cfs, and a maximum-recorded discharge of approximately 480,000 cfs. Construction began in 1952 and the dam became operational in 1955. Figure 1.2 shows the locations of the six main-stem dams located upstream of Yankton, South Dakota.

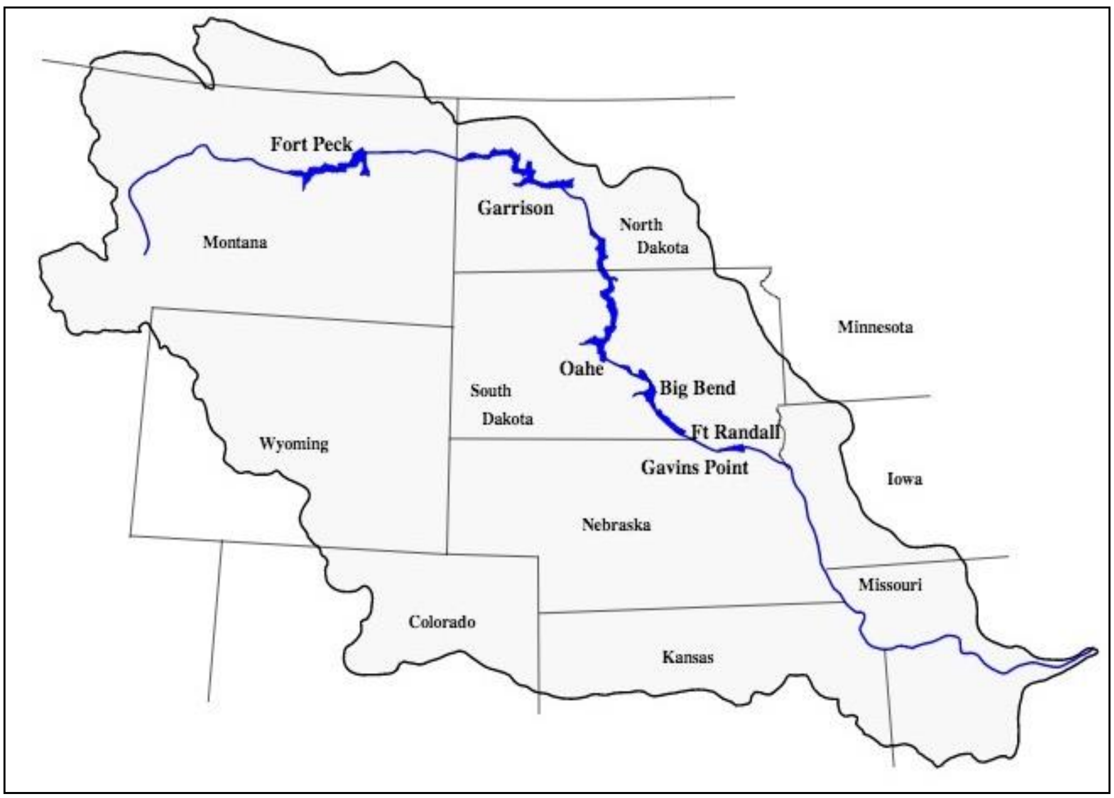

Figure 1.2 Locations of Main-Stem Dams North of Yankton, South Dakota

The United States Geological Survey (USGS) historical water quality and precipitation record shows that, notwithstanding the flood protection works, large flooding events occurred in the Missouri River basin. For example, there was widespread flooding in the Central United States in 2011. The flooding was a result of the combination of a higher than normal amount of snowpack found upstream in the Rocky Mountains, higher than normal snowfall in the Central Plains, and record rainfall in the Upper Missouri River Basin (Vining and others, 2013; Griggs and others, 2012). The releases measured at Gavins Point Dam were the largest measured in both magnitude and volume since the dam became operational in 1955 (Alexander, et. al. 2012). Other recent significant floods occurred in 1993 and 2008.

There are no locks located on the Missouri River but the United States Army Corps of Engineers (USACE) engineered the river and its tributaries with other forms of civil infrastructure. These control structures include wing dams, weirs, and commercial dredging has also been performed to enable increased water transportation. A wing dam extends partway into river and forces water into the center of the channel, which reduces sediment accumulation and decreases the water velocity in proximity to the channel banks. A weir is a smaller barrier that spans across the river and pools water behind itself while simultaneously allowing steady flow over its top, prevents flooding, and controls discharge. A system of levees exists downstream from Omaha, Nebraska yet flooding is prevalent in the area due to overbank flows in the upstream reaches (U.S. Army Corps of Engineers, 2006).

The redirection of flow in the Missouri River first began with diversions for irrigation purposes. Periods of low and high precipitation impacted control discharge at each of the six main-stem dams. Typical flows were shallow and the river did not excessively meander, the slope was low – on the order of 10^{-4}-10^{-5} – and the bed material was sand. The intentional flow confinement increased the water depth and the velocity thus increasing the sediment transport capacity of the Missouri River. As a result there was a decrease in sediment availability associated with the changes in river slope and channel geometry. The lowermost ~1400 kilometers of the Missouri River, which is the reach of the Missouri River studies herein, is defined as the segment of the river beginning approximately downstream of Gavins Point Dam located near Yankton, South Dakota, and downstream to the city of St. Louis, Missouri.

The lowermost Missouri River is here divided into three sub-segments identified in river miles (RM) upstream from the confluence with the Mississippi River. The upper segment, from approximately Gavins Point Dam, herein defined as RM 811.1 to approximately Ponca, Nebraska, at RM 753, is generally unchannelized and unconfined. The middle segment, from approximately Ponca to Fort Calhoun, Nebraska, at RM 634 is generally channelized and partially confined. The lowest segment, from approximately Fort Calhoun, Nebraska to St. Louis, Missouri, is both channelized and confined. Identifying the many different physiographic regions within the Missouri River Basin is important to understand the transport of sediment in the lower Missouri River. The Missouri River Basin can be divided into seven physiographic regions that include the Central Lowland, Great Plains, Middle Rocky Mountains, Northern Rocky Mountains, Ozark Plateaus, Southern Rocky Mountains, and Wyoming Basin.

Figure 1.3 shows the entire Missouri River Basin divided into each physiographic region with primary tributaries, main-stem dams, and United States Geographical Survey monitoring stations included. Red triangles represent daily-suspended sediment monitoring stations, yellow triangles represent continuous suspended sediment monitoring stations, green triangles represent periodic suspended sediment monitoring stations, and black tick marks represent the main-stem dams.

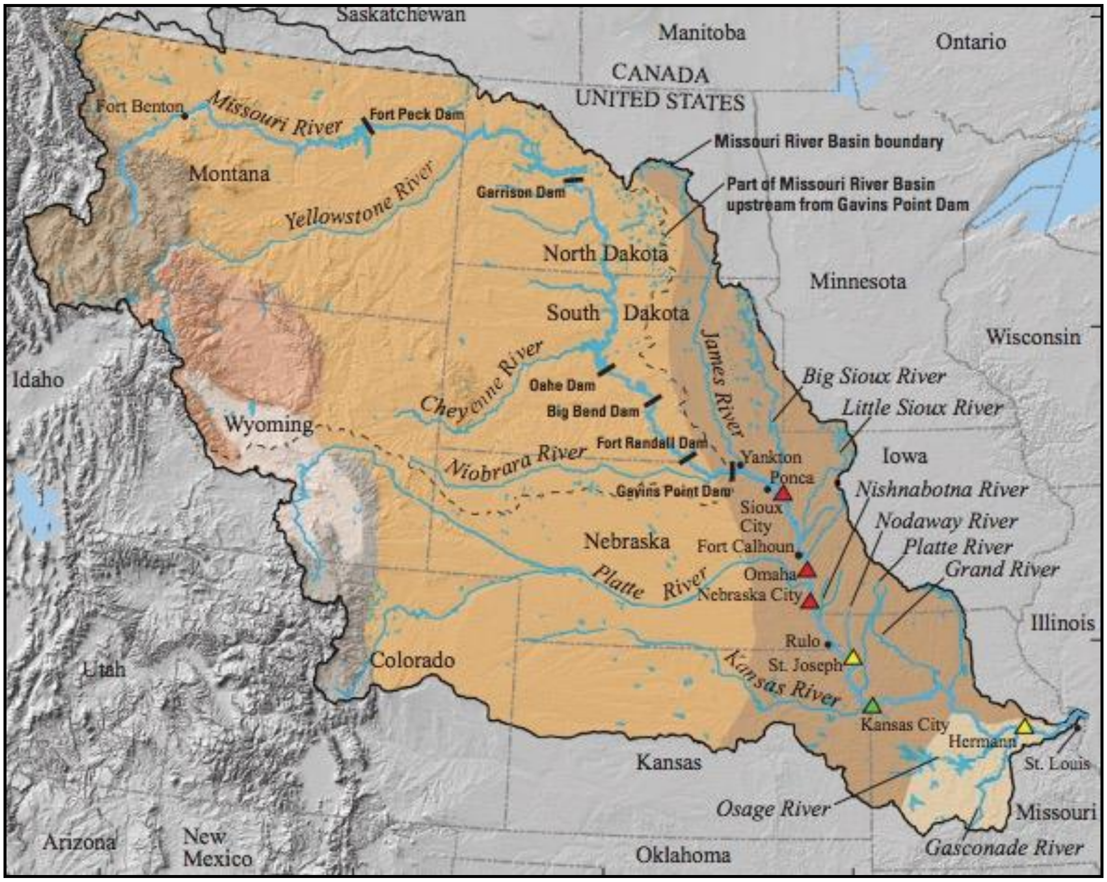

Figure 1.3 Physiographic Regions within the Missouri River Basin

The lowermost Missouri River is nearly entirely contained within the Central Lowland region with a small part of the defined segment contained in the Ozark Plateaus region in the vicinity of the city of St. Louis, Missouri. The Central Lowland region is generally characterized by low-slope, unconfined in natural conditions rivers flowing through easily erodible sediments. Due to the river's unconfined nature and easily erodible sediments the region produced a large sediment load and made the Missouri River the largest source of sediment to the Mississippi River system (Heimann et. al 2011). The Missouri River main-stem reservoir system (MRMRS) was constructed during the 1930s through 1960s and is made up of six dams located upstream of the Gavins Point Dam. Due to the MRMRS, sediment supply to the six main-stem downstream dams has decreased causing the channel to become more incised in some parts. It is estimated that sediment delivery has been reduced by more than fifty percent of the estimated pre-settlement rate (Jacobson and other, 2009; Heimann and others 2010), however very little is known on the partition of this reduction in terms of sand (bed material) and mud (floodplain material defined as sediment with grain size finer than 62.5 microns) loads. The objective of this research work is to estimate the reduction in sand load in the lowermost Missouri River associated with the construction of civil engineering infrastructures.

CHAPTER 2

DATA ANALYSIS

The data used to constrain the flow and the sediment transport regime on the Missouri River are the USGS daily water discharge (ft^3 s^{-1}), suspended sediment concentration (mg L^{-1}or suspended sediment discharge (T day^{-1}), and the volume content of mud in suspension. Data was collected at the USGS monitoring stations located at Yankton, SD, Sioux City, IA, Omaha, NE, Nebraska City, NE, Saint Joseph, MO, and Waverly, MO (Survey Station ID: 06467500, 06486000, 06610000, 06807000, 06818000, and 06895500 respectively). Figure 1.3 shows the location of the USGS monitoring stations located along the lowermost Missouri River.

To characterize the transport of sand, i.e. the material preferentially transported in the Missouri River main channel, we consider the suspended sediment data that were partitioned between sand (>62.5 μm grain size) and mud (<62.5 μm) by sample sieving. The raw data contained in each data set includes a begin date of sampling, begin time of sampling, end date of sampling, and end time of sampling. The beginning sampling date for each station varies but all data sets date back to at least the 1950s. Daily water discharge measurements, reported as ft^3 s^{-1}, are converted to m^3 s^{-1}. Total suspended load measurements, reported as T d^{-1}, are converted to metric T yr^{-1}. The portion of total suspended load as sand and portion of total suspended load as mud are calculated using the reported mud fraction data. Suspended sediment concentration measurements, reported as mg L^{-1}, are converted to daily suspended sediment discharge (metric T day^{-1}) as per conventional USGS methods that use the daily water discharge (cfs converted to $m^3 s^{-1}$) measured for the same day as when the sediment sample was collected. Water discharge is measured daily while suspended sediment concentrations are measured less frequently.

To calculate the annual sediment flux, the water discharges are plotted versus the sediment discharge to develop a sediment-rating curve by fitting the data with a power regression function (e.g. Nittrouer and Viparelli, 2014). Suspended sediment rating curves, which represent a site specific sediment transport relation, are produced for both sand and mud fractions and are used to estimate the mean annual load from the flow duration curves.

It is important to note here that we assume that the suspended sediment rating curves are representative of the mode of sediment transport in a reach and thus do not change from pre- to post-Gavins Point dam conditions. While this approximation allows us to reasonably approximate the suspended sand load because it occurs at-capacity (there is enough sand in the channel bed that the flow can pick up and transport what it is able to carry), this approximation may not be very accurate to estimate the pre-Gavins Point Dam mud load because the data describing the transport of mud in suspension may be significantly affected by the regulated regime and the sediment deposition in the reservoirs. In particular, noting that 1) the mud load is primarily controlled by the exchange of sediments between the river channel and the adjoining floodplains, 2) long reaches of the Missouri River are not allowed to migrate in the adjoining floodplain, and 3) the travel distance of mud particles is on the order of 100s of kilometers (Parker, 2004), the distance from the dams necessary to have a mud load that is not influenced by the deposition in the reservoirs has to be on the order of several hundreds of kilometers.

Figure 2.1 shows the suspended sediment rating curve for USGS monitoring station located at Yankton, South Dakota approximately 9 River kilometers downstream of Gavins Point dam. Blue symbols pertain to the mud and orange symbols pertain to the suspended sand.

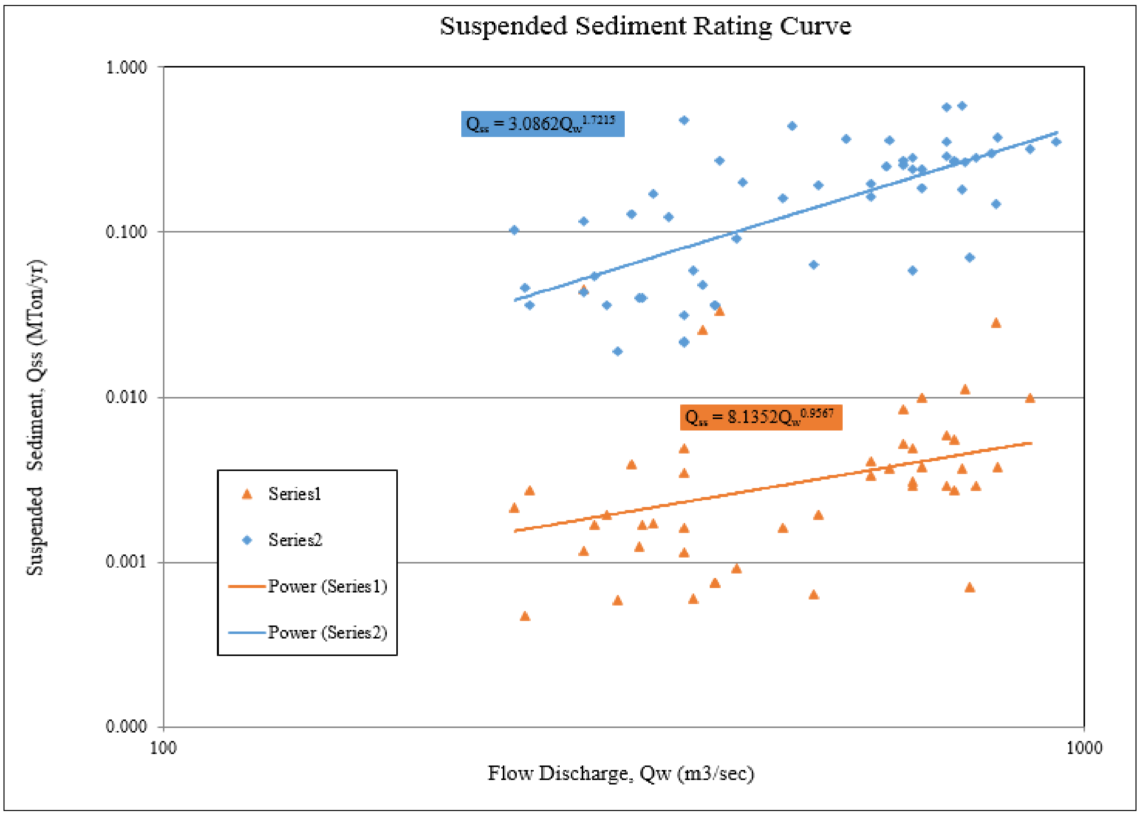

Figure 2.1 Suspended Sediment Rating Curve for USGS Monitoring Station at Yankton, South Dakota

The field data of Figure 2.1 indicates that for a given flow rate the mud load is greater than the suspended sand load. The USGS monitoring station located at Yankton is between the dam and the first Missouri River tributary, therefore the only source for the sand load and mud load is the Missouri River main channel.

