Appendix C

Future Without-Project Model Projections with Risk and Uncertainty

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US Army Corps
of Engineers
Kansas City District

Missouri River Bed Degradation Study

Technical Appendix

Future Without Project Model Projections with Risk and Uncertainty

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March 2017

1. Introduction

The purpose of this appendix is to document the degradation projections conducted in conjunction with the Missouri River Bed Degradation Feasibility Study for the Future Without Project condition, including the risk and uncertainty. The model creation and calibration process are described in the *Missouri River Bed Degradation Study Mobile Bed Model Calibration Appendix*, referenced herein as the *Model Calibration Appendix*. This appendix describes updates to model geometry, explains the development of the hydrologic boundary condition for the projection period and provides Future Without Project bed elevation and water surface elevation projections. This appendix also documents sensitivity analysis and the development of a *less degradation* and *more degradation* scenario, developed by combining model uncertainty and natural variability.

2. Geometry Updates

The model was built with 1994 bathymetric data and calibrated to water surface, velocity, and bed change from 1994 to July 2014 as described in the *Model Calibration Appendix*. Following model calibration, model bathymetric data was updated to a summer 2014 hydrographic survey and December 2013 river training structure survey. This updated geometry provides a starting geometry for Future Without Project conditions and the baseline geometry to which Future With Project changes will be made. Incorporating the recent survey information provides a more accurate starting geometry than the end-of-simulation geometry from the calibration model.

2.1 Bed Bathymetry: The 2014 bathymetric survey included measured bed transects at 500 ft spacing. The nearest 2014 bathymetric transect was used to update the model bathymetry. Transects were merged into the HEC-RAS cross-sections using geo-referenced stationing and/or lining up revetments in the graphical cross-section editor.

2.2 **Structure Elevations:** Structure elevations in the calibration model were based on design criteria as an offset from the construction reference plane. These structure elevations were adjusted to the current heights based on a survey of structure elevations conducted in December of 2013. The average adjustment in dike and sill height was -3.0 and -2.5 ft, respectively. These lower structure elevations are a function of the lowering of the Construction Reference Plane by 2.6 ft between the 1982 and 2010 CRPs. Perched structures in the most degraded reaches were mechanically lowered and when deficient structures were repaired, they were repaired based on the most recent (degraded) CRP.

During the 2013 structure survey, the water surface was measured at defined benchmarks and the effective structure height was estimated as an offset from the water surface. The structure survey was an “effective elevation” survey, meaning the average offset from the water surface was approximated for the entire length of the dike or sill. The portion of the structure outside of the rectified channel lines (RCL) are considered dikes and the portion inside are considered sills. While the sill is typically lower than the dike, dike notches can cause the average effective elevation of the dike to be lower than the elevation of the sill. This situation is depicted in Figure 2.

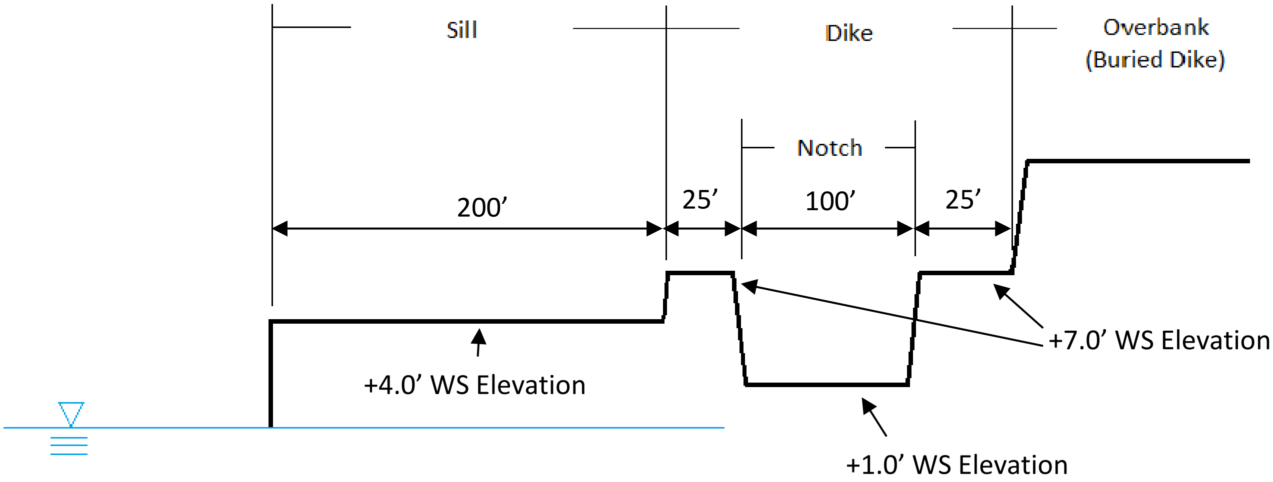

Figure 2. Example sketch where the effective elevation of a notched dike is lower than the sill

In the example above the sill portion of the structure has an effective water surface offset of +4.0’ and the dike portion of the structure has an effective water surface offset of +3.0’. The WS Elevation is -6.0’ CRP and all structures are at design criteria. Using an average elevation for the dike portion of the structure introduces less than 2% error in additional flow area in the range of stages that fall between the bottom and top of the dike notch. When flow is below the bottom of the notch or above the top of the dike the error is 0%.

The degradation model cross-sections typically fall between structures. The lengths and elevations included for the structures in the model cross-sections represent an average of the lengths and elevations of adjacent structures. The representative length and elevation used in the model was determined differently for the following two cases.

First and most common, where model cross-sections are bounded by structures of similar type (e.g. dikes or sills on both upstream and downstream sides), the structure lengths and elevations were interpolated linearly based on the distance of the model cross-section from each structure. For example, a model cross-section having a sill 500 ft upstream at an elevation of 801.50 ft and a sill 1000 ft downstream at an elevation of 800.00 ft has a representative model structure elevation of 801.00 ft. Figure 3 depicts this example.

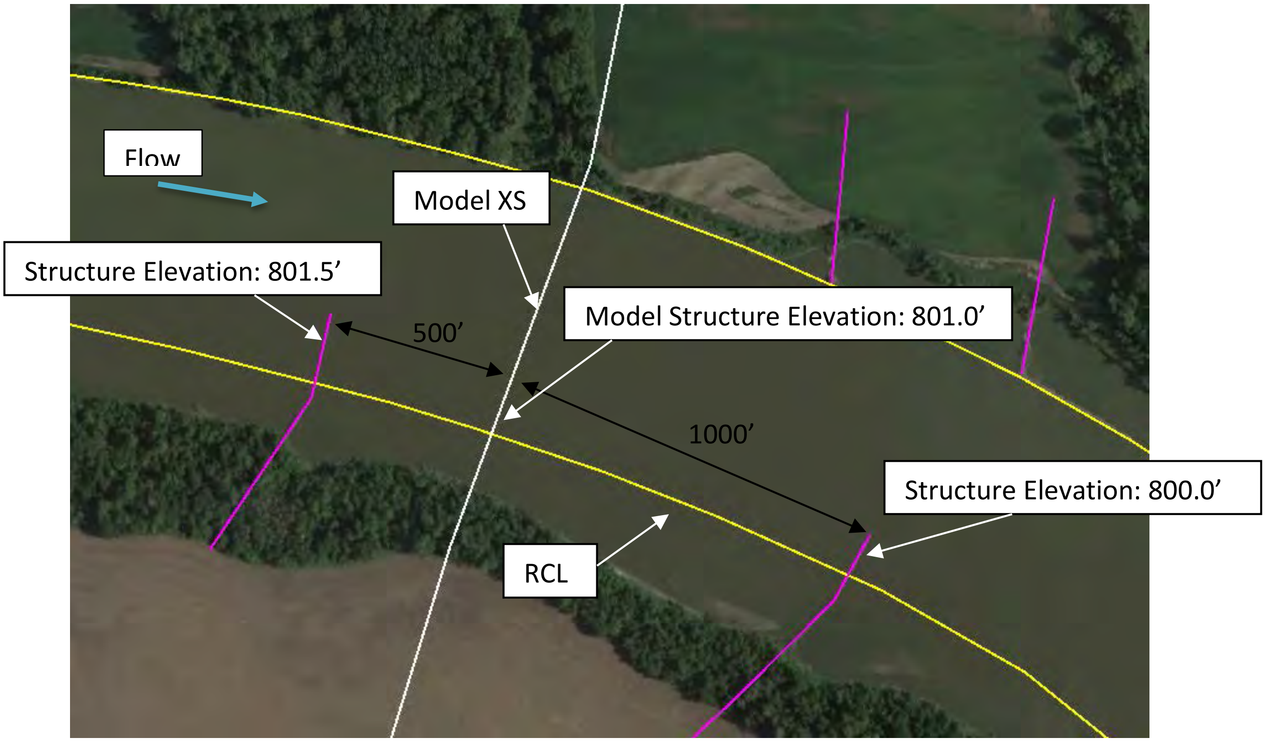

Figure 3. Cross-Section bounded by structures of similar types

The second case is where model cross-sections fall between two structures that are not similar, for example the downstream structure has a sill and the upstream structure does not. In this case, the length of the sill is linearly interpolated by intersecting the cross-section with a line connecting the tip of the sill at the downstream structure to the tip of the dike at the upstream structure, as shown in Figure 4. The elevation of the sill in the model is calculated using the water surface offset of the adjacent sill, applied to the water surface elevation at the model cross-section. A similar procedure is followed if one bounding structure is exposed to flow and the other is buried in the bank. Revetment structures were not updated from the original model, as described in the *Model Calibration Appendix*.