Figure 2.2 shows the suspended sediment rating curve for USGS monitoring station at Sioux City, Iowa, approximately 127 River kilometers downstream of Gavins Point dam.

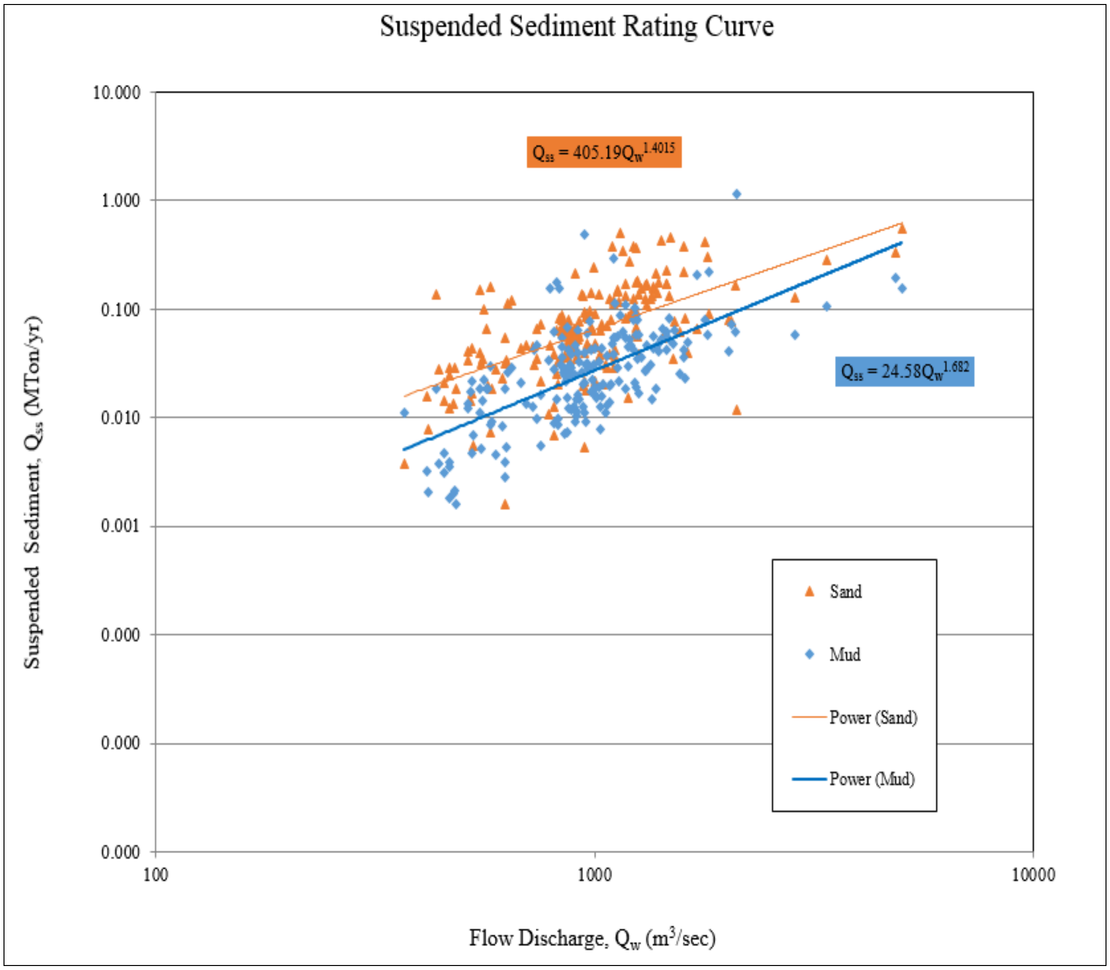

Figure 2.2 Suspended Sediment Rating Curve for USGS Monitoring Station at Sioux City, Iowa

For the post-dam Missouri River at Sioux City that the mud load is smaller than the suspended sand load, which is unusual for a sand bed river. Whether the small mud load at Sioux City is an effect of the channelization works, or of the confluence with the Sioux River, a tributary located few kilometers upstream of the USGS station, has to be determined with detailed studies.

Figure 2.3 shows the suspended sediment rating curve for USGS monitoring station located at Omaha City, Nebraska approximately 314 River kilometers downstream of Gavins Point dam.

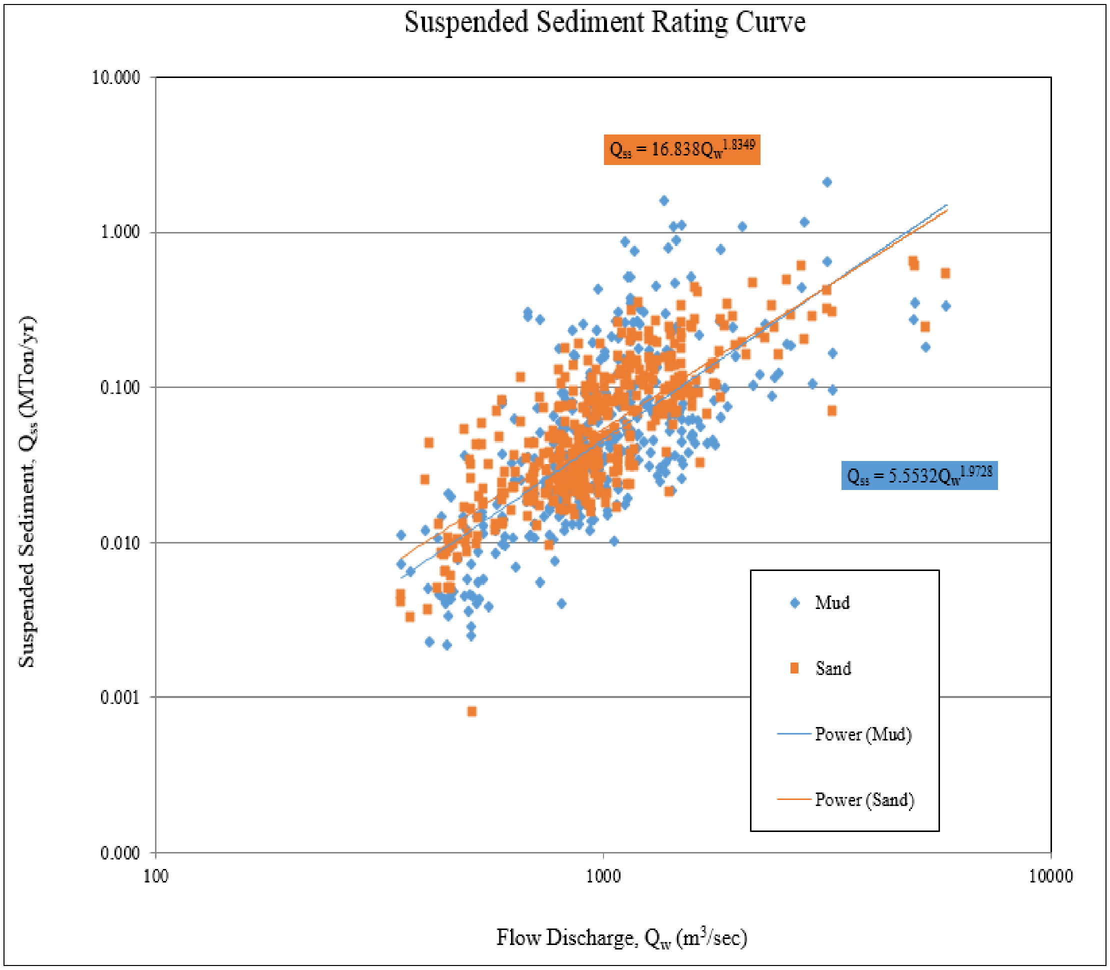

Figure 2.3 Suspended Sediment Rating Curve for USGS Monitoring Station at Omaha City, Nebraska

The mud load and the suspended sand load at Omaha City, Nebraska, are approximately the same, confirming what observed at the Sioux City station located approximately 187 km upstream. It is important to note here that there are not major tributaries between the two gaging stations, and this further explains the similarities between the suspended loads.

Figure 2.4 shows the suspended sediment rating curve for USGS monitoring station located at Nebraska City, Nebraska approximately 365 River kilometers downstream of Gavins Point dam.

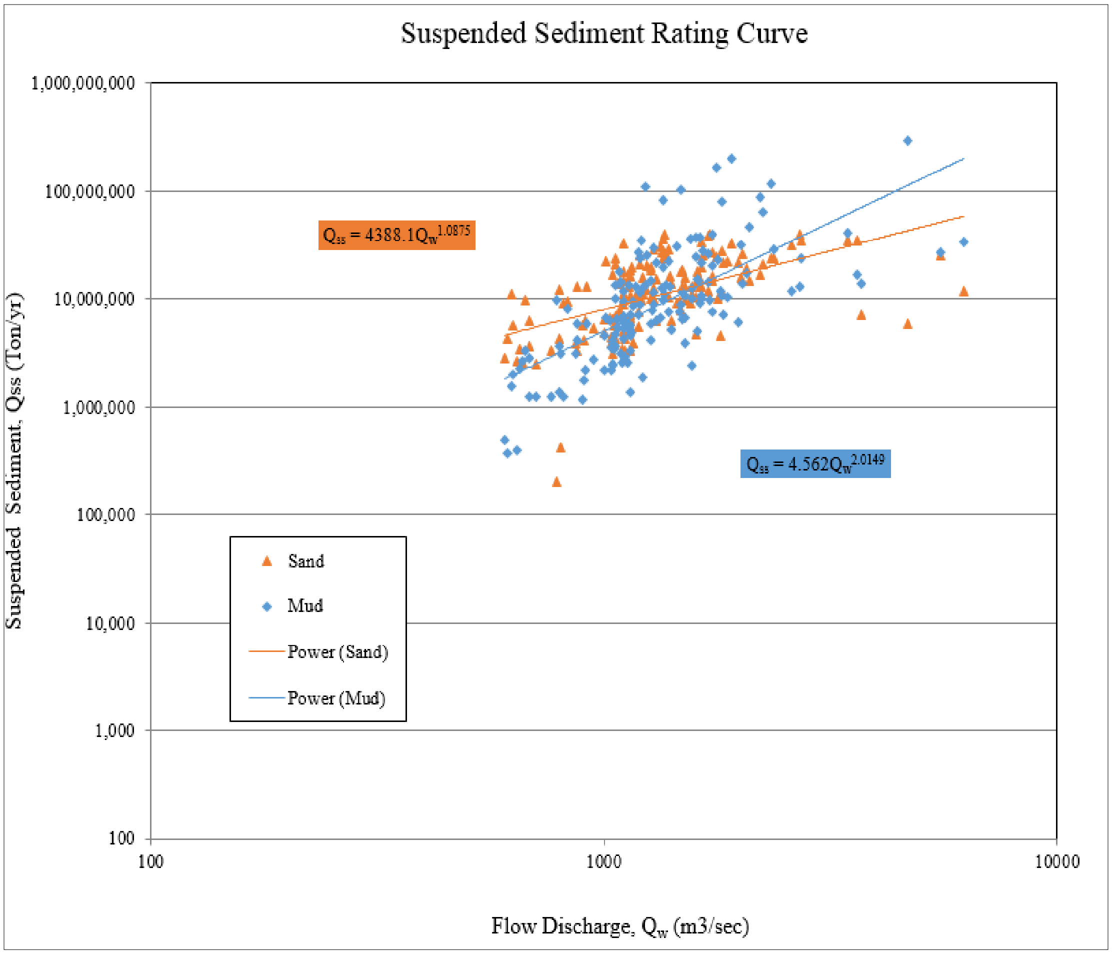

Figure 2.4 Suspended Sediment Rating Curve for USGS Monitoring Station at Nebraska City, Nebraska

Notwithstanding the confluence with the Platte River approximately 348 River kilometers downstream of Gavins Point dam, the suspended sand load and the mud load at the USGS station Missouri River at Nebraska City are approximately the same, confirming that in this reach of the Missouri River 50% of the suspended load is sand and 50% is mud (cf. Figures 2.2. and 2.3). Further study are needed to constrain a pre-Gavins

Point dam mud budget to investigate if the mud load of the undisturbed Missouri River was significantly finer than today

Figure 2.5 shows the suspended sediment rating curve for USGS monitoring station located at Saint Joseph, Missouri approximately 586 River kilometers downstream of Gavins Point dam.

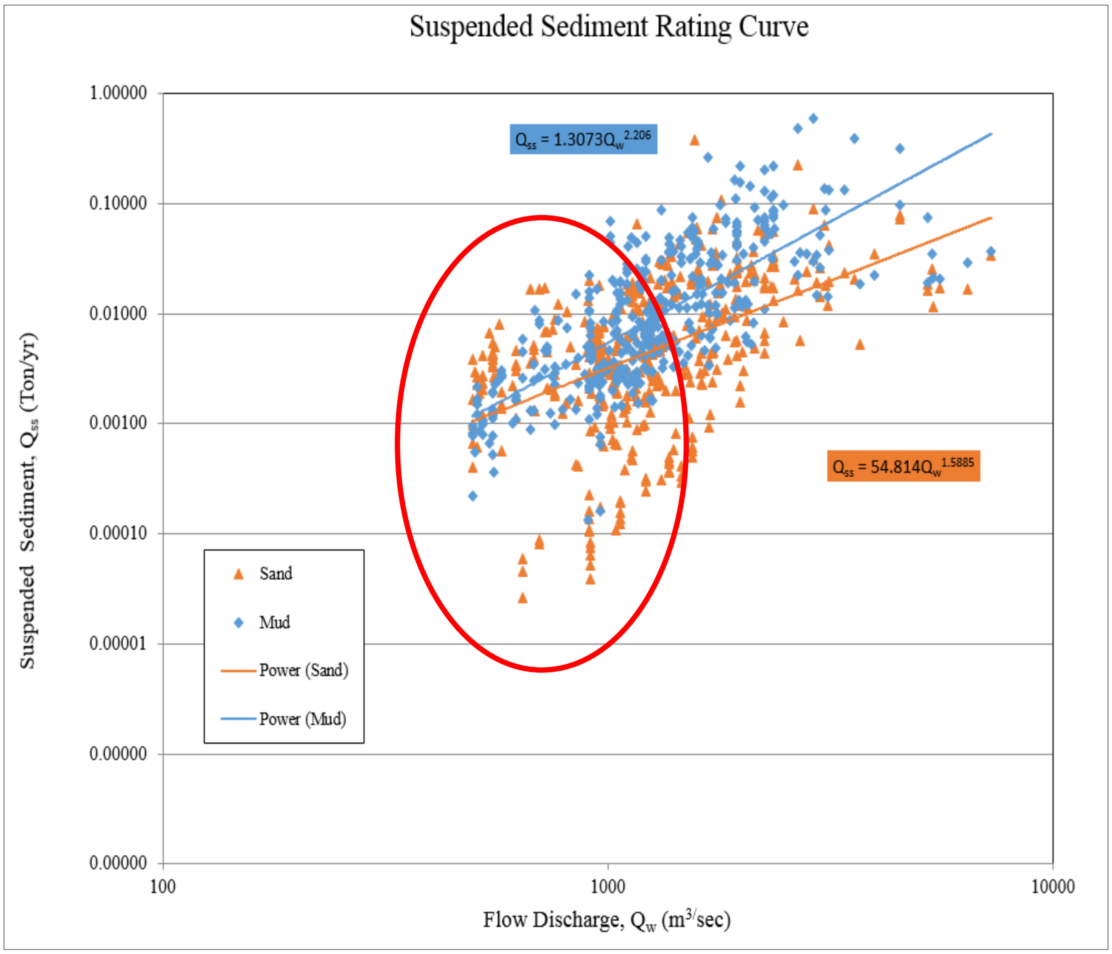

Figure 2.5 Suspended Sediment Rating Curve for USGS Monitoring Station at Saint Joseph, Missouri

The mud load at Saint Joseph, Missouri, is larger than the total sand load, however further studies are needed to explain the highly variable sand load measured at relatively low flows (red circle in Figure 2.5).

A flow duration curve (FDC) shows the average fraction of a year in which a river flow exceeds a given value. From the time series of daily flows rates, a number of characteristic discharge intervals, N, are chosen, each discharge interval is characterized in terms of a characteristic flow discharge Q_i. The number of daily flows in each discharge bin, n, is computed and the frequencies p_i representing the average fraction of time that the flow rate is in a given discharge bin are estimated as n/(N+1). Finally the probability of exceedance is estimated.

To identify and investigate if the construction of the Missouri River main channel dams and the changes in land use in the watershed modified flow regime, at each station we built the flow duration curves for the entire period of record, pre-Gavins Point Dam and post-Gavins Point Dam conditions, and for 20-year intervals. The comparison of the FDCs shows that at some location, i.e. close to the dam, the flow regime significantly changed, while further downstream the flow duration curve pertaining to pre- and post-Gavins Point dam conditions do not show significant differences denoting that the flow regime did not significantly change due to the increase in drainage area and the presence of large tributaries like the Platte River and the Kansas River. The flow durations curves for the stations at Sioux City, Iowa, Nebraska City, Nebraska, Saint Joseph, Missouri, Waverly, Missouri, and Hermann, Missouri.

Figure 2.6 shows the FDC for USGS monitoring station located at Sioux City, Iowa. The orange curve represents the pre-dam scenario while the grey, dark blue, and yellow curves represent post-dam scenarios. The light blue curve represents all of the data collected.

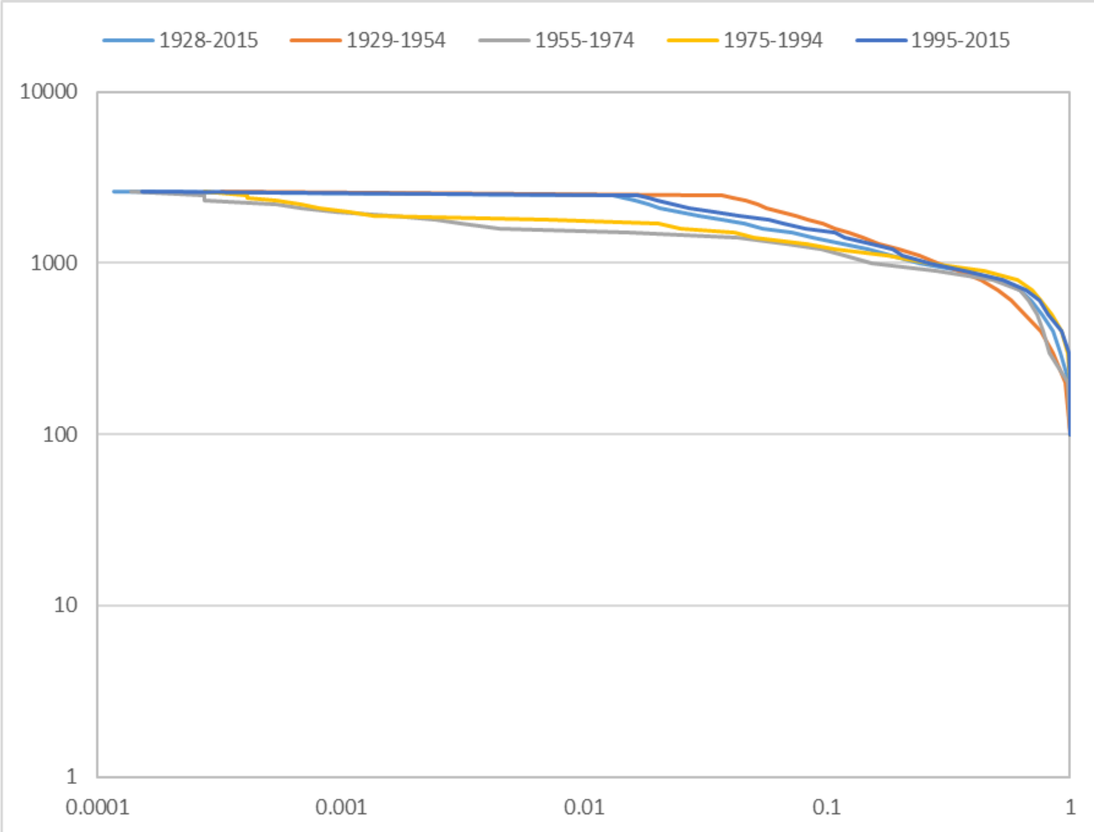

Figure 2.6 Flow Duration Curve for USGS Monitoring Station at Sioux City, Iowa

Figure 2.6 indicates that there was a significant decrease in flow discharge after the dam was constructed, which is to be expected at a gaging station located approximately just 128 River kilometers downstream of the dam. After the dam construction and closure, the flow discharge increased gradually from the period from 1955-1974, to the end of recorded data in 2015. Current flow discharge has not reached pre-dam levels but has grown closer to doing so over time. The contribution of the nearby Sioux River is accounted for the measurements because the USGS station is located downstream of the Sioux River – Missouri River confluence.

Figure 2.7 shows the FDC for USGS monitoring station located at Nebraska City, Nebraska. The light blue curve represents the pre-dam scenario while the grey, dark blue, and yellow curves represent post-dam scenarios. The orange curve represents all of the data collected.

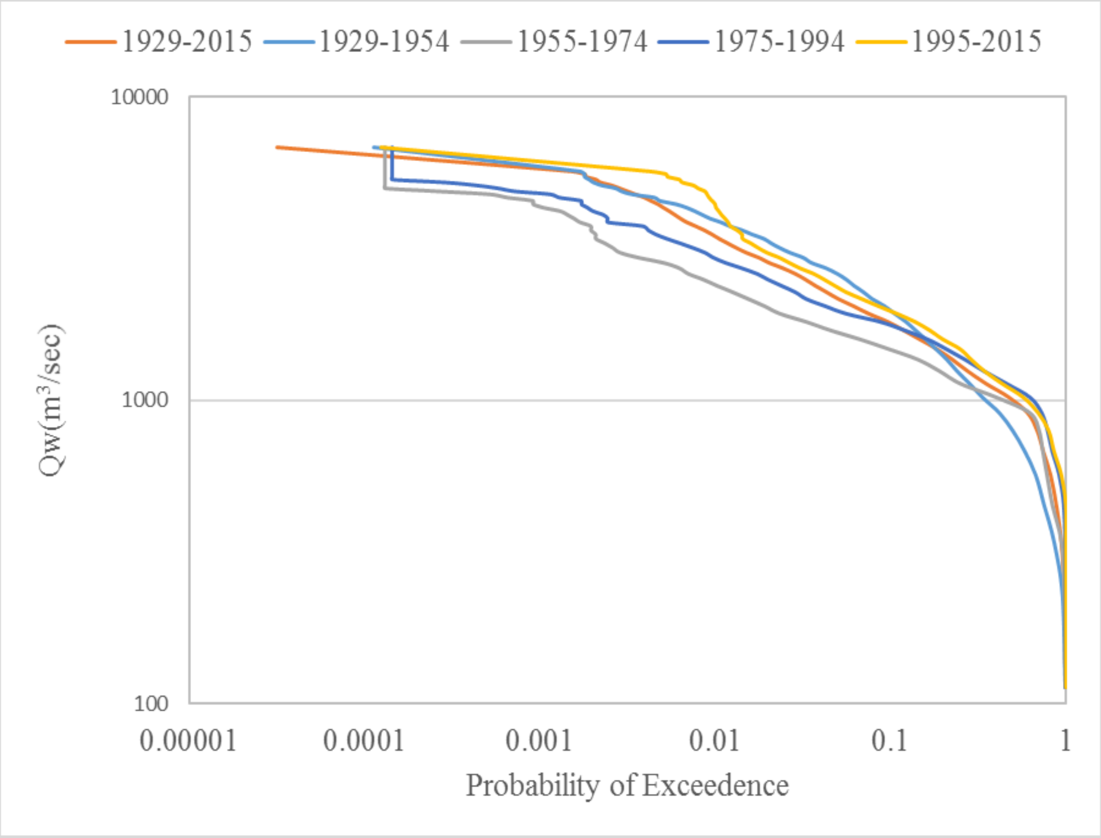

Figure 2.7 Flow Duration Curve for USGS Monitoring Station at Nebraska City, Nebraska

The comparison between the flow duration curves at Nebraska City, downstream of the Platte River-Missouri River confluence shows a decrease of flows between the dam closure and the 1994 compared to pre-dam conditions. The FDC for the last 20 years (1995-2015) denotes an increase of high flows compared to pre-dam conditions, which may corresponds to a change in land use in the watershed.

Figure 2.8 shows the FDC for USGS monitoring station located at Saint Joseph, Missouri. The orange curve represents the pre-dam scenario while the grey, dark blue, and yellow curves represent post-dam scenarios. The light blue represents all of the data collected.

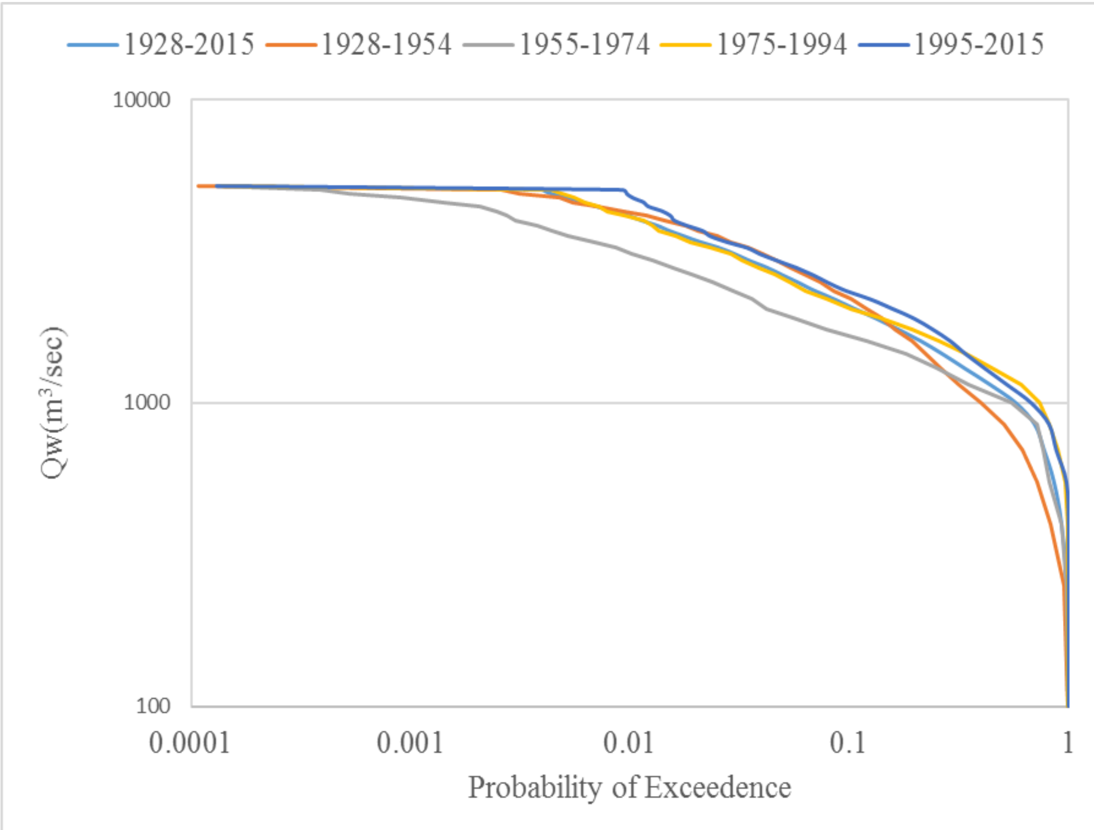

Figure 2.8 Flow Duration Curve for USGS Monitoring Station at Saint Joseph, Missouri

Figure 2.8 indicates that there was a significant decrease in flow discharge from pre-dam to post-dam from 1955 to 1974. This is reasonable given that the most significant change in flow discharge from pre to post dam should be immediately after the construction of the dam. The flow discharge has then reached the pre-dam conditions since 1974.

Figure 2.9 shows the FDC for USGS monitoring station located at Waverly, Missouri. The orange curve represents the pre-dam scenario while the grey, dark blue, and yellow curves represent post-dam scenarios. The light blue curve represents all of the data collected.

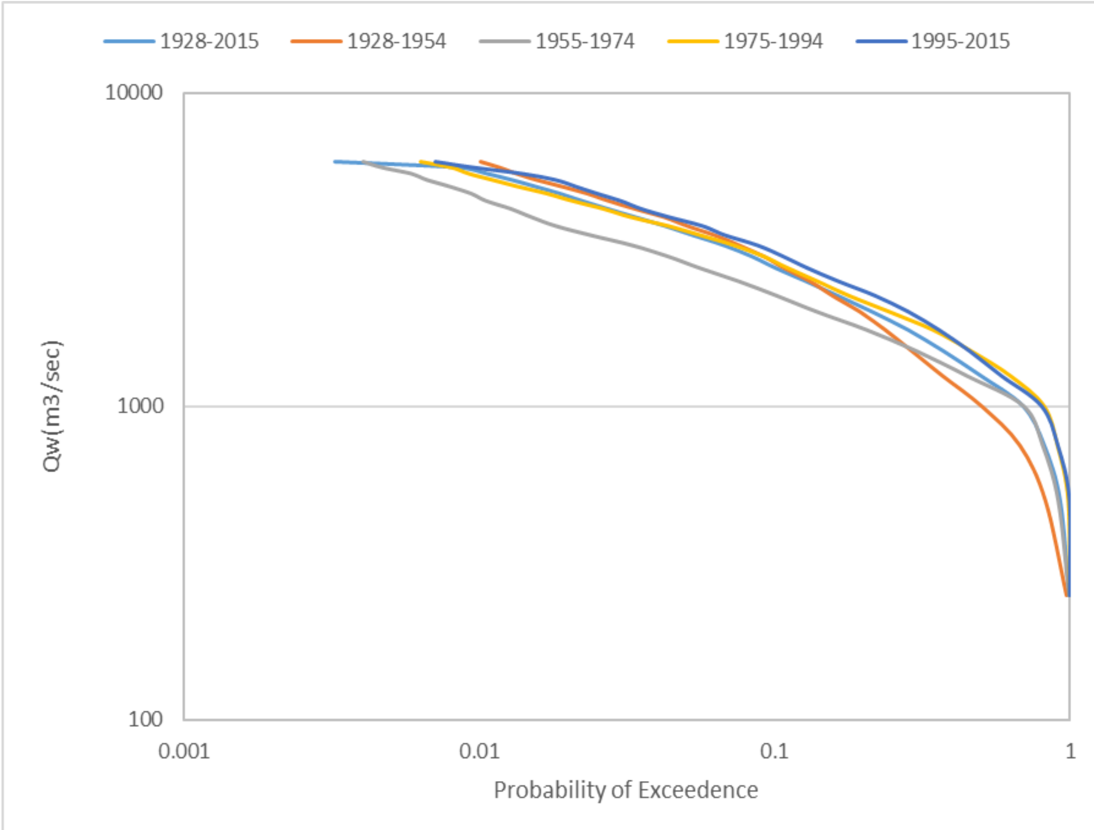

Figure 2.9 Flow Duration Curve for USGS Monitoring Station at Waverly, Missouri

Figure 2.9 indicates that the change in flow rate at Weaverly follows the same patterns observed at Saint Joseph, Missouri. The flow discharge decreased significantly immediately after the construction of the dam and after 1974 up it went back to pre-dam conditions.