In both cases, structure lengths were reduced to account for flow in the inter-dike region, as explained in the *Reduction in Dike Lengths* technical note included with the *Model Calibration Appendix*. This is consistent with the representation of the dikes during the calibration period.

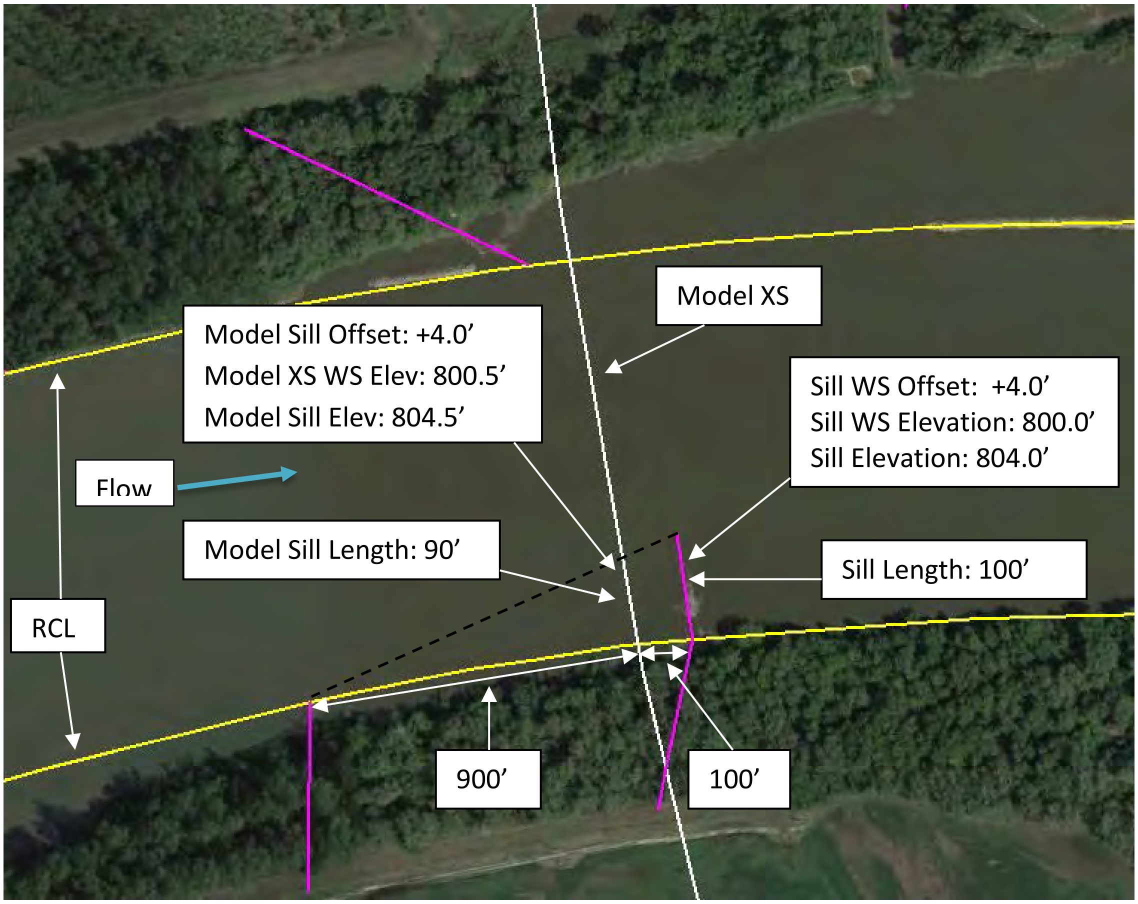

Figure 4. Cross-section bounded by structures of different types

2.3 Hydraulic Verification of Updated Model: The model with updated channel bathymetry and dike elevations was run using USGS gaged flows from July 28, 2014 to September 30, 2015. Figure 5 depicts both the measured and modeled water surfaces and the St. Joseph and Kansas City gages. On average, the model water surface is 0.72 ft below and 0.78 ft above the measured water surface at the St. Joseph and Kansas City gages, respectively. Degradation damages are assessed based on the minimum elevation in a given year. The model minimum water surface over this time period elevation is 0.03 ft below and 0.69 ft above the measured elevations, at the St. Joseph and Kansas City gages, respectively.

It is not desirable to alter roughness values or other model parameters which were calibrated to long-term flow and sediment measurements in order to improve the agreement in a single year of simulation. However, for computing the standard estimate of error to develop the *less degradation* and *more degradation* scenarios, equal weight was given to the one year of error in the updated model as to the calibration model. This was accomplished using the following equation and by including the values for year 2015 an equal number of years.

$$S_{deg} = \sqrt{\frac{\sum_{i=1}^{N}(X_i - M_i)^2}{N-1}}$$

where S_{deg} represents the standard deviation of error between the minimum elevation predicted in the degradation model and the observed low water surface for a given year, X_i = the measured minimum water surface elevation for a given year, M_i = the model estimate minimum water surface elevation for the same year, and N = the number of years. Table 1 indicates the values used. The standard estimate of error is 0.57 ft and 0.56 for the St. Joseph and Kansas City gages, respectively.

Table 1. Modeled and Measured Minimum Daily Water Surface

	Saint Joseph		Kansas City	
Year	Measured	Model	Measured	Model
1994	794.84	794.96	715.48	715.62
1995	793.57	793.83	713.99	714.26
1996	795.16	794.14	714.39	715.07
1997	796.28	796.80	716.94	717.42
1998	795.95	796.03	717.81	717.38
1999	795.83	796.64	716.1	716.52
2000	791.04	791.92	711.55	711.90
2001	792.75	793.09	712.99	712.90
2002	792.01	792.56	711.63	711.26
2003	791.29	791.98	710.64	710.63
2004	791.03	791.71	710.24	710.21
2005	791.52	792.00	710.08	710.35
2006	791.65	792.45	710.47	710.00
2007	790.54	791.69	709.59	709.71
2008	790.55	792.26	711.81	711.42
2009	792.11	793.35	711.4	711.78
2010	794.55	795.67	713.77	713.56
2011	795.65	796.60	714.73	715.12
2012	791.05	790.93	711.74	711.21
2013	789.99	790.12	710.81	710.22
2014	790.21	790.24	710.91	710.56
2015*	793.06	793.03	713.53	714.22

* Repeated 20 times in the equation to give equal weight to the model post geometry updates.