Figure 2.10 shows the FDC for USGS monitoring station located at Hermann, Missouri. The orange curve represents the pre-dam scenario while the grey, dark blue, and yellow curves represent post-dam scenarios. The light blue curve represents all of the data collected.

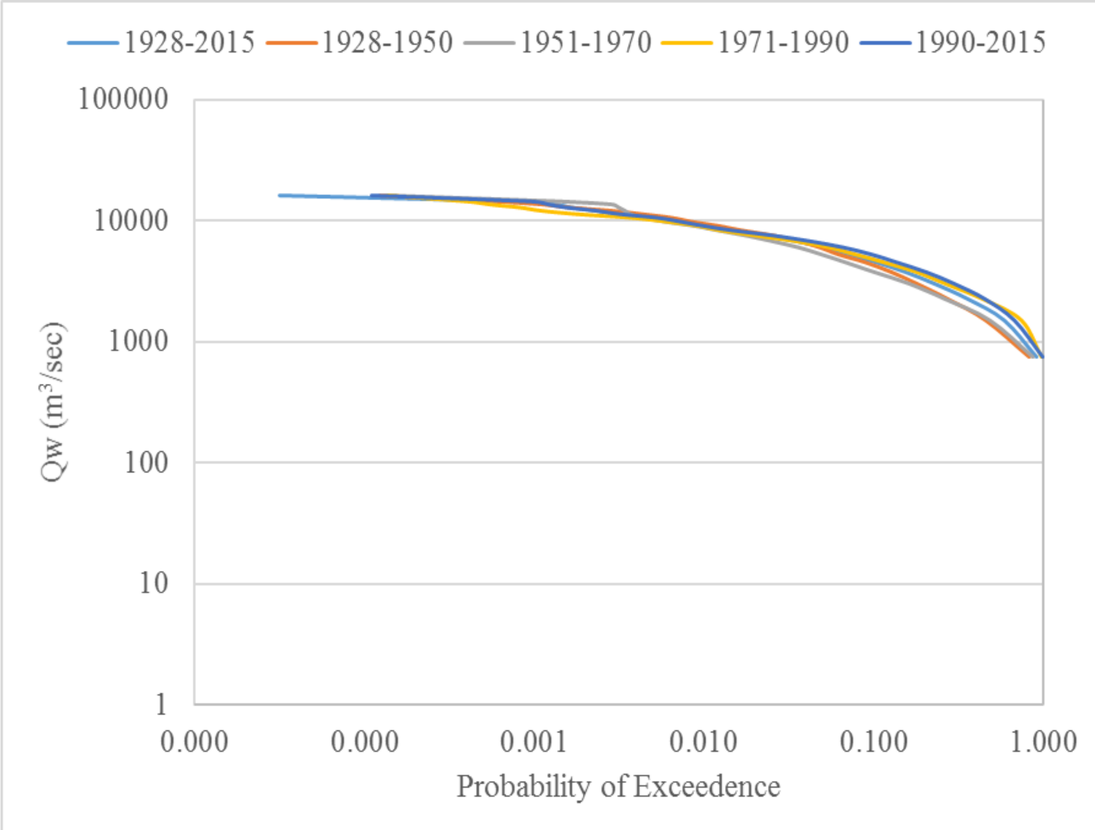

Figure 2.10 Flow Duration Curve for USGS Monitoring Station at Hermann, Missouri

Figure 2.10 indicates that there a significant change in flow regime at Herman, Missori, downstream of the Kansas River –Missouri River confluence is not observed.

The mean annual suspended load is determined using the suspended sediment rating curves and the FDCs. For each characteristic flow discharge Q_i the suspended sand/mud load is computed with the suspended sand/mud rating curve and the FDC describing the regulated flow regime. The suspended sand and mud load are then averaged over the flow duration curve to compute the mean annual loads (Parker, 2004).

Table 2.1 shows the calculations of the mean annual suspended mud and sand load for USGS monitoring stations.

Table 2.1 Mean Annual Suspended Load for USGS Monitoring Station at Yankton, SD

USGS Monitoring Station	Mud Load (Mton/yr)	Sand Load (Mton/yr)
Yankton, South Dakota	0.149	0.049
Sioux City, Iowa	3.000	6.834
Omaha City, Nebraska	7.255	7.89
Nebraska City, Nebraska	10.481	11.23
Saint Joseph, Missouri	12.758	5.47

As indicated in Table 2.1 the mean annual suspended load for mud and sand at Yankton, South Dakota are 0.149 metric Mton yr^{-1} and 0.049 metric Mton yr^{-1} respectively, approximately 75 percent and 25 percent respectively.. The mean annual mud and suspended sand load at Sioux City, Iowa are 3.000 metric Mton yr^{-1} and 6.834 metric Mton yr^{-1} respectively, approximately 30 percent of the suspended load is mud and 70 percent is sand respectively. It is interesting to note here that the large sand load at Sioux City is associated with in-channel sediment deposition downstream of the Sioux River – Missouri River confluence. The mean annual suspended load for mud and sand at Omaha City, Nebraska are approximately 7.25 metric Mton yr^{-1} and 7.89 metric Mton yr^{-1}. Approximately 47 percent of the suspended load is sand and 52 percent is mud The mean annual suspended load for mud and sand at Nebraska City, Nebraska are approximately 10.48 metric Mton yr^{-1} and 11.23 metric Mton yr^{-1} respectively. Approximately 48 percent of the total load is sand and 52 percent is mud. There is significant increase in total sand load from Omaha City to Nebraska City, which we interpret as a consequence of the confluence with the Platte River. The mean annual suspended load for mud and sand at Saint Joseph, Missouri, are approximately 12.758 metric Mton yr^{-1} and 5.47 metric Mton yr^{-1} respectively. Approximately 69 percent of the suspended load is mud and 31 percent is sand. Large tributaries are not present between

Nebraska City and Saint Joseph. However, the large decline in sand load from ~11 Mtons/year at Nebraska to ~5 Mtons/year at Saint Joseph requires further investigation.

CHAPTER 3

MODEL FORMULATION

The one-dimensional model of river morphodynamics is implemented in Spyder, a Python iterative developing environment (IDE), to study riverbed degradation in response to changes in sediment supply throughout the lowermost ~1400 kilometers of the Missouri River.

Model governing equations are the shallow water equations for open channel flow simplified with a quasi-normal approximation and the equation of conservation of channel bed material (sand) (Parker, 2004). The river channel is modeled as a sediment feed flume analog, the flow rate and the sand input rate are specified at the upstream end of the computational domain, and at the confluences with major tributaries. Due to the quasi-normal approximation, the downstream boundary condition is specified in terms of a fixed bed elevation at the downstream end. This choice is justified because the flow is modeled in terms of a characteristic, formative flow discharge and the corresponding water surface elevation at the Missouri River – Mississippi River confluence is unknown. Flow resistances and suspended load calculations are based on the work on flow resistances and suspended load in large low slope sand bed rivers (Wright and Parker, 2004). The Wright and Parker methods allows for predictions of the flow depth, grain-size specific near-bed sand concentration, and suspended sand sediment transport rate. To simplify the problem for this study on the Missouri River we assumed that the bed material can be represented as uniform sand with characteristic grain size $D = D_{50}$.

The Wright and Parker flow depth-discharge relation is adjusted to account for density stratification.

The governing equations for the flow are the shallow water equations of mass and momentum balance in the case of a rectangular wide channel

$$\frac{\partial H}{\partial t}+\frac{\partial UH}{\partial x}=0 \tag{1}$$

$$\frac{\partial UH}{\partial t}+\frac{\partial U^2 H}{\partial x}=gH\frac{\partial H}{\partial x}+gHS-C_f U^2 \tag{2}$$

where x and t respectively are a down channel and a temporal coordinate, U denotes the mean flow velocity, H the cross sectionally averaged flow depth, C_f is a constant nondimensional friction coefficient, g is the acceleration of gravity and S is the bed slope equal to $\frac{\partial \eta}{\partial x}$ with η denoting the channel bed elevation. Equations (1) and (2) are simplified with the quasi-steady approximation (de Vries, 1965). Dropping the time dependence in equation (1), the conservation of water mass takes the form

$$q=\frac{U}{H} \tag{3}$$

where q denotes the volumetric flow rate per channel width, $q=\frac{Q}{B}$, with Q being the flow discharge. Dropping the time dependence in equation (2), the momentum balance equation takes the form

$$\frac{U}{g}\frac{\partial U}{\partial x}+\frac{\partial H}{\partial x}+\frac{\partial \eta}{\partial x}=-\frac{C_f U^2}{gH} \tag{4}$$

To model the lowermost Missouri River we further assume that the flow is locally normal, so that the momentum equation (4) simplifies in

$$S = S_f \qquad (5)$$

With S_f denotes the friction slope defined as $C_f Fr^2$, with Fr denoting the Froude number, which is defined as $\frac{U}{(gH)^{0.5}}$

A standard one-dimensional equation of sediment mass conservation is used to calculate the change in channel bed elevation, $\partial\eta$ based on the divergence of the sand flux, sum of the suspended sand load and the sand load transported as bedload. The equation of conservation of bed material takes the form

$$(1-\lambda_p)\frac{\partial \eta}{\partial t} = -I_f \frac{\partial q_{sand}}{\partial x} \qquad (6)$$

Where λ_p denotes the bulk porosity of the bed, if represents the fraction of time in a year that the river is in flood (morphologically active) and q_{sand} is the volumetric sand flux per unit channel width.

In the simulations presented herein the spatial distance between two computational nodes is 1400 m (the approximate downstream length of the Lower Missouri River reach segment).

The initial flow depth, H_1 is assumed to be equal to h_0, i.e. the water depth in the absence of stratification effects and bedforms (form drag)

$$H_0 = H_1 \qquad (7)$$

The mean flow velocity, U is then estimated with the continuity equation (3) as

$$U_1 = \frac{q_w}{H_1} \qquad (8)$$

The Shields number, i.e. the non-dimensional bed shear stress, τ_{sk1} , is dependent upon h_1, bed slope, S , specific gravity, R , and grain size, D .

$$\tau_1^* = \frac{H_1 S}{RD} \tag{9}$$

Wright and Parker (2004) noted that the Froude number, Fr as defined above, is an important parameter in stability of bedforms. In other words, the magnitude of Fr plays a major difference between large, low-slope rivers, and small, steeper rivers. In a larger rivers like the Missouri River at high flow rates the Fr remains relatively low and therefore the transition from dunes to upper regime becomes very infrequent, if not impossible. Given the flow depth and the mean flow velocity Fr_1 and U_1, the Froude number is computed as

$$Fr_1 = \frac{U_1}{\sqrt{gH_1}} \tag{10}$$

In the dune regime, the Shields number due to skin friction, τ_{sk1} , is small compared to the total Shields number τ_{sk1} in their words, the form drag cannot be neglected during floods. In the Wright and Parker formulation τ_{sk1} is computed as in equation (11), which is only applicable for small values of S.

$$\tau*_{sk1} = 0.05 + 0.07(\tau*_1 \, Fr^{0.7})^{0.8} \tag{11}$$

After defining τ_{sk1} , h_{sk1} , the flow depth associated with skin friction, can be determined as shown in Equation (13). This is necessary in order to determine the shear velocity due to skin friction, $u*_{sk1}$, as illustrated by Equation (13).

$$\mathrm{H}_1 = \frac{\tau_{sk1}^* \mathrm{RD}}{\mathrm{S}} \tag{12}$$

$$u*_{sk1} = (gSh_{sk1})^{0.5} \tag{13}$$

Given the shear velocity associated with skin friction, under the assumption of equilibrium suspension the near bed concentration of suspended sand, C_{ob} is equal to the entrainment rate of sand in suspension, E . According to the Wright and Parker formulation, the entrainment rate is a function of $u*_{sk1}$, the bed slope S and the grain diameter D through the particle Reynolds number R_p and the particle settling velocity v_s and C_{ob}, as reported in equation (15).

$$C_{ob} = \frac{BX_1}{1+(B/0.3)X_1^5} \tag{15}$$

Where X_1 is the entrainment parameter, defined in equation (16)

$$X_1 = \frac{u^*_{sk1}}{v_s} R_p^{0.6} S^{0.08} \tag{16}$$

with v_s denoting the particle settling velocity. When the C_{ob} is known, stratification effects can be computed. In the Wright and Parker formulation stratification effects are accounted for through a variable α that multiplies the von Karman constant in the exponent of the suspended sediment concentration profile and at the denominator of the velocity profile (Wright and Parker 2004). The relation to compute α as a function of the near bed concentration and the bed slope is shown in equation (17)

$$\alpha_1 = 1 - 0.06(C_{ob}/S)^{0.77} \quad \text{for} \quad (C_{ob}/S) \le 10 \tag{17}$$

$$\alpha_1 = 0.67 - 0.0025(C_{ob}/S) \quad \text{for} \quad (C_{ob}/S) > 10$$

At this point a new estimate for H, H_2, as defined in equation (18) below.

$$H_2 = D\left[\frac{\alpha_1 q^*}{8.32 S^{0.5}}\left(\frac{k_{c1}}{D}\right)^{1/6}\right]^{3/5} \quad (18)$$

where k_c denotes the composite roughness height, which is computed as

$$k_{c1} = k_s + (h_1 / h_{sk1})^{0.25} \quad (19)$$

where k_s is the roughness height associated with skin friction and it is defined as

$$k_s = mD \quad (20)$$

with m = 3.

The flow depth computed with equation (18), H_2, is compared with the initial flow depth, H_1. If the condition given in equation (21) is satisfied the iterative scheme ends. If the condition of equation (21) is not satisfied the loop starts again with $H_1 = H_2$ until equation (21) is satisfied

$$abs((H_2 - H_1)/H_2) > 0.01 \quad (21)$$

The non-dimensional volumetric bedload transport rate per unit channel width, q_{b^*} is computed with the Ashida and Michiue formulation reported in equation (22a) (Viparelli et l., 2015 as a function of the Shields number associated with skin friction, τ^*_{sk}

$$q_{b*} = 17(\tau^*_{sk} - \tau^*_c)((\tau^*_{sk})^{0.5} - (\tau^*_c)^{0.5}) \text{ where } \tau^*_c = 0.05 \quad (22a)$$

The volumetric bedload transport rate per unit channel width, q_b, is equal to

$$q_b = (RgD)^{0.5} D \quad (22b)$$

with R representing the submerged specific gravity of the sediment and g being the acceleration of gravity.

The volumetric suspended sand load per unit channel width, q_s, is computed with equation (23)

$$q_{s1} = \frac{9.7 C_{o1} u_1^* H}{\alpha_1} \left(\frac{H}{k_c} \right)^{1/6} I \tag{23}$$

Where I is the integral over the water column of the equilibrium profile of suspended sediment concentration and Co_b is the near bed concentration of suspended sediment.

The integral of the water column can be defined as

$$I = \int_{0.05}^{1} y^{1/6} \left(\frac{1-y}{y} \frac{0.05}{1-0.05} \right)^{Zr_1} dy \tag{24}$$

where Zr is a dimensionless number defined as

$$Zr = \frac{v_s}{\alpha k u^*}$$

where u^* is the von Karman constant equal to 0.41 in the calculations.

Wright and Parker (2004) give the following approximated form to compute the integral of equation (24)

$$I \approx 0.679 e^{-2.23 Zr} \quad \text{for} \quad Zr \le 1 \tag{25a}$$

$$I \approx 0.073 Zr^{-.144} \quad \text{for} \quad Zr > 1 \tag{25b}$$

CHAPTER 4

MODEL RESULTS

Model results are organized in 5 scenarios. Scenario 1 represents the model zeroing. Under the assumption that the undisturbed Missouri River was at mobile bed equilibrium, the model is run with pre-dam bankfull discharge and sand load to reach a pre-dam (2000 m3/s and 29.4 Mt/yr respectively) equilibrium slope of 0.00022, which is in reasonable agreement with previous observations.

Post-dam/channel training works are explored in scenarios 2-5. In scenario 2 we study the effects of a reduction of flow discharge and bed material load associated with the closure of Gavins Point dam – Q = 800 m^3, sand load = 0.557 MT/yr. Scenario 3 focuses on the effects of a reduction in channel width due to engineering works from 190 m to 140 m for the first 90 kilometers of the defined reach and from 190 m to 175 m for the rest of the defined reach with pre-dam flow and sediment load. Scenario 4 considers the combined effects of the reduction in flow and sediment regime associated with dam construction and the channel narrowing. Finally, scenario 5 pertains to post-dam/channel training works conditions with the addition of the contribution of two tributaries, the Sioux River and the Platte River (increase in flow rate with an input of sand) respectively 127 km and 348 km downstream of Gavins Point dam. The effects of the Kansas River are not accounted for in the simulations, and this has a significant impact on the sand load in the downstream most part of the model domain, as further discussed.

Input parameters for the scenarios are summarized in Table 4.1 and 4.2. Table 4.1 summarizes the flow rate and the sand input to the model domain, the flow intermittency and the bed slope (final slope for the zeroing run of Scenario 1 and initial slope for the post-Gavins Point dam simulations), and the sediment grain size.

Table 4.1 Summary of Selected Input Parameters I

Scenario	Flow Discharge (m^3)	Total Sediment Feed (Mton/yr)	Slope (m)	Intermittency	D_{50}	D_{90}
Scenario 1	2000	29.4	0.00022	0.4	0.2	0.3
Scenario 2	800	0.557	0.00022	0.5	0.3	0.4
Scenario 3	2000	0.557	0.00022	0.4	0.2	0.3
Scenario 4	800	0.557	0.00022	0.5	0.3	0.4
Scenario 5	800 (from 0 to 130 km) 950 (from 130 to 310 km) 1015 from (310 to 1400 km)	0.557 (from 0 to 130 km) 0.21 (from 130 km to 310 km) 0.9 (from 310 to 1400 km)	0.00022	0.5	0.3	0.4

The model geometry is summarized in Table 4.2 in terms of channel width and the length of the modeled domain. Noting that channel alignment works were performed in the second half of the 1950s, in the post-Gavins Point dam runs it is assumed that the reduction in cross section width and the change in flow rate and sand load occurred simultaneously.

Table 4.2 Summary of Selected Input Parameters II

Scenario	Channel Width (m)	Total Length of Reach (km)
Scenario 1	190	1400
Scenario 2	175	1400
Scenario 3	175 (first 90km) 140 (remain reach)	1400
Scenario 4	175 (first 90km) 140 (remain reach)	1400
Scenario 5	175 (first 90km) 140 (remain reach)	1400

In scenario 1, the model is zeroed to establish a reasonable initial conditions for the post-Gavins Point dam/channel training runs and to establish if the model is able to reasonably model the flow resistances and the bed material load. The model is run using pre-dam conditions, constant channel width, and approximately no change in channel bed slope. Given an arbitrary initial condition, the model reached equilibrium over an 80 year time span as illustrated in Figure 4.1, in terms of longitudinal profiles of channel bed elevation. Note that the 60 yr and the 80 yr profile coincide showing that the model reached mobile bed equilibrium.

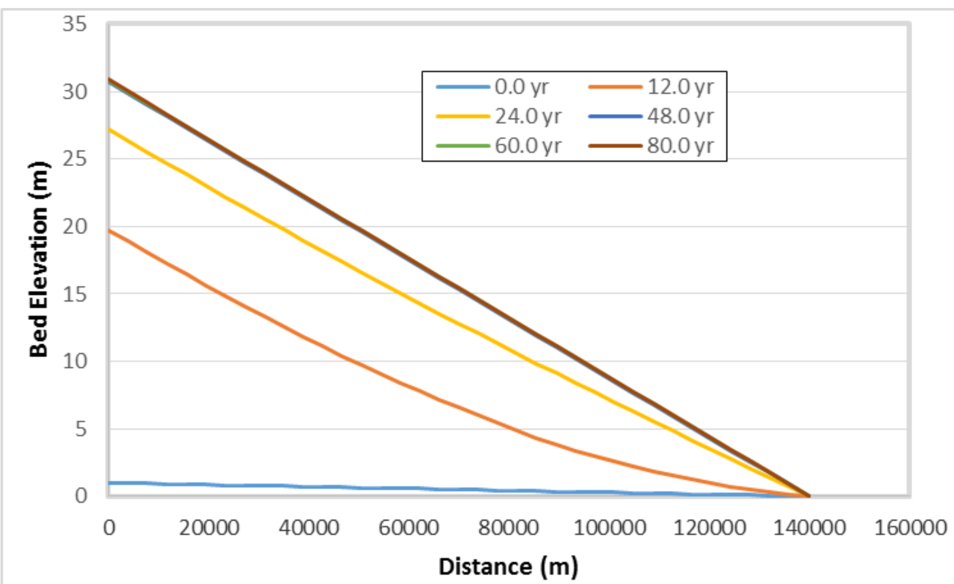

Figure 4.1 Change in Bed Elevation with Pre-Dam Conditions with Constant Channel Width

In scenario 2 the model was run with post-dam conditions with a constant channel width. The model was run over a 300 year time span (long engineering time scale) and the output was printed with 15 year intervals. Figures 4.2 and 4.3, and 4.4 show the changes in bed elevation, flow depth, and total sand load respectively over the length of the channel with 60 year intervals. Figures 4.2-4.4 show channel bed erosion in the upstream part of the modeled reach, associated with a reduction in channel bed slope, an increase in water depth (Figure 4.3) and a reduction in bed material load (Figure 4.4).

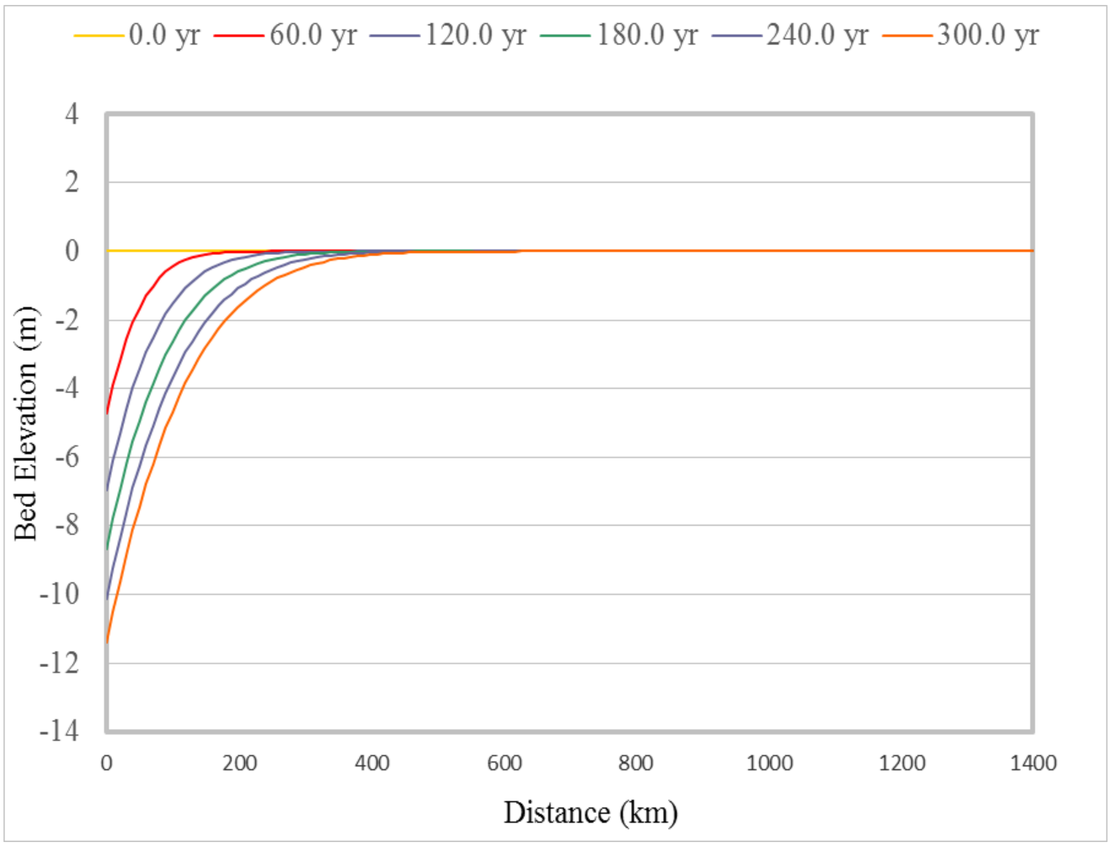

Figure 4.2 Change in Bed Elevation with Post-Dam Conditions with Constant Channel Width

Bed elevation is observed to increase over time with the occurrence of upstream channel erosion. As the change in bed elevation begins to decrease the channel bed slope decreases as well. At approximately 500 km, all profiles show no change in bed elevation after 60 years of simulation.

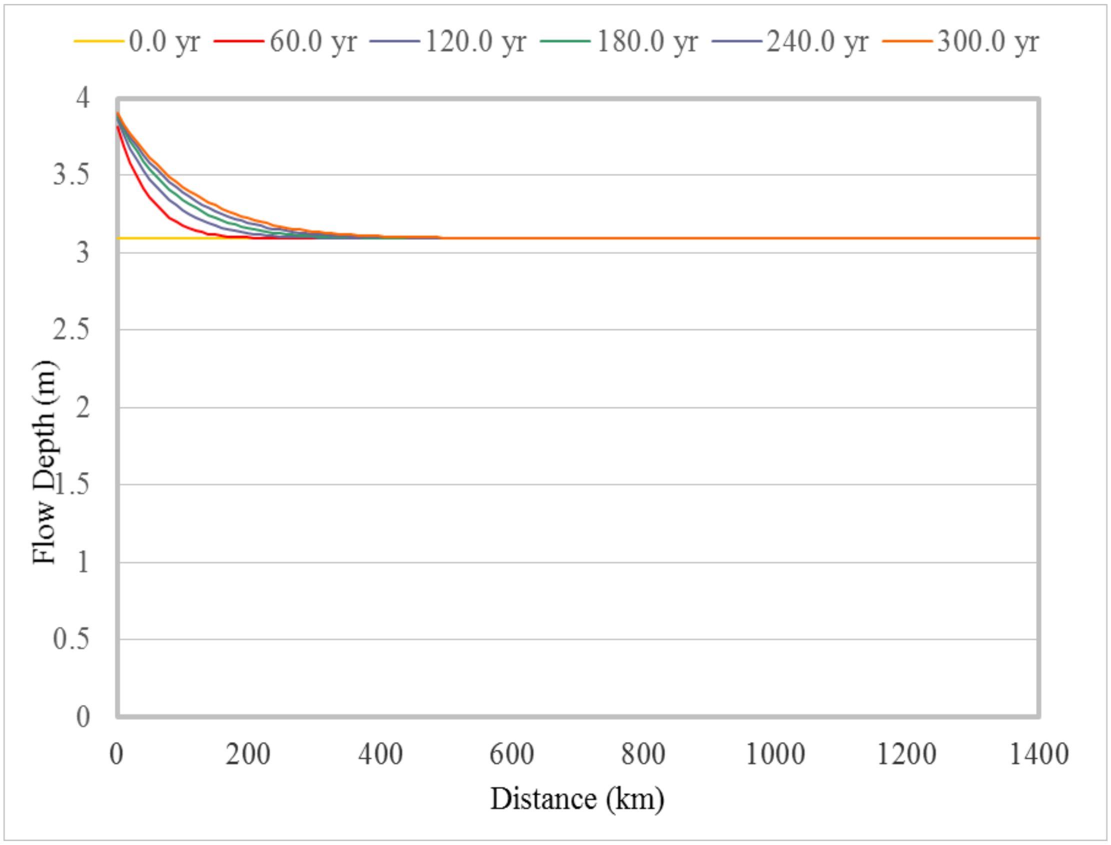

Figure 4.3 Change in Flow Depth with Post-Dam Conditions with Constant Channel Width

Over time, flow depth increases in the upstream part of the reach. As erosion of the channel bed occurs and sand is transported downstream, the flow depth increases. After 60 years of simulation the changes in bed elevation and channel depth are observed in the 500 km reach at the upstream end of the model domain.

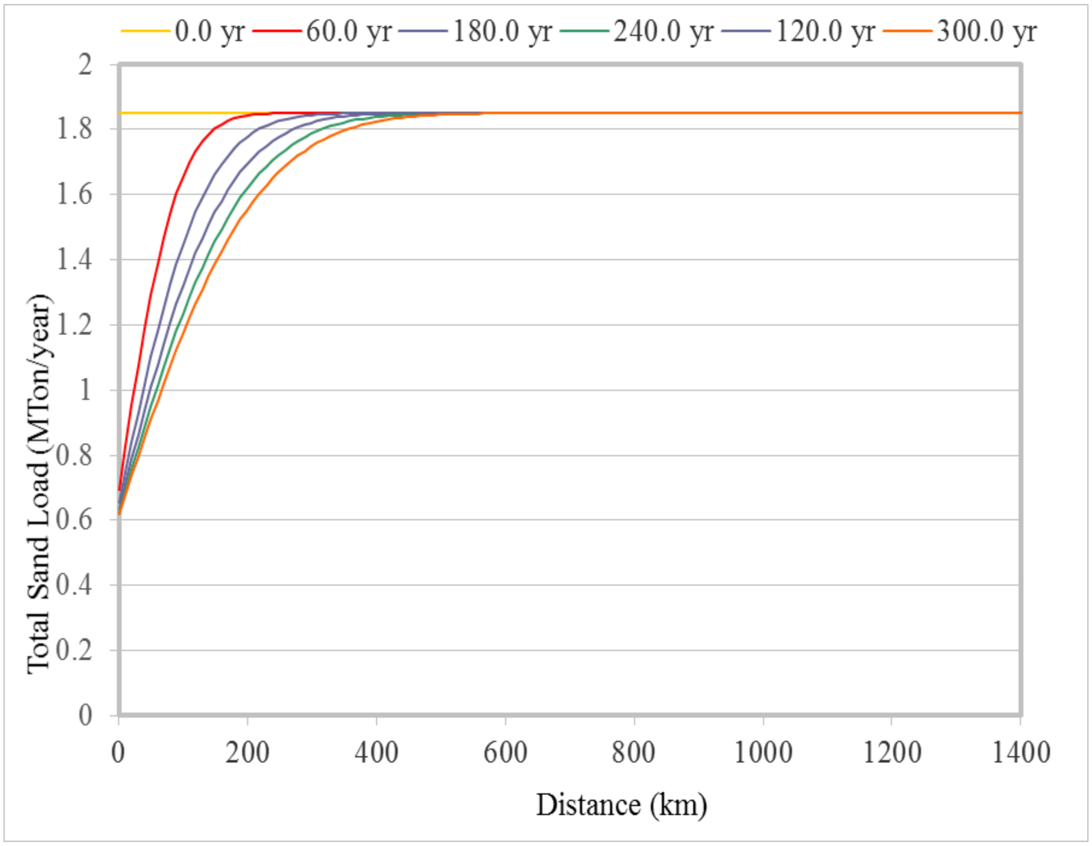

Figure 4.4 Change in Total Sand Load with Post-Dam Conditions with Constant Channel Width

The rate of channel bed erosion downstream of Gavins Point Dam decreases over time and without the effect of tributaries which, as shown in Scenario 5, would add sediment the change in total sand load becomes zero at approximately 500 km downstream.

In scenario 3 the model was run with pre-dam conditions with channel narrowing from 175 m to 140 m in the reach that starts 90 km downstream of Gavins Point dam to explore the system response to channel narrowing.

The model was run for 60 years span and the results were printed with a 4 year interval. Figures 4.5 and 4.6 show the changes in bed elevation and flow depth respectively over the length of the channel with 12 year intervals.