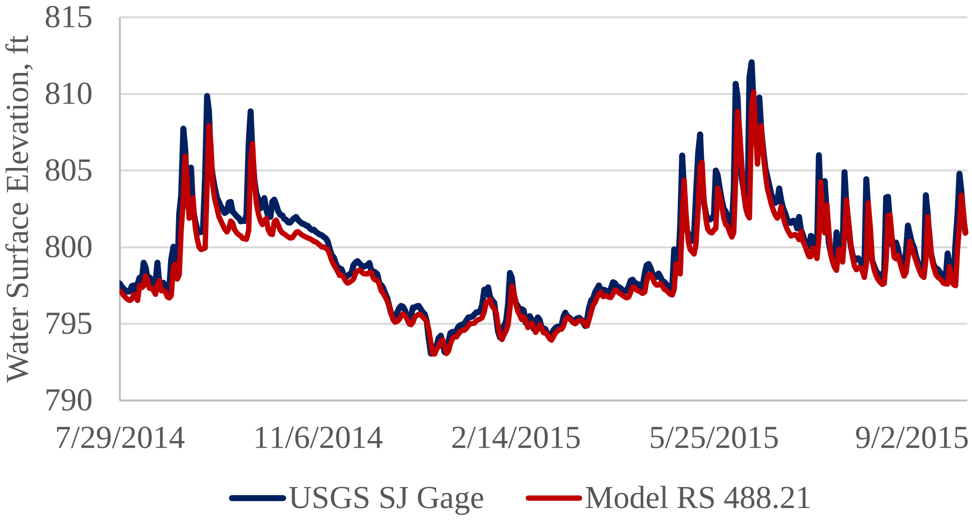

Figure 5. Modeled and measured water surface 28 July 2014 to 30 Sep 2015 at the St. Joseph gage

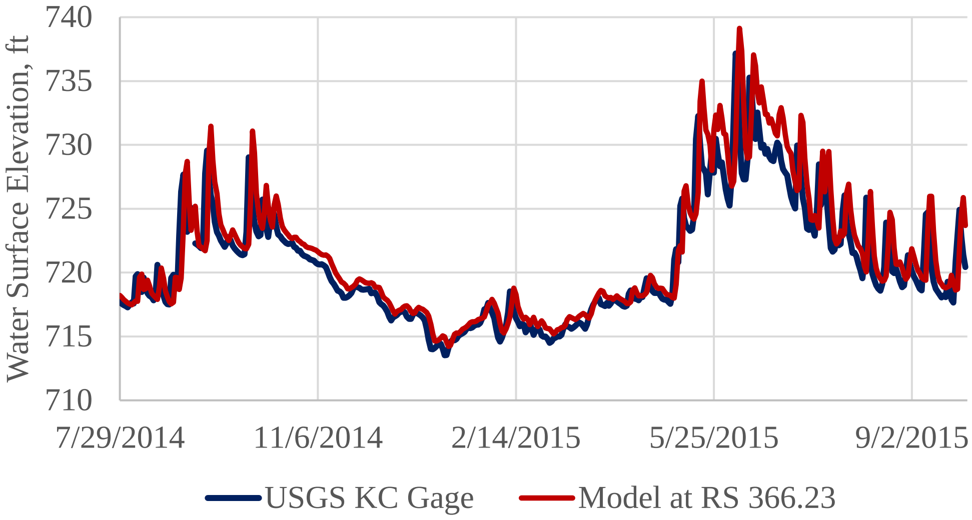

Figure 6. Modeled and measured water surface 28 July 2014 to 30 Sep 2015 at the Kansas City gage

As a second verification, channel velocities in the updated model were compared to velocities using the end-of-simulation geometry from the calibration model. On average, velocities from model runs with the different geometries for low flow, minimum navigation flow, 10-year flow and 50-year flow varied by less than 0.1 ft/s. This validates the use of the updated model with the original calibrated parameters.

3. Hydrologic Inputs

The flow boundary conditions during the calibration period were set to measured flow values at USGS gages, as described in the *Model Calibration Appendix*. The flow boundary condition for future projection base case was developed to have a 50% exceedence probability for cumulative sediment transport at the St. Joseph gage, as described in this section.

3.1 Hydrologic Uncertainty and the Timing of High Flows: High flows, including major flooding, are natural phenomenon on the Missouri River. However, the river's response to high flow events is a function of river confinement by flood protection and river training structures and channel incision from previous years of degradation. Historically, high flows could spread out and dissipate energy over a wide floodplain. Additionally, the main channel could avulse and increase its sediment supply by capturing floodplain sediments deposited by previous floods. Currently, high-energy flows are confined to the channel and the main channel is cut off from additional floodplain sediments due to construction and operations of the Corps' Bank Stabilization and Navigation Project (BSNP). Significant flood-related degradation was observed in the 1993 and 2011 flood events. Although the bed did show some minor signs of rebound following the 1993 flood, the end result of the flood was a sustained drop of the river bed. The 2011 flood event caused the degradation that had been centered in Kansas City to headcut upstream by 25 to 30 miles (USACE 2015a). Bathymetric cross-sections surveyed in 2014 indicate that the reaches downstream from the Kansas River confluence have rebounded to pre-flood or slightly higher elevations, while the reaches above the confluence saw as much as 4.3 ft of sustained degradation from 2009 to 2014.

The timing of this aspect of geomorphic change for Future Without Project and Future With Project conditions coincides with the timing of high flows, defined not by an annual peak flow but by the sediment transporting power of all the flows that year (a function of both discharge and duration). If high flows happen immediately, the upstream reaches degrade very soon in the 50-year planning horizon and results in relatively large damages in present-day dollars. If the high flows occur near the end of the 50-year planning horizon, the tremendous damages incurred are discounted back to a relatively small amount of present-day dollars. To avoid bias in either direction, a 50-year flow scenario was developed that conveys the median volume of sediment, as described in the following section. This represents an "average" condition.

3.2 Development of Hydrologic Condition for Future Projections: An ordering of flows that has sediment transport potential with a 50% chance of exceedance provides a hydrologic condition for this project consistent with a "median" or "most likely" future condition. The development of the 50% sediment flow series followed a Monte Carlo approach and was accomplished with the following steps:

1- The hydrologic record of daily flows at the Kansas City gage from October 1, 1898 to Dec 31, 2010 was acquired from the Missouri River Basin Water Management office (MRBWM). The MRBWM utilized the Missouri River Reservoir System Daily Routing Model (DRM) to create a consistent data set that accounts for historic and more recent level depletions and holdouts that would have occurred over time. Two data sets are generated from the DRM, Unregulated and Regulated daily flow records. Unregulated flows were generated by adding in historic depletions to the extended observed inflow records. Regulated records were then generated by subtracting "current" level depletions (representative of conditions from 2002, including mainstem and tributary dams) from the unregulated flow record. Use of the DRM Regulated daily flow record was selected for this analysis as it provides a consistent data set essentially reflective of current levels of reservoir regulation and consumptive use. Additional information on the DRM may be found in the MRBWM Hydrologic Statistics Technical Report (USACE 2013). The DRM flow record was extended using USGS gage records for daily flows from Jan 1, 2011 to Sept 30, 2011, making 113 complete water years.
2- The bed material rating curve (flow versus bed material transport in tons per day) at the St. Joseph gage developed for the dredging EIS for Kansas City was used to transform daily flows into daily bed material loads.
3- The daily bed material loads at the St. Joseph gage were summed for each water year to provide an annual bed material volume of transported sediment.
4- Fifty years were randomly selected from the 113 available water years. Any given year could be chosen once, more than once, or not at all.
5- The progressive, cumulative volume of bed material transported by the random 50-year sequence of flows was computed at each year of sediment movement (i.e. the volume of bed material transported after 3 years included the sum of the volumes of bed material transported in years 1, 2, and 3).
6- Steps 4 and 5 were repeated for a total of 999 fifty-year flow scenarios.
7- The 999 flow realizations were ordered and ranked according to the cumulative volume bed material transported by the end of five, ten, fifteen, twenty five, and fifty years. The flow realization with the highest bed material volume was given a rank of 1. The realization with the lowest bed material yield was given a rank of 999.
8- The probability of exceedence for each flow realization was computed by the following Weibull plotting position formula:

$$P = m/(n+1)$$

where P = the probability of exceedence

m = the rank of the flow scenario for cumulative bed material yield by the end of a specified number of years (5, 10, 15, 25, and 50)

n = the total number of flow scenarios, in this case 999

9- By the above formula, the cumulative bed material transported corresponding to the scenario ranked as number 500 out of 999 has a 50% probability of exceedence for the stated time period. The cumulative bed material load with 50% exceedence probability for five, ten, fifteen, twenty five, and fifty years are shown in Figure 7.