A reduction in channel width alone resulted in rapid channel bed aggradation (Figure 4.5) associated with a higher bed slope and a shallower flow (Figure 4.6). It is interesting to note here that, due to the higher pre-dam bed material load compared with the post-dam conditions of scenario 2, the wave of channel bed aggradation reaches the downstream end of the modeled domain in almost 60 years. In other words, the response of the unregulated Missouri River to a change in channel width would have been fast and would have affected the entire study reach at engineering time scales.

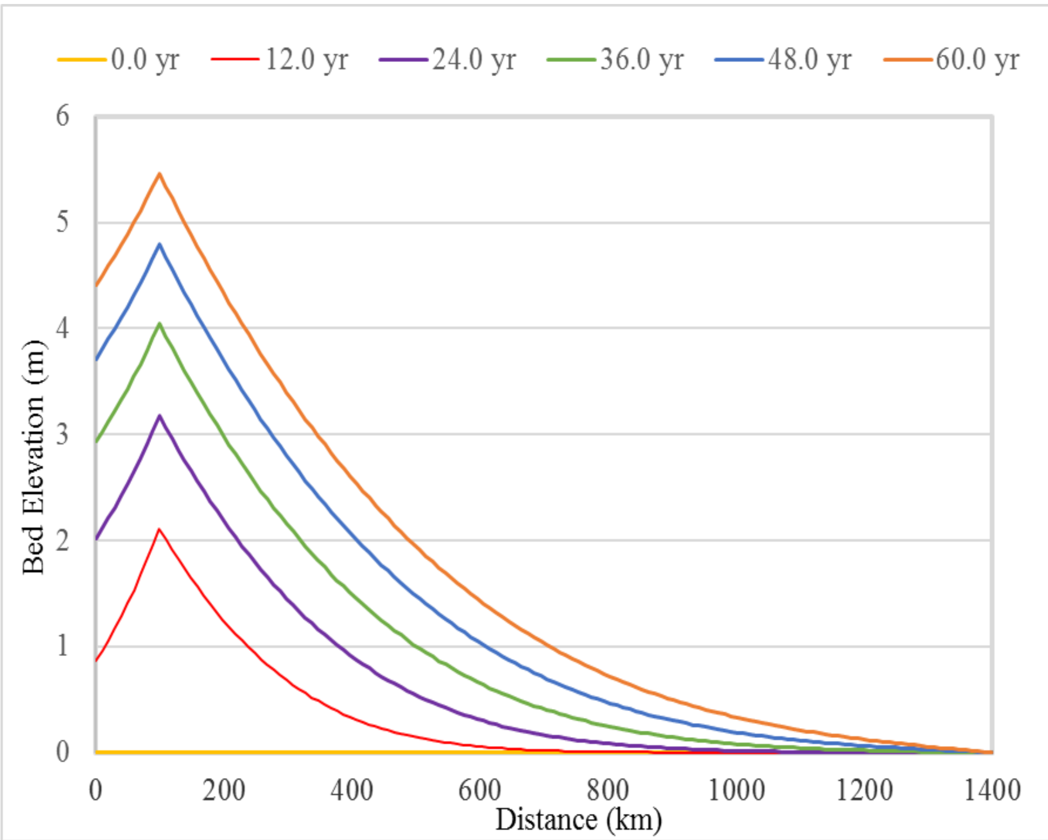

Figure 4.5 Change in Bed Elevation with Pre-Dam Conditions with Channel Narrowing

The reduction in channel width from 175 km to 140 km at approximately 90 km downstream of Gavins Point Dam resulted in rapid aggradation.

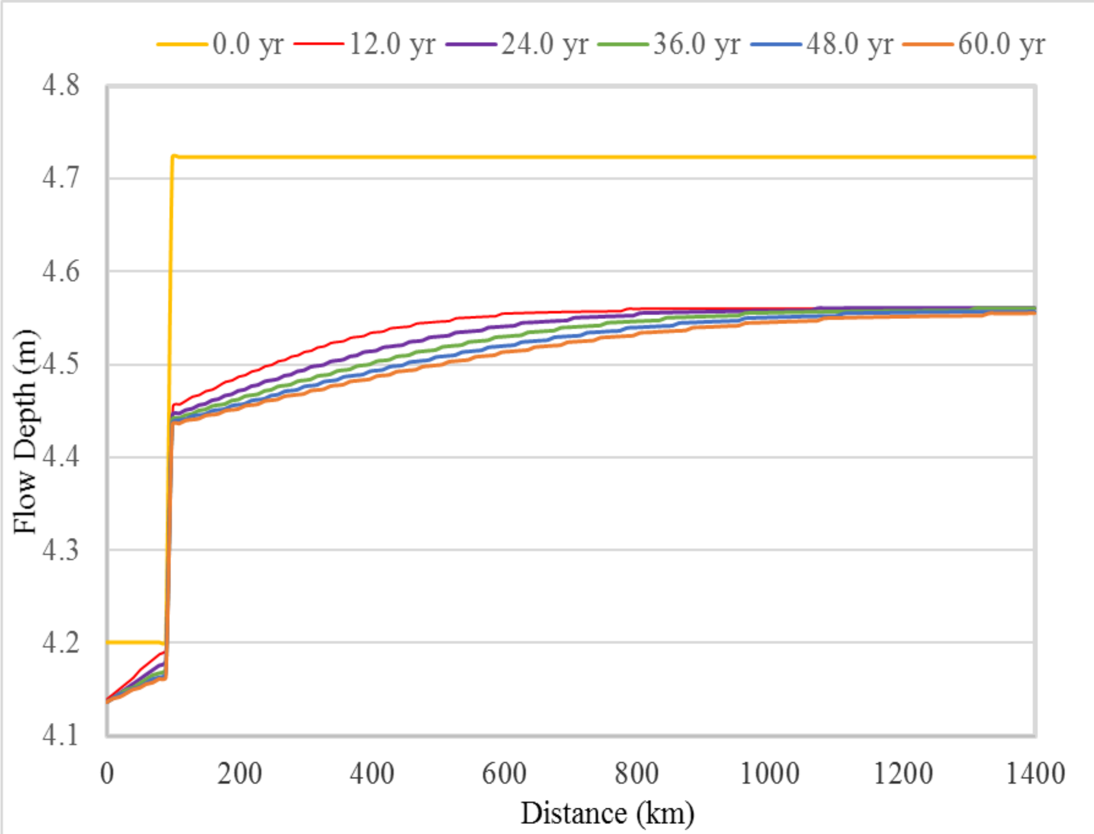

Figure 4.6 Change in Flow Depth with Pre-Dam Conditions with Channel Narrowing

During channel bed aggradation, the flow depth increased gradually for the 90 km downstream from Gavins Point Dam where the channel is 175 m wide. In the narrow reach (channel width = 140 m), and due to the streamwise reduction in channel slope, the flow depth continues to increase in the flow direction. Overall, flow depth increased by approximately 0.12 m (0.4 feet) in 60 years.

In scenario 4 the model was run with post-dam conditions and channel narrowing. The model was run over a 300 year span and the results were printed with a 15 year interval.

Figures 4.7, 4.8, and 4.9 respectively show the temporal changes in bed elevation, flow depth, and total sand load in the streamwise direction.

As in scenario 2, due to the reduction in flow rate and bed material input the upstream part of the modeled domain experiences channel bed erosion. However, the increase in bed material transport capacity that occurs in the narrowed section somewhat reduces the channel bed degradation compared to scenario 2.

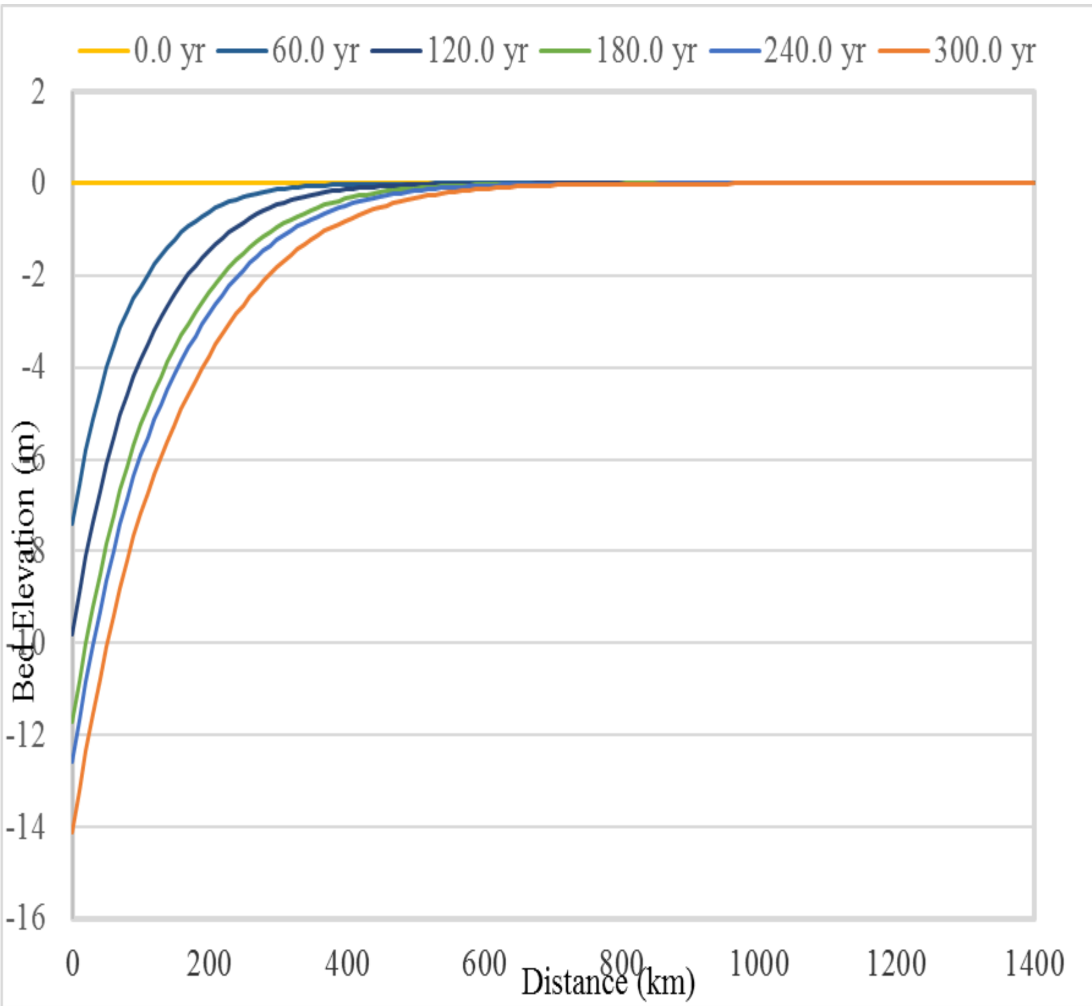

Figure 4.7 Change in Bed Elevation with Post-Dam Conditions with Channel Narrowing

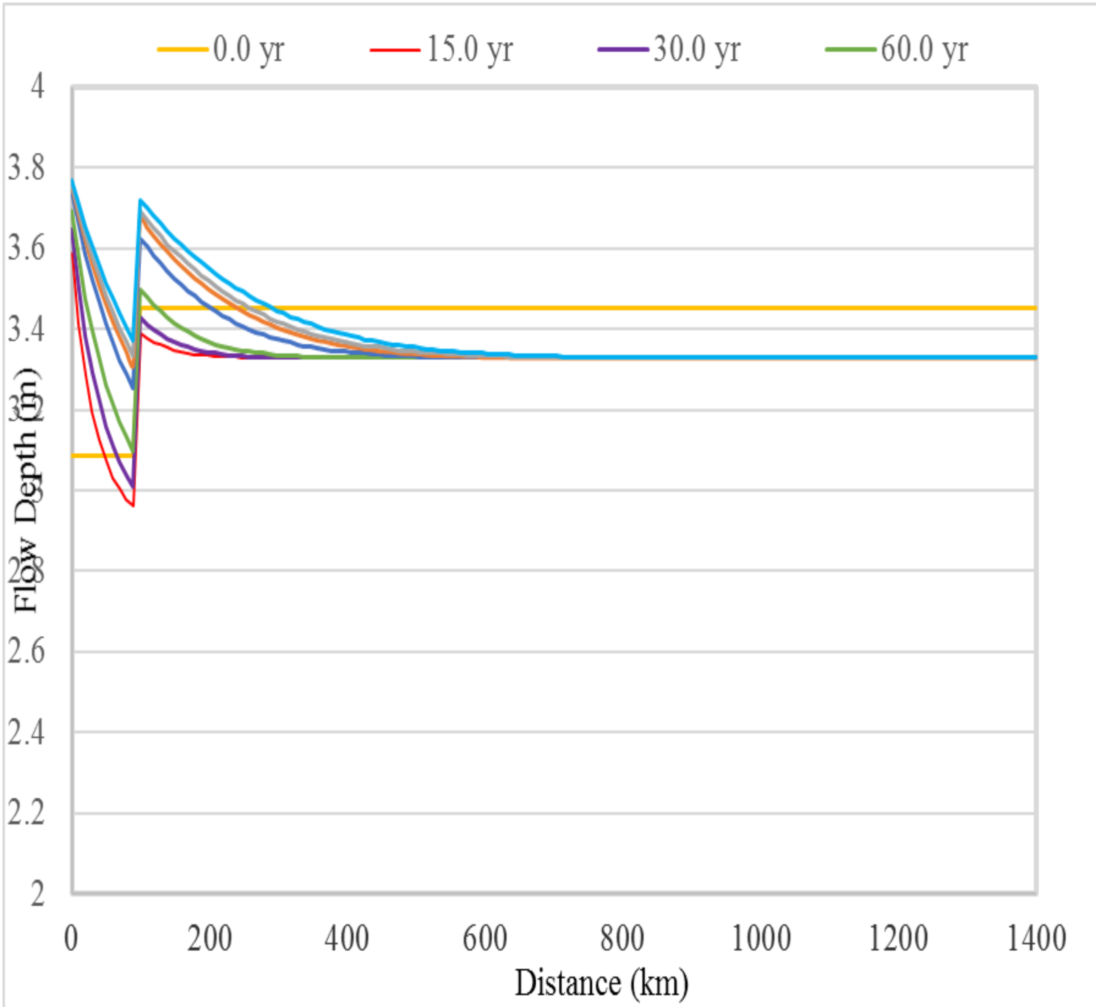

Figure 4.8 Change in Flow Depth with Post-Dam Conditions with Channel Narrowing

With post-dam conditions and channel narrowing the flow depth increases due to channel bed erosion. The flow depth suddenly increases in the narrow section due to the reduction in channel width. In the narrow reach the water depth decreases in the flow direction due to the relatively slow migration of the wave of channel bed erosion. In the narrow reach the flow depth increases in time due to channel bed erosion.

In figure 4.9 total sand transport capacity increases in the narrow reach from approximately 7.5 metric Mton yr^{-1}, at the upstream end of the modeled domain to ~18 Mton yr^{-1} in the narrowed reach.

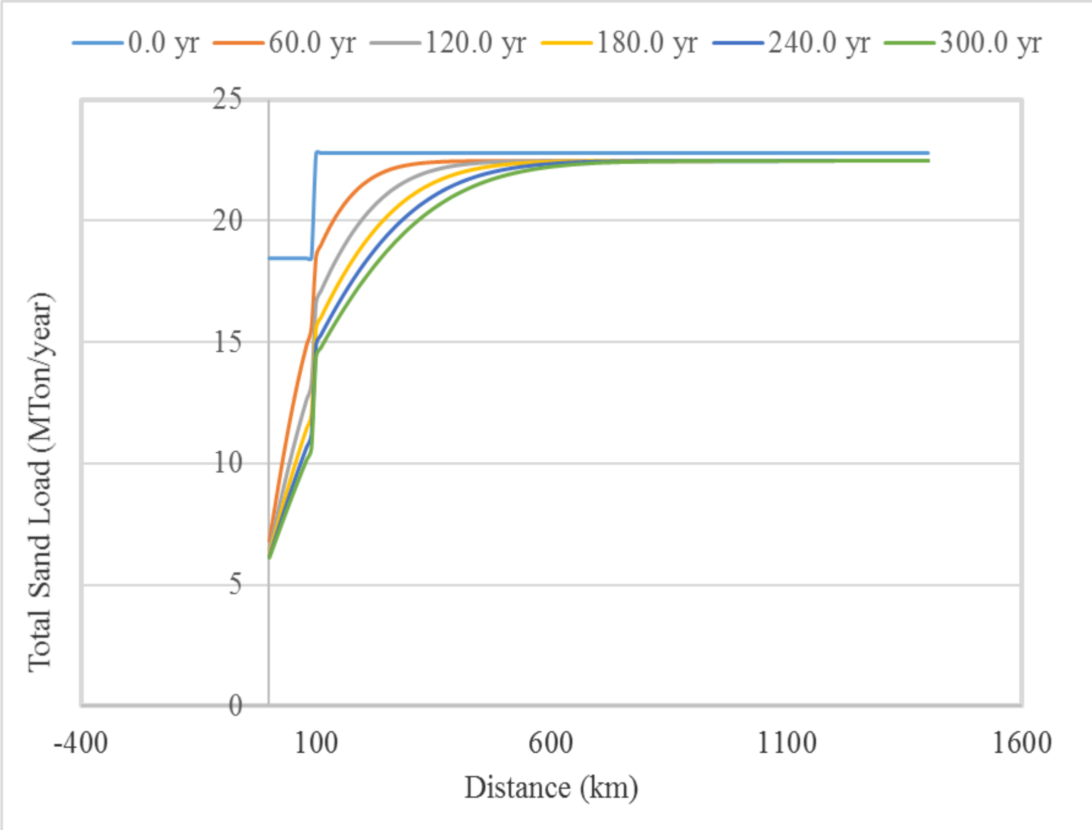

Figure 4.9 Change in Total Sand Load with Post-Dam Conditions with Channel Narrowing

In scenario 5 the model was run with post-dam flow and sand input conditions, channel narrowing, and tributaries. The model was run for 100 years and the results were plotted every 5 year intervals. Figures 4.10, 4.11, and 4.12 respectively show the temporal changes in bed elevation, flow depth, and total sand load with 20 year intervals. The input of water and sand of the Sioux River at approximately 130 km downstream from Gavins Point dam results in a reduction of channel erosion compared to scenario 2, while the Platte River generates a downstream migrating wave of aggradation and the USACE currently dredges to guarantee safe navigation. The Sioux River contributes approximately 11 Mton of sand load per year and approximately 6.8 Mton of mud load per year. The Platte River contributes approximately 11.2 Mton of total sand load per year and approximately 10.4 Mton of mud load per year. These contributions are based upon the flow duration curve and suspended sand rating curve analysis presented above.

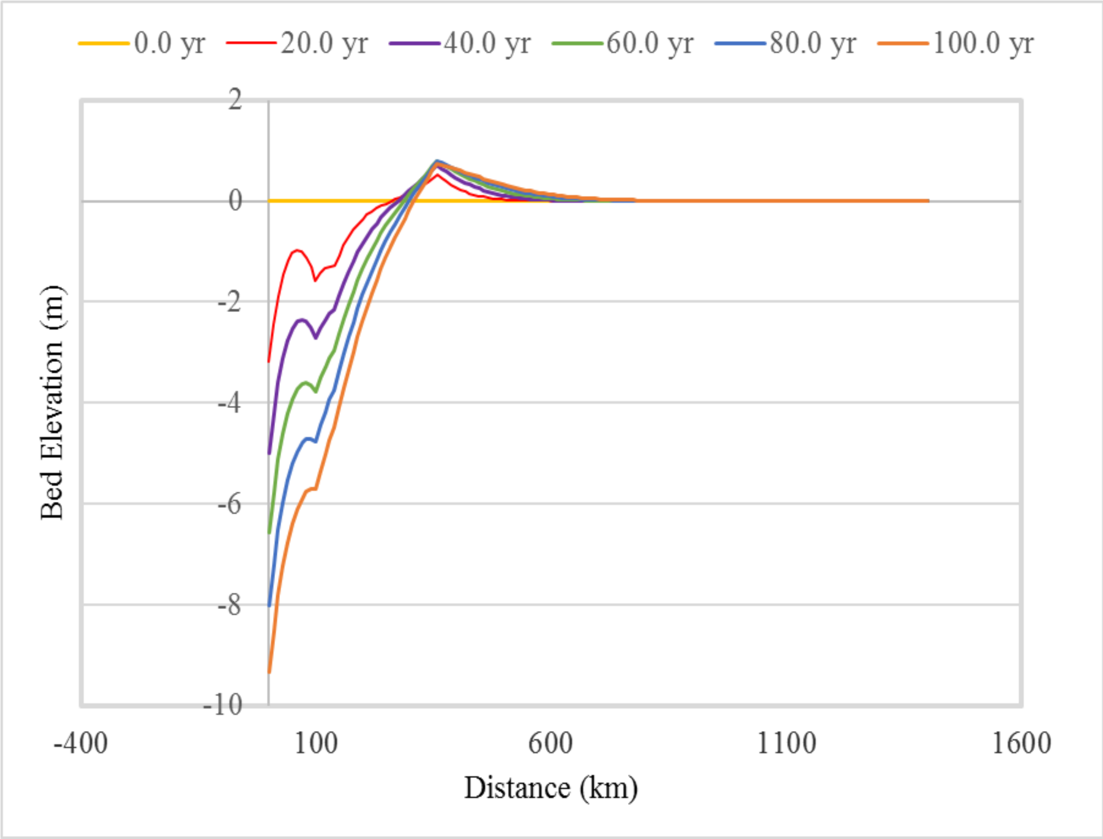

Figure 4.10 Change in Bed Elevation with Post-Dam Conditions with Channel Narrowing and Tributaries

Bed elevation increases gradually up until approximately 90 km downstream where the channel narrows. The Sioux River, approximately 40 km further downstream, serves to stabilize the bed elevation by reducing channel erosion. The Platte River, approximately 400 km downstream, is responsible for aggradation and accounts for the observed increase in bed elevation.

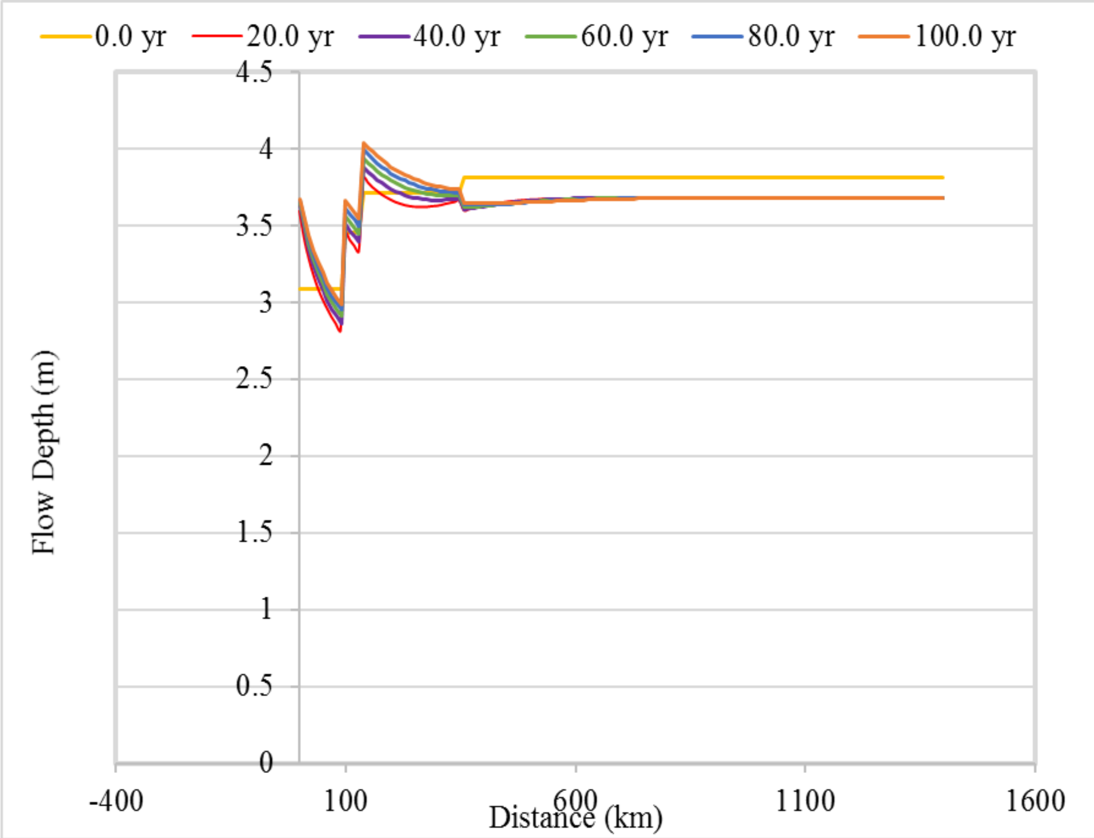

Figure 4.11 Change in Flow Depth with Post-Dam Conditions with Channel Narrowing and Tributaries

The flow depth at the upstream end of the modeled reach is approximately 3.6 m and then decreases to approximately 2.75 m at 90 km downstream at which point the channel bed erosion is reduced due to the channel narrowing. Another reduction in channel bed erosion corresponding to an increase in flow discharge and depth occurs at confluence of the Sioux river and the Missouri River. Overall, the flow depth remains nearly constant in the downstream part of the modeled reach, where significant changes In channel bed elevation are not observed.

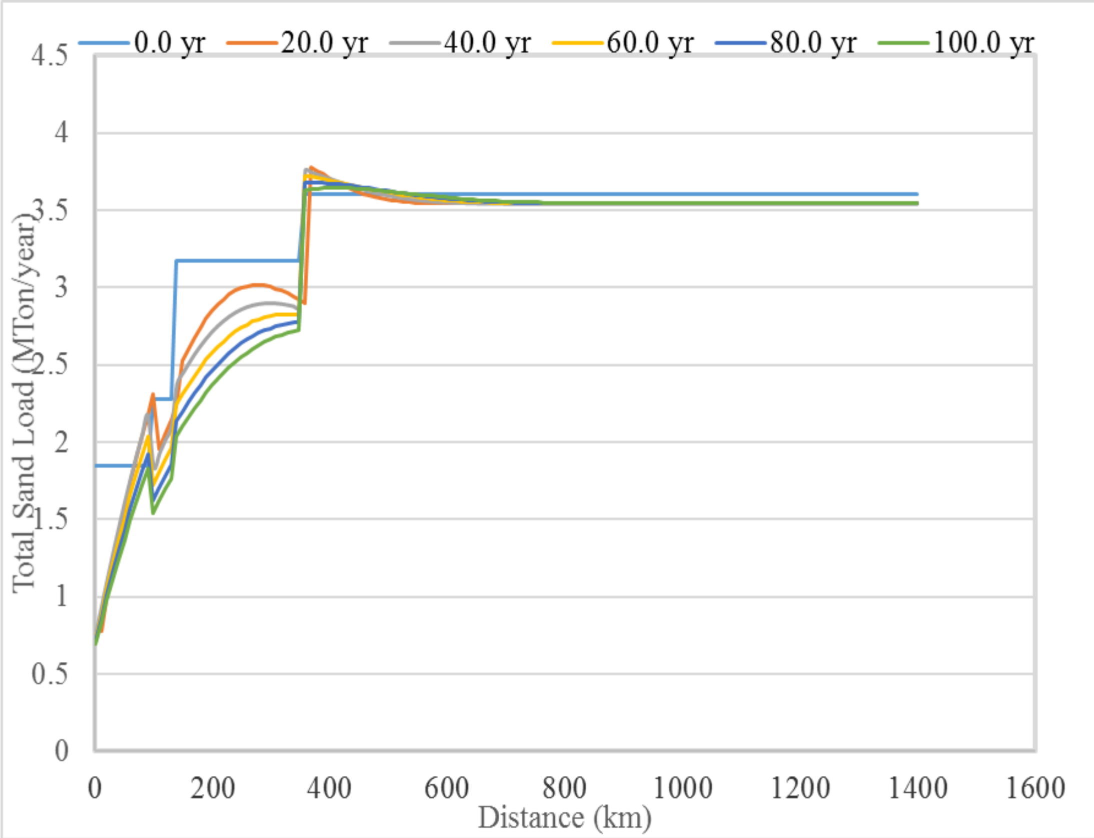

Figure 4.12 Change in Total Sand Load with Post-Dam Conditions with Channel Narrowing and Tributaries

The total sand transport capacity increases in the upstream part of the modeled reach with jumps corresponding to 1) the beginning of the narrowed reach, 2) the Sioux River confluence and 3) the Platte River confluence. Overall, the total sand load changes by approximately 2.5 Mton yr-1 in the upstream most 400 river kilometers.

Figure 4.13 shows the comparison between measured and predicted changes in the bed elevation with post-dam conditions with channel narrowing and tributaries (scenario 5) at Sioux City (downstream distance from Gavins Point dam = 130 km), Nebraska City (downstream distance from Gavins Point dam = 400 km), and Rulo (downstream distance from Gavins Point dam = 500 km). The comparison of Figure 4.13

shows that, notwithstanding the model simplifications, the results reasonably reproduce the available measurements.

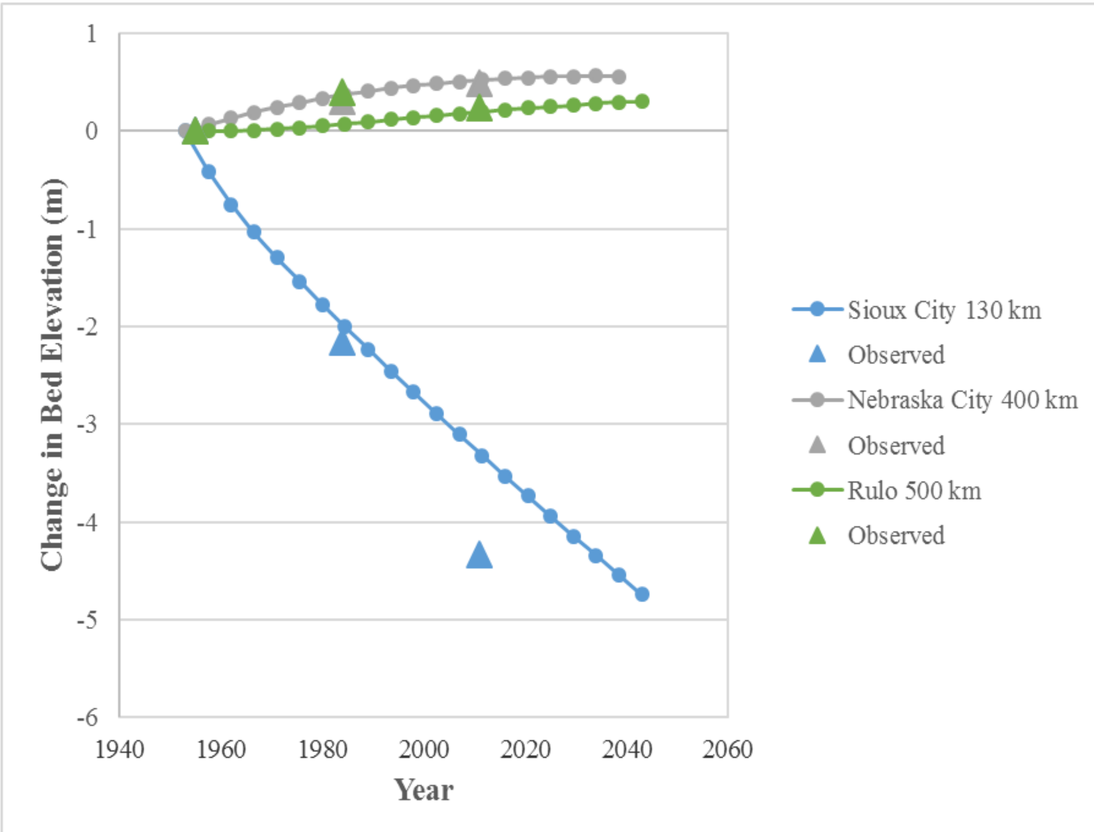

Figure 4.13 Change in Bed Elevation over Time with Post-Dam Conditions with Channel Narrowing and Tributaries

CHAPTER 5

DISCUSSION

The comparison between the scenarios 2, 4 and 5 in terms of the migration rate of the wave of channel bed erosion due to the change in flow and bed material load subsequent to the closure of Gavins Point dam is presented in Figure 5.1.and 5.2. The position of the wave of degradation in time is determined by looking at what point the bed erosion stops. The migration rate of the wave is presented in Figure 5.1 and the position in time of the downstream end of the wave of erosion is presented in Figure 5.2.