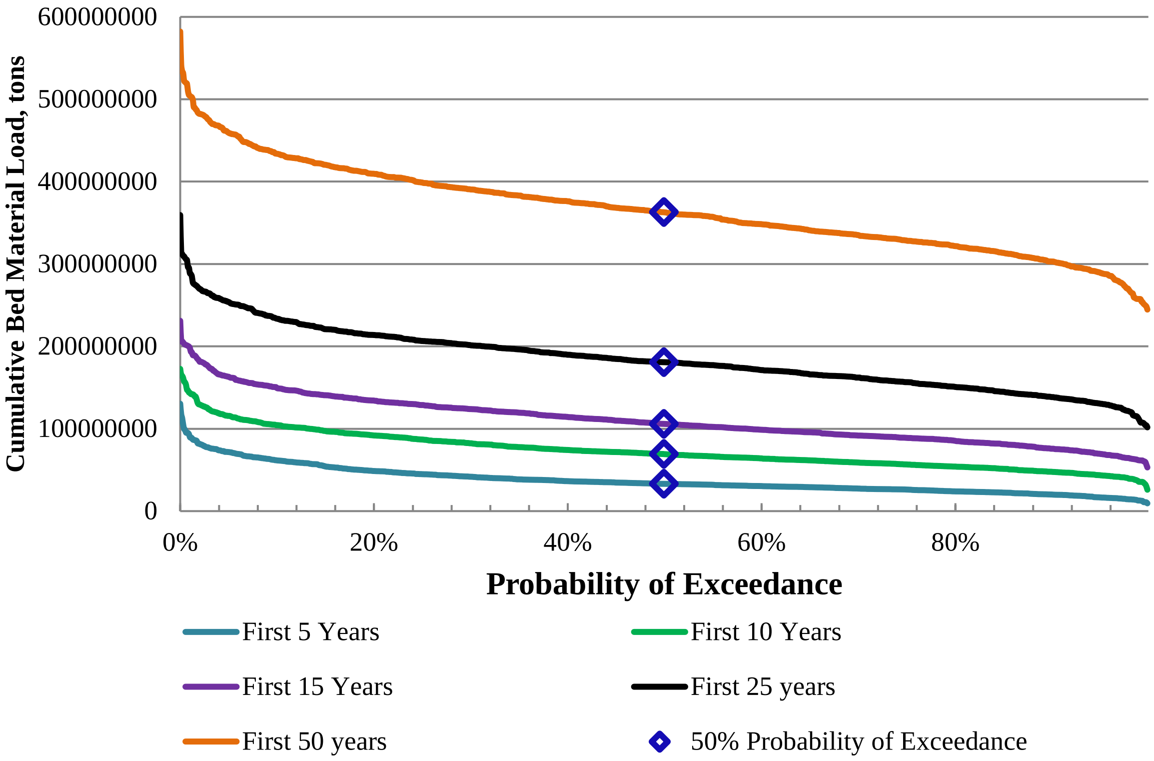

Figure 7 Cumulative bed material transported with percent exceedence probability

10- The final flow scenario chosen as the future hydrologic planning condition was developed to yield values for total bed material moved with a 50% chance of exceedence at the end of five, ten, fifteen, twenty five, and fifty years. This flow scenario was developed by incrementally applying the random flow year process described above to each successive set of years in order to hit the cumulative bed material targets shown in Figure 6. For example, the Monte Carlo approach described above was used to find a flow scenario with a 50% chance of exceedence after five years. Then, given the occurrence of those five years, the Monte Carlo approach was used to find an additional five years of flow such that at the end of ten years, the bed material moved equates to the 10-year, 50% exceedence value. Figure 8 presents the cumulative bed material load curve for the base case flow series (50% exceedence probability) plotted against first 250 of 999 random flow scenarios. For comparison, Figure 7 also plots the cumulative bed material load using historic flow years (from the same MRBWM data set) from 1961 to 2011.

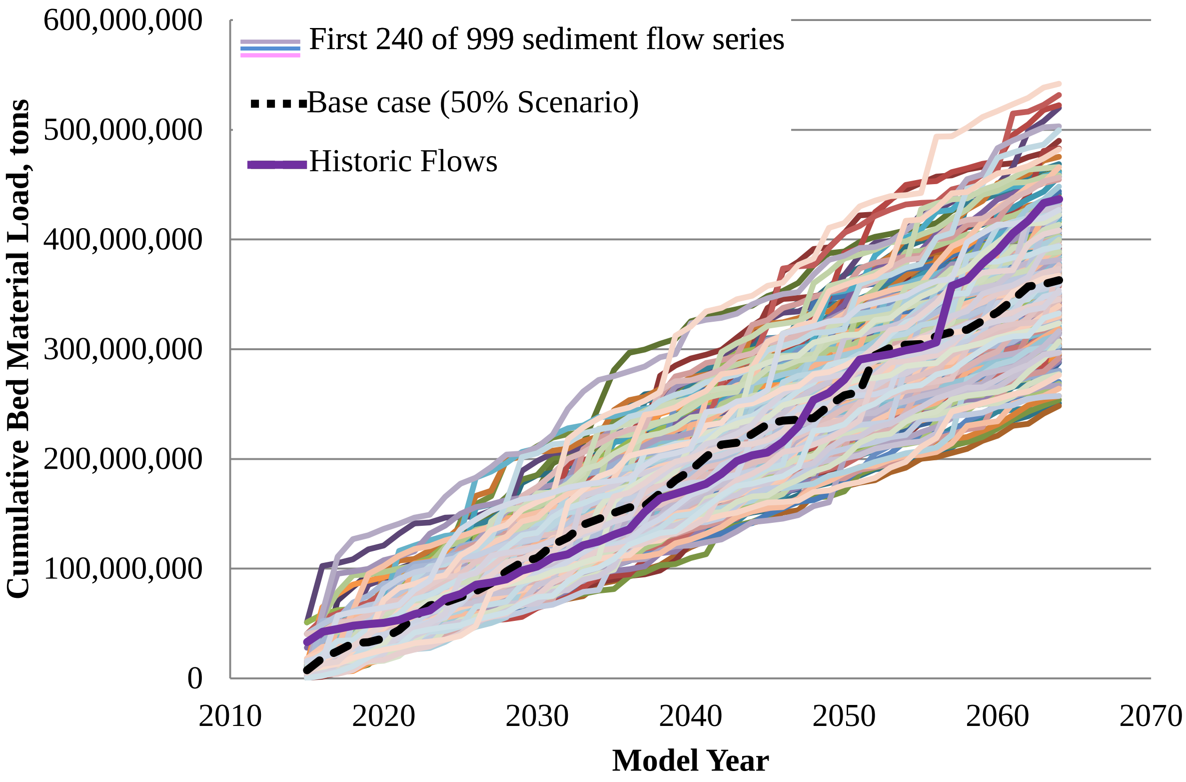

Figure 8. Cumulative bed material for the base case flow series (50%) and 250 other flow series

Table 2 presents the flow order for the selected base case flow series that produces a bed material transport with a 50% probability of exceedence:

Table 2: Selected Base Case Flow Order with a 50% Probability of Bed Material Transport Exceedence

Model Year	Water Year	Model Year	Water Year	Model Year	Water Year	Model Year	Water Year	Model Year	Water Year
1	1900	11	1973	21	1995	31	1979	41	1938
2	2009	12	1925	22	1973	32	1927	42	1921
3	1972	13	1921	23	1942	33	1935	43	1967
4	1900	14	1918	24	1917	34	1956	44	1947
5	1939	15	1945	25	1975	35	1917	45	1930
6	1933	16	1960	26	1979	36	1953	46	1966
7	1950	17	1997	27	1997	37	1901	47	1917
8	1997	18	2002	28	1917	38	1952	48	1975
9	1961	19	1980	29	1956	39	2002	49	2007
10	1955	20	1981	30	1970	40	1954	50	1922

3.3 Most Likely Conditions vs. More Extreme Scenarios: The focus of the preceding analysis for developing the planning hydrologic scenario was to determine the most likely future conditions flows in terms of sediment transport. A presentation of a reasonable range of 50-year series of flows, including more extreme hydrologic scenarios (including the 1% and 99% sediment exceedance scenarios) and the quantification of a standard deviation for use in uncertainty propagation is provided later in this appendix.

4. Dredging Condition

The Missouri River Bed Degradation Reconnaissance Report (USACE 2009) and the Missouri River Dredging Environmental Impact Statement (USACE 2011a) identified commercial sand and gravel extraction (commercial dredging) of the Missouri River as a significant contributor to bed degradation. This section defines the dredging condition used in the base case. Additional information of the effects of commercial dredging and a sensitivity analysis is provided later in this document. Commercial dredging was included in the calibration period as described in the *Model Calibration Appendix*. Commercial dredging for the Future Without Project scenario is based on the currently permitted level of commercial dredging, as defined by the 2015 permit record of decision (USACE 2016), which includes a “ramping up” period for the first several years and a steady annual value thereafter, as listed in Table 3. The locations and relative magnitudes of dredging from 2010 to 2015 establish the distribution of dredging within each dredging reach for modeling purposes. Note that dredging included in the model is less than that permitted for the full Waverly reach because some of the Waverly reach dredging occurs outside of the model extents. The 50-year total for sediment extraction from commercial dredging is approximately 131 million tons. Reductions in commercial dredging are included as a measure in many of the project alternatives.

Table 3. Annual Dredging Amounts (tons) Included in FWOP Projection

	Model Dredging (tons/year)				
EIS Dredging Reach	Year 2016	Year 2017	Year 2018	Year 2019	Years 2020 - 2065
St. Joseph (RM 391 to 498)	330,000	330,000	330,000	330,000	330,000
Kansas City (RM 357 to 391)	540,000	540,000	540,000	540,000	540,000
Waverly (RM 250 to 357)	1,109,500	1,264,733	1,419,965	1,575,198	1,730,431
Annual Total	1,979,500	2,134,733	2,289,965	2,445,198	2,600,431

5. Extraction due to Floodplain Deposition

During significant floods, the Missouri River floodplain becomes a morphologically significant sink for sediment that should not be ignored in long-term sediment budgeting (Alexander et. al 2013). Similar to the calibration model, the projection model accounts for sediment lost to floodplain deposition as negative lateral loads which are specified a priori rather than computed during the modeling. The annual extraction due to floodplain deposition was scaled from 2011 floodplain deposition according to the following equation (performed separately for the Saint Joseph to Kansas City reach and the Kansas City to Waverly reach):

$$\boldsymbol{D_i = n_i * \frac{D_{2011}}{n_{2011}}}$$

where D_i = the annual floodplain deposition in year i
D_{2011} = the annual floodplain deposition in the year 2011
n_i = the number of days in year i that the flow threshold is exceeded
n_{2011} = the number of days in 2011 that the flow threshold is exceeded

The flow threshold chosen was 90% of the 10-year discharge, or 175,000 cfs at the St. Joseph gage and 245,000 cfs at the Kansas City gage. Many smaller levees are overtopped at or around these discharges. Most years do not exceed the threshold and hence do not include any extraction due to floodplain deposition. In years that do include floodplain deposition, the total reach amount is specified as a uniform lateral sediment load from Saint Joseph to Kansas City and/or from Kansas City to Waverly. This procedure provides a reasonable, repeatable method for including floodplain deposition in future scenarios. The Future Without Project base case flow series includes flows high enough to meet this threshold at one or both gages in nine out of fifty years. Loss due to floodplain deposition totals approximately 18 million tons over the 50-year simulation, which is small compared to the total sediment transport.

The amount of floodplain deposition that will occur in the future is highly uncertain and could be either less or more than that included in the FWOP projection. The uncertainty derives from uncertainties in the volume and gradation of floodplain deposition in 2011 and in the transferability and scalability of that event to future events. Later in this appendix, it is shown that the model is insensitive to this parameter within the reasonable range of uncertainty.

6. Model Spin-up

Individual cross-sections may experience rapid change in the first year of 1D model projections, as the model equilibrates to the new geometry. To prevent this initial equilibration from obscuring the overall bed change trend at individual features of interest, the model was run from 28 July 2014 to 01 Oct 2015 as a "spin-up" period. This spin-up period includes measured flow and dredging data and is hot-started with bed gradations from the end of the calibration model. Degradation projections will use the 01 Oct 2015 model output as the baseline for the purposes of showing future trends.

7. Future Without Project Base Case Model Results

This section provides projected bed and water surface elevations for the Future Without Project condition. Values are given as change in mean effective invert elevation (average bed elevation) from 01 Oct 2015 conditions or as the projected water surface elevation for a consistent low discharge. The model geometry, hydrologic inputs, and dredging inputs are described in preceding sections and summarized in Table 4.

Table 4. Summary of Modeling Parameters Used in the Future Without Project Base Case

Parameter	Condition
Flow Series	Flows that generate cumulative bed material transport with a 50% probability of exceedance at the end of 5, 10, 25, and 50 years.
Sediment Load	Flow-load relationship as calibrated during the calibration time period (1994 to 2014).
Floodplain Deposition	Floodplain deposition scaled from the 2011 deposition according to days above a significant flood threshold. The 2011 floodplain depositional volume was determined by 2 ft times the areal extent of sand deposition.
Dredging	As permitted in the December 2015 decision. Locations based on 2010 to 2015 locations.
Flood-Related Degradation	Model reproduces long-term trend, not short-term degradation and rebound.

7.1 Future Without Project Bed Elevations

Figure 6 presents the average bed degradation averaged into 5-mile reaches in years 2015, 2025, 2040, and 2065 (simulation years 0, 10, 25, and 50). As seen in Figure 9, the upstream reaches near St. Joseph, Missouri are projected to degrade up to an additional 5.5 feet over the next 50 years. Short-term recovery then a return to a long-term degradation trend is expected in Kansas City. Downstream of Kansas City is projected to degrade up to 4.3 ft over the next 50 years. The Kansas City metro (RM 350 to 370) is expected to experience slight recovery in the short term. This is due to an increased sediment load from a headcutting channel upstream of Kansas City. Over time two factors influence a return to a degradational trend, (1) as the headcut moves further upstream, the contribution of the increased sediment load to Kansas City decreases, (2) as dredging continues near the upstream end of the Waverly reach (around RM 350), new degradation headcuts into Kansas City.

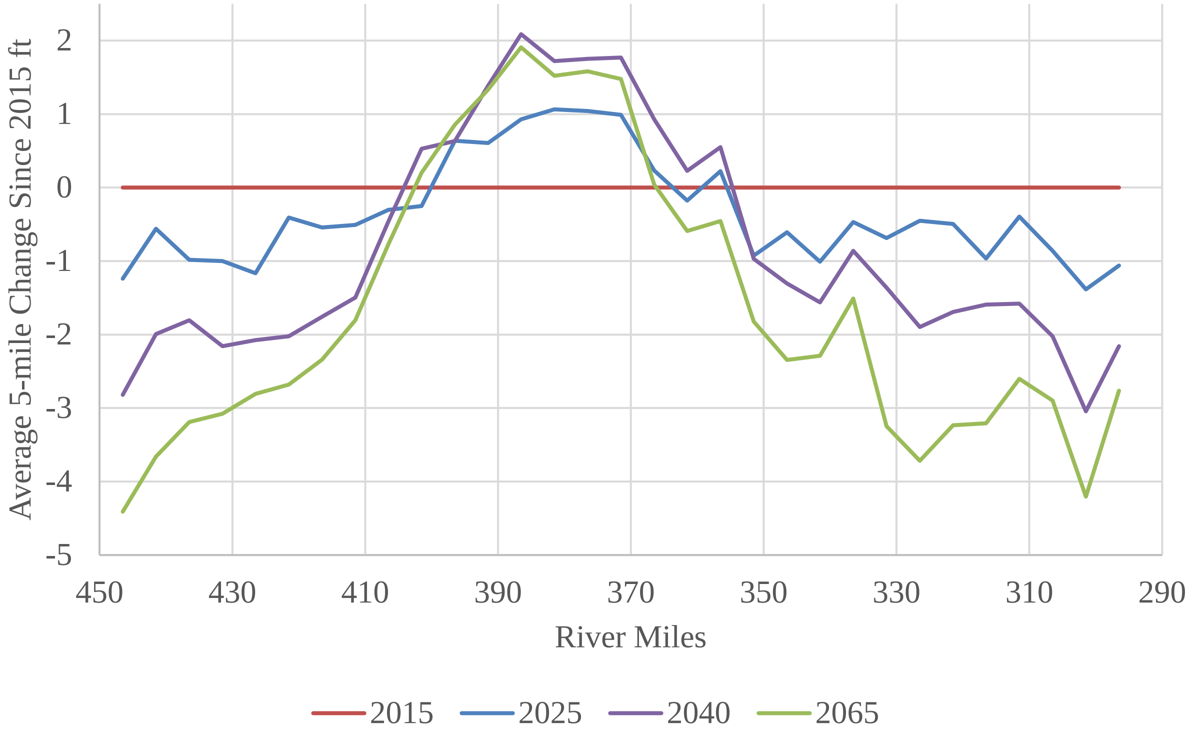

Figure 9. 5-mile Reach Average Degradation since 2015 for Future Without Project Base Condition

The model outputs a value for the change in mean effective invert elevation every 60 computational intervals. At the lowest flows, the computational interval is 24 hours, yielding an output every 60 days. At the highest flows, a computational interval is 12 minutes, yielding two outputs per day. The greater resolution during high-flow events better describes the rapidly-changing bed conditions during major floods. The economic model takes as input the minimum model elevation at each feature for the year.

7.2 Future Without Project Water Surface Elevations

Much of the critical infrastructure is dependent on the water surface elevation for a low discharge rather than the bed elevation. The HEC-RAS Specific Gage Analysis tool was used to generate water surface profile changes over time at locations of interest. This tool runs a steady flow analysis with a given discharge at user-specified points in time. Several options were examined for which low flow to use. Values for these options at St. Joseph are listed in Table 5.