Scenario 5, i.e. post-dam conditions with channel narrowing and tributaries, has the most severe temporal change in migration rate, which would indicate that the tributaries most certainly affect the rate at which changes in channel bed elevation migrates through the system.

Each point in Figure 5.2 indicates the downstream position, at a certain time, in which the change in bed elevation is equal to zero and therefore how the length of the eroded reach varies from one scenario to the other. In particular, Figure 5.2 shows the location downstream of the wave of degradation over time for the first 60 years of simulation. For scenarios 2 and 4 the apparent stop of the erosional wave is due to a reduction in migration rate that cannot be captured by the model simulations.

As shown in the modeled results section, the waves of degradation continue to move in the streamwise direction with migration rates that decrease in time. On the contrary, in scenario 5 due to the presence of the Platte River confluence, the erosional wave gets to a physically meaningful stop, as confirmed by the formation of a downstream migrating wave of aggradation.

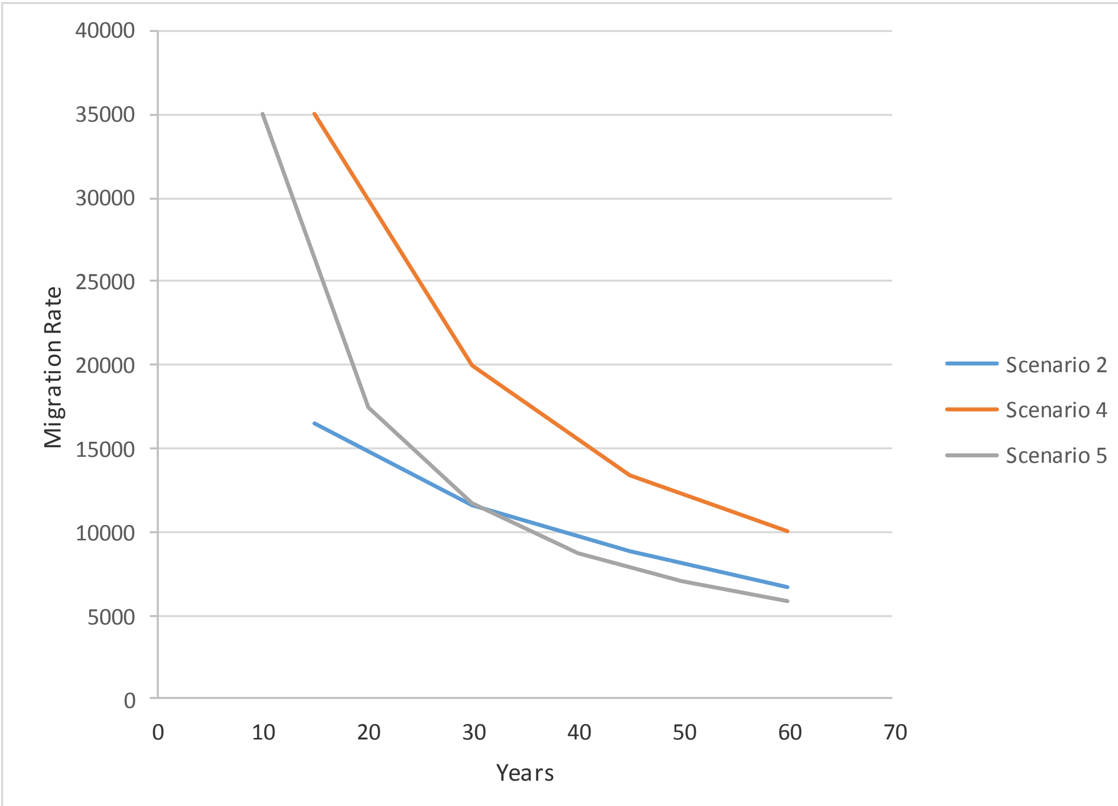

Figure 5.1 Migration Rate of Wave of Degradation over Time

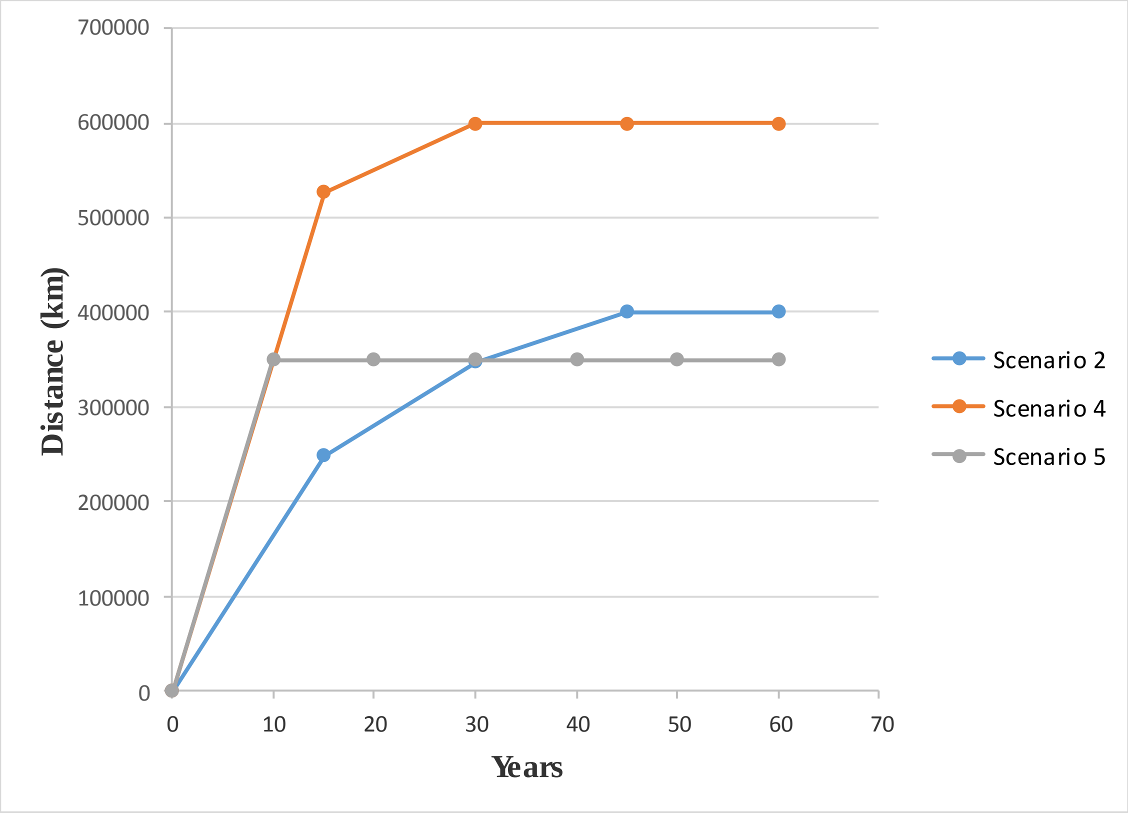

Figure 5.2 Location Downstream of Wave of Degradation over Time

The comparison of mean annual load after 60 years of simulation (approximately present day) with estimated mean annual load (observed in the legend) is presented in Figure 5.3. The blue and yellow series of points represent data collected from USGS monitoring stations. The blue series represent mean annual loads calculated at the USGS monitoring stations included in Chapter 2. From left to right in the figure the USGS monitoring stations are Yankton, South Dakota, Sioux City, Iowa, Omaha City, Nebraska, Nebraska City, Nebraska, and Saint Joseph, Missouri. The yellow series represents data estimated by the USGS (Blum personal communication). In addition to the data for the same stations in the blue series, data for the USGS monitoring stations at Kansas City and Hermann, Missouri is also included.

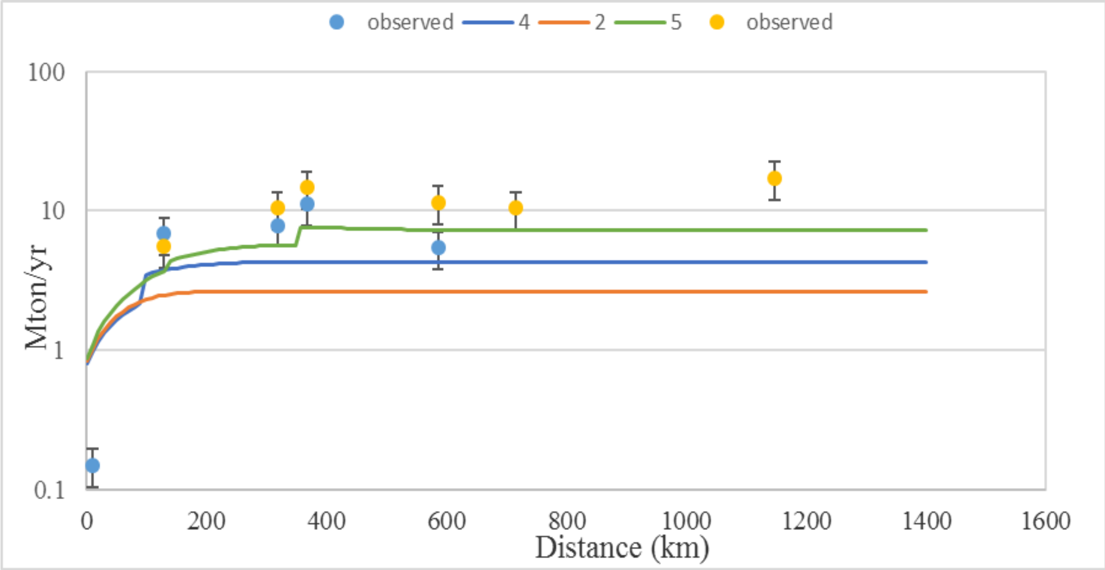

Figure 5.3 Comparison of Changes in Suspended Sand Load Downstream of Gavins Point Dam

A 30 percent error has been added to account for errors associated with the model simplifications and the use of a semi-empirical model to compute bed resistances and suspended sand load. Figure 5.3 shows that the gathered data and numerical simulation data are in reasonable agreement showing that the numerical model is able to capture the change in total sediment load originating at Gavins Point Dam.

The large difference between numerical predictions and observations in the downstream part of the modeled reach is a consequence of neglecting many tributaries that would cause a significant change in the formative discharge and in the sand supply. With that said, due in part to the high number of tributaries located on the river, changes in the flow and sediment regimes and the total sand load originating from Gavins Point Dam and extending to the ~1400 kilometer defined reach do not have a great impact on conditions near the confluence of the Missouri and Mississippi Rivers near St. Louis, Missouri. To observe the influence of Gavins Point Dam on the sand load at the Missouri

– Mississippi River confluence the model should have run for significantly more than say 10 years.

CHAPTER 6

CONCLUSIONS AND IMPLICATIONS

The importance of the Missouri River for the United States cannot be understated as it provides natural resources to the surrounding area and its lakes provide hydroelectric power and recreation. With the widespread installation of civil infrastructure designed for bank stabilization, channelization, and flood control among other things the natural hydrologic and morphologic characteristics of the river were irreversibly changed. To understand the impact of dams on the flow, sediment transport, and degradation on the river a one-dimensional morphodynamic model for large, low slope sand bed rivers was used and the results compared to available observed data. The model was first zeroed under the assumption that the unregulated Missouri River was at mobile bed equilibrium. Subsequently we used the zeroed model to 1) predict the magnitude and migration rate of the waves of degradation at engineering time scales, approximately 150 years into the future, and 2) quantify the changes in sand load delivered to the Mississippi River. To reiterate, scenario 2 was post-dam conditions with constant channel width. Scenario 4 was post-dam conditions with channel narrowing, and scenario 5 was post-dam conditions with channel narrowing and tributaries. In looking at the migration rate of the waves of degradation for all three scenarios, clearly scenario 5 had the most activity and largest change in position from upstream to downstream of the three scenarios as evidenced in Figure 5.1. Tributaries certainly play a role in the amount of total sand load found over the length of the defined reach as evidenced by Figure 5.1.

However it is evident that as you progress further downstream the flow regime did not significantly change in time, and consequently the suspended sand load remained nearly constant in space and the sand load delivered to the Mississippi River remained constant since Gavins Point dam closure and will remain constant for the foreseeable future. Further, the simulations presented herein show that the channel bed aggradation observed at the Platte River – Missouri River confluence halts (or significantly slows down) the wave of channel bed erosion generated at Gavins Point dam. Future modeling efforts are needed to 1) consider the interannual variability of the flow discharge, 2) account for the tributaries that were neglected in the present simulations, and 3) quantify the impact of the engineering work on the mud load.

REFERENCES

Alexander, Jason, Robert Jacobson, and Davis Ruis, "Sediment Transport and Deposition in the Lower Missouri River during the 2011 Flood," United States Geologic Survey Professional Paper 1798-F, 27 p., accessed July 22, 2016, doi: 10.3133/pp1798f

Blevins, Dale, "The Response of Suspended Sediment, Turbidity, and Velocity to Historical Alterations of the Missouri River," United States Geological Survey Circular 1301, 8 p., accessed July 20, 2016

Fenneman, Nevin, 1928, "Physiographic Divisions of the United States," Annals of the Association of American Geographers v. 17, p 261-353, accessed July 14, 2016

Heimann, David, Rasmussen, P.P., Cline, T.L., Pigue, L.M., and Wagner, H.R., 2010, "Characteristics of Sediment Data and Annual Suspended- Sediment Loads and Yields for Selected Lower Missouri River Main-Stem and Tributary Stations," United States Geological Survey Data Series, 1976-2008 530, 58 p., accessed July 26, 2016

Heimann, David, Lori Sprague, and Dale Blevins, 2011, "Trends in Suspended Sediment Loads and Concentrations in the Mississippi River Basin," United States Geological Survey Scientific Investigations Report 2011-5200, 33p., accessed July 20, 2016

Jacobson, Robert, Dale Blevins, and Chance Bitner, "Sediment Regime Constraints on River Restoration: An Example from the Lower Missouri River," Geological Society of America Special Paper, p. 1-22, accessed July 28, 2016

Morgan, Jacob. "Bed Degradation of the Lower Missouri River." MS Thesis, University of Missouri – Kansas City, 2011.

Nittrouer, Jeffrey, and Enrica Viparelli, "Sand as a Stable and Sustainable Resource for Nourishing the Mississippi River Delta," *Nature Geoscience*, accessed July 20, 2016, doi: 10.1038/NGEO2142

United States Army Corps of Engineers: Missouri River Region, Northwestern Division, Reservoir Control Center. Missouri River Stage Trends. Missouri, 2007. Accessed April 14, 2016

United States Department of Agriculture: Natural Resources Conservation Service. Phase II Sedimentation Assessment for the Upper Missouri River Basin. Montana, Nebraska, North Dakota, South Dakota, 2009. Accessed April 20, 2016

United States Army Corps of Engineers: Northwestern Division Reservoir Control Center. Missouri River Main-Stem Reservoir System Master Water Control Manual – Missouri River Basin. Omaha, Nebraska, 2006. Accessed August 2, 2016

Vining, Kevin, Katherine Chase, and Gina Loss, 2013, "General Weather Conditions and Precipitation Contributing to the 2011 Flooding in the Mississippi River and Red River of the North Basins, December 2010 through July 2011," United States Geological Survey Professional Paper. Accessed August 4, 2016

Wright, Scott, and Gary Parker. "Flow Resistance and Suspended Load in Sand-Bed Rivers: Simplified Stratification Model," Journal of Hydraulic Engineering 130 (2004): 796-805. Accessed July 1, 2016. Doi: 10.1061/(ASCE) 0733-9429(2004) 130:8(796