Table 5. Potential Low-Flows for Tracking Water Surface Elevation Changes Over Time

Low-Flow Definition	**Flow at St. Joseph, MO (cfs)**
Lowest daily discharge since reservoir filling (1967)	4,600 (08 Feb 1989)
Lowest daily discharge since 1993 flood (USGS data)	16,200 (18 Jan 2007)
Lowest discharge in MRBWM flow dataset since 1993 flood	11,540
Lower decile of non-navigation flows in MRBWM flow dataset	15,500

The lowest daily flow since reservoir filling was considered too small for this analysis. In the current, degraded bed, a flow of 4,600 cfs would render infrastructure dependent on water surface elevation inoperable. The risk of low stages from this flow can’t be assumed sufficient to induce major rebuilds of water supply and power supply infrastructure, because that risk is present with current bed levels, yet the major infrastructure rebuilds have not occurred.

The other three values are more probable and reasonable. The lowest daily discharge since the 1993 flood includes the effects of the current practice of supplemental winter releases for water supply, whereas the lowest discharge since the 1993 flood in the MRBWM flow dataset does not. Releases during winter low-flow periods are not mandated by the Master Manual, although they have often occurred as needed for several years provided sufficient storage is available. The lower decile of non-navigation flows in the MRBWM flow dataset was selected as reasonable value. This is the value for which 10% of the daily flows in the non-navigation season are smaller. These values are 15,500 cfs, 17,100 cfs, and17,400 cfs at the St. Joseph, Kansas City, and Waverly gages, respectively. No averaging was needed for the water surface, as the water surface naturally smoothes out bed fluctuations. Figure 10 provides the low water surface profile projection from 2015 to 2065. The low water surface profile follows the same general trend as the bed. However, the water surface inherently averages change over a distance and responds more gradually to advancing headcuts than the bed, as seen in Figure 11 which compares low water surface change to bed change at a single cross section (River Mile 422.53).

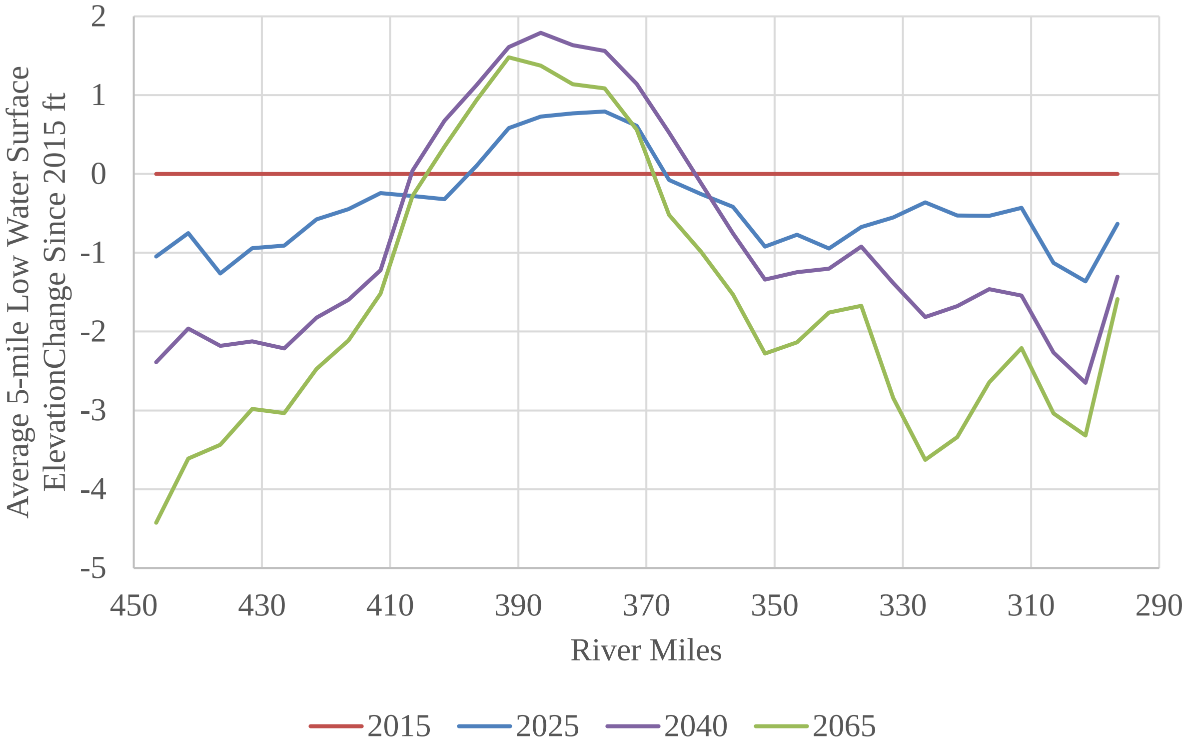

Figure 10. Change in Low Water Surface Profile

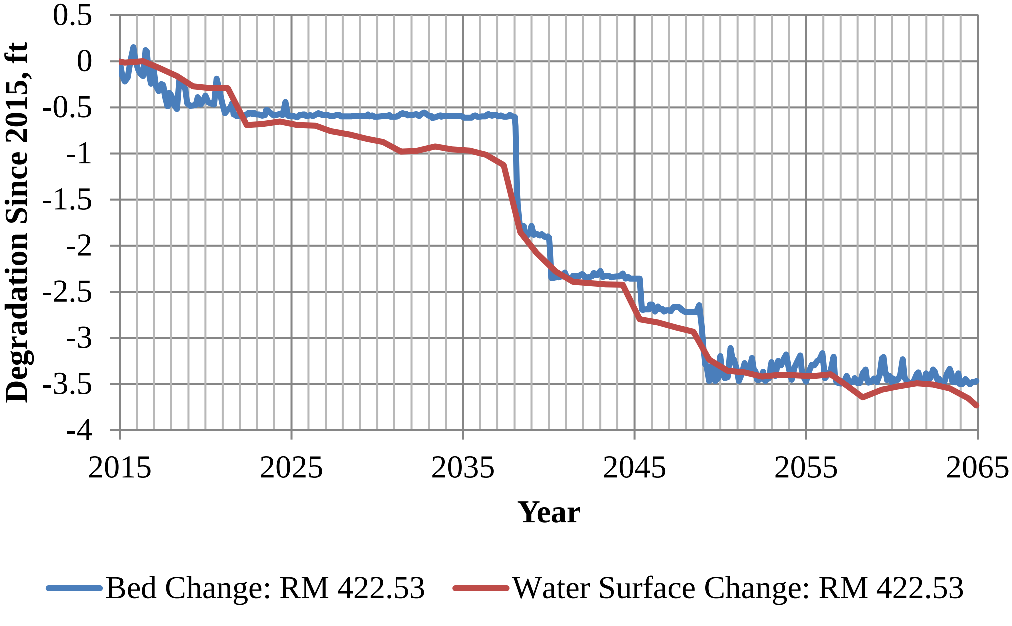

Figure 11. Comparison of Average Change in Water Surface and Bed Elevation at RM 422.53.

7.3 Future Without Project Bed Elevations in Historical Context

The previous figures presented bed and water surface change with respect to 2015. This section compares projected bed elevations to historic bed elevations, starting with the 1987 survey. Figure 12 plots the profile of the average bed from measurements in 1987, 1994, 2009, 2014, and the projected 2065.

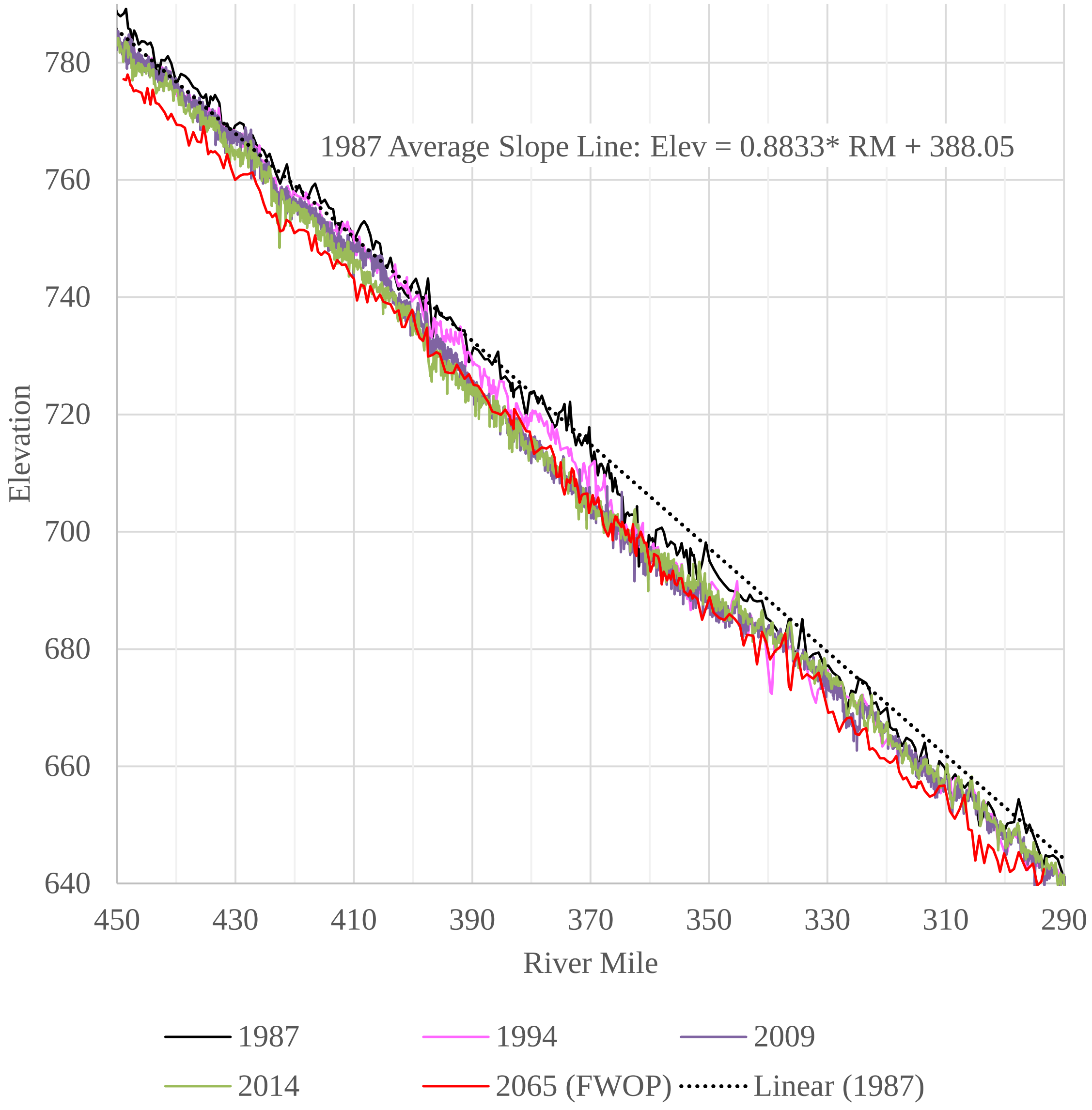

Figure 12. Average bed elevations in 1987, 1994, 2009, and 2014

Differences between surveys can be hard to detect in Figure 12 due to the large upstream-to-downstream elevation trend. Figure 13 presents the departure from the 1987 average slope line for each survey, which longitudinally de-trends the data. This removes the upstream to downstream elevation change in order to more clearly depict changes between surveys. Figure 13 shows that the upstream progression of degradation over time is projected to continue. The reach from RM 350 to 290 is also projected to degrade significantly. As demonstrated in Section 13 later in this appendix, this is caused by excessive commercial dredging (channel mining) in the Waverly segment. While slight recovery is projected, by the end of the 50-year simulation Kansas City remains in a highly degraded condition compared to historic bed elevations.

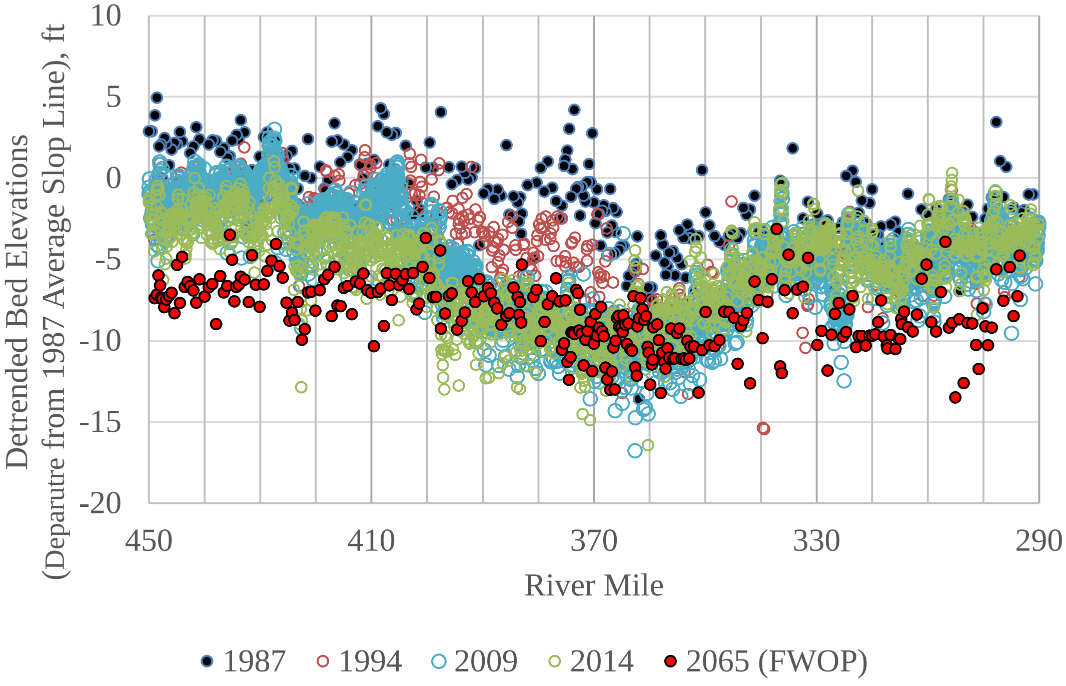

Figure 13. Spatially De-trended Average Bed Elevations

8. Temporary, Flood-related Degradation

The Missouri River Bed Degradation Reconnaissance Report (USACE 2009) indicates that major flood events on the Missouri River result in short-term bed scour that recovers to levels nearly consistent with the long-term trend of bed degradation. The Missouri River exhibited this behavior during the 1951, 1952, 1993, 2007, and 2011 flood events (USACE 2009, USACE 2015b). Analysis at the Kansas City gage indicates that this temporary, flood-related degradation occurs at flows higher than 220,000 cfs, which is between a 20% and 10% exceedance value (5 to 10 year flood). Figure 14 demonstrates this effect for the 1993 flood event, with the average bed elevations in the channel based on the hydraulic depth computed from USGS flow records.

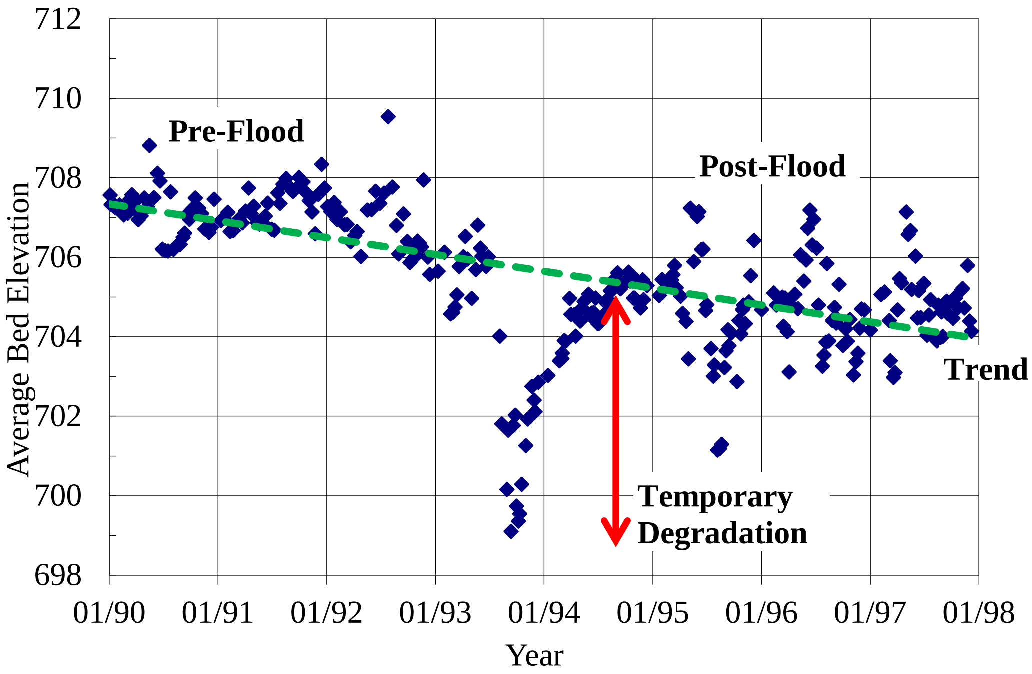

Figure 14. Temporary, flood-related degradation at the Kansas City Gage during the 1993 flood.

During the 1987, 1993, and 2007 high flow events, bed recovery lagged behind the end of the flood hydrograph by several months, i.e. the flood waters receded but the bed remained degraded. In less than 6 months the bed had recovered to the 3-year average bed. The 2011 flood event was unique in that during and post-flood, the watershed downstream of the dams contributed little water or sediment, which slowed bed recovery. Based on the cross section analysis, the bed recovery occurred over the course of three years.

During the 2011 flood event, the Kansas City District performed emergency stabilization of two revetments based on the temporary, flood-related degradation. This demonstrates expenditures resulting from temporary degradation for features that depend on the bed elevation.

On the other hand, there is no evidence of expenditures due to temporary, flood-related degradation for features such as the water intakes that depend on water level. Rather, this infrastructure depends on supplemental upstream releases to keep the water levels high until bed conditions normalize. Thus, damages for water surface dependent infrastructure are a function of persistent conditions (i.e. the long-term trend), not temporary degradation that can be mitigated with temporary, supplemental discharges. The owners of these infrastructure features did not take emergency action during or following the 2011 flood.

Figure 15 illustrates the temporary, flood-related degradation during the 2011 flood event at River Mile 448.13 (slightly downstream from the St. Joseph Gage). To compute the temporary degradation, the maximum degradation (2009 to 2011) is reduced by the permanent degradation (2009 to 2014) to yield the degradation that occurred but was not reflected in the long-term trend. This is equivalent to computing the maximum rebound, with the opposite sign (negative instead of positive). For example, at River Mile 448.13 the average bed elevation of the active channel was 782.12, 778.64, and 780.86 in 2009, 2011, and 2014, respectively. The maximum degradation = 778.64 ft – 782.12 ft= -3.48 ft. The permanent degradation = 780.86 ft – 782.12 ft = -1.26 ft. The temporary degradation = -3.48 ft + 1.26 ft = -2.22 ft.

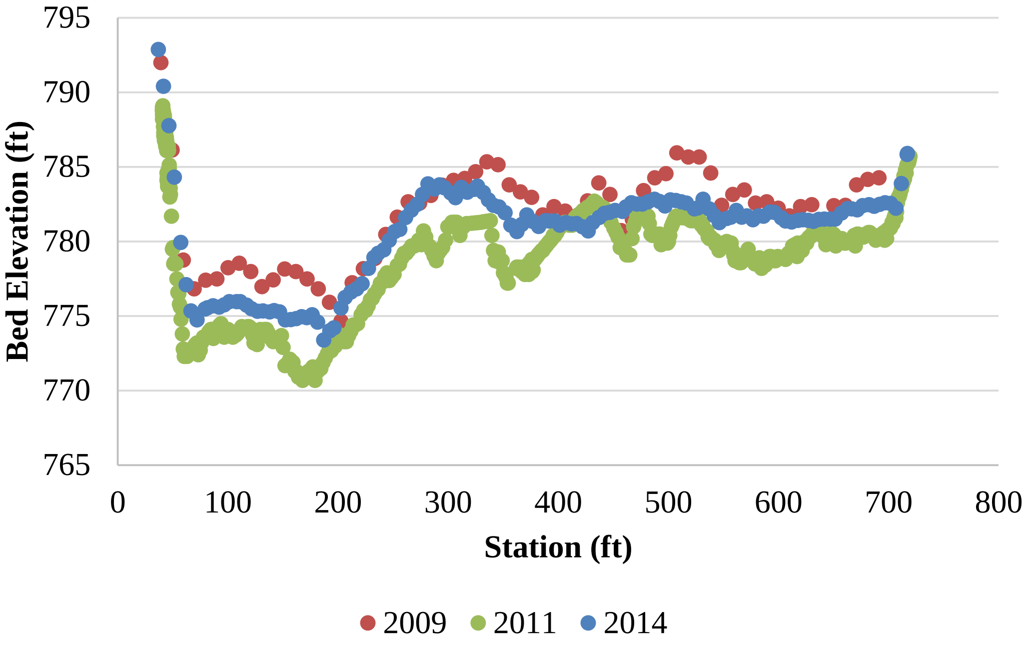

Figure 15. Cross-sectional measurements at RM 448.13 demonstrating temporary, flood-related degradation during the 2011 flood

Based on 2,125 paired bathymetric measurements taken in 2009, November of 2011, and 2014 (during, immediately after, and three years after the 2011 flood), the mean temporary bed change is -1.54 ft, with a range from -3.26 to +0.87 and a standard deviation of 0.86 ft. The mobile-bed model was calibrated to the long-term trend of bed degradation and does not fully reproduce the temporary, flood-related degradation and rebound. To compensate, the mean temporary degradation amount (-1.54 ft) is included as an offset from the long-term degradation projection in those years in the base case hydrologic series in which peak flow at Kansas City exceeds 220,000 cfs. This occurs in future simulation years 12, 16, 17, 23, 44, 45, and 50. Uncertainty in this value is factored into the overall uncertainty analysis, as explained below.

9. Risk and Uncertainty

The focus of the preceding analysis was to develop the base case Future Without Project scenario based on average boundary conditions and calibrated model parameters. However, the future bed and water surface elevations may be lower or higher than those predicted due to uncertainty in model predictions and uncertainty in future boundary conditions (flow, sediment, and dredging locations) which may differ from the average. The rest of this appendix documents sensitivity analysis and the development of *less degradation* and *more degradation* scenarios, following the guidance in EM 1619, adapted to the particulars of this study.

Standard of Practice

Sedimentation analysis may be undertaken in support of many different types of studies (dredging frequency studies, flood risk management studies, ecosystem restoration studies, litigation support, etc.) There is no universal, Corps-wide policy for handling risk and uncertainty in sedimentation studies for all cases, though the specific study which the sedimentation analysis is supporting may have requirements (as is the case for flood risk management studies). Corps analysis has utilized a myriad of approaches over the past several decades. The most common approach is sensitivity testing, in which the model inputs (typically flows and sediment loads) are increased or decreased by a set percentage and the results compared against the base case. Typically, the results from the sensitivity test have been stated separately, with no attempt to combine or propagate errors.

When sedimentation analysis is undertaken to inform a flood risk management analysis, uncertainty in sedimentation analysis and modeling can be included in a more standardized process to account for risk and uncertainty. This approach, outlined in EM 1619, combines hydrologic uncertainty with stage uncertainty and damage uncertainty to compute an overall annual expected damage. The Corps has developed the computer program HEC-FDA to facilitate this analysis. Sediment deposition can be included in the flow-stage uncertainty parameter in FDA.

While the Missouri River Degradation Feasibility Study is not a flood risk management study, the flood risk management approach was assessed for applicability and practicability.

Ultimately, the typical risk and uncertainty procedure used for flood risk management studies, which includes the software FDA, was decided against for the following reasons:

1- In consultation with HEC staff, it was determined that the current, certified version of FDA is insufficient to perform the required Annual Exceedance Probability analysis. A new version of FDA is forthcoming (release date unknown) that includes the needed functionality, but at the time of this study the needed model version is uncertified, not available on the HEC website, and not ACE-IT approved for installation.
2- The already approved one-time-use economic model for this study assesses single scenarios, not probabilities of exceedance. In order to interface with the economic model, a base case, less degradation, and more degradation scenario is needed. The approval documentation for the one-time-use econ model is provided in Appendix P.
3- Computational tools are not available for facilitating the computation of uncertainty in sediment transport modeling and its contribution to non-flood-related damages. For example, damages assessed in the Degradation Study are related to low flows or are tied to bed elevations which, while a function of the cumulative history of flows, are largely independent of the flow rate on the day the damage occurs.

That said, the principles of risk and uncertainty are important for guiding the selection of a robust alternative in the Degradation Study. In order to provide a *less degradation* and *more degradation* scenario for use in the economic model, the sensitivity analysis approach was combined with the equations in Engineering Manual 1619 to compute and combine uncertainties. This was done by the following equation: (which mirrors Equation 5-5 in EM 1619):

For low water surface dependent features (water supply intakes, power supply intakes, etc.):

$$S_{t,ws} = \sqrt{S_{wsdeg}^2 + S_{Qseries}^2 + S_{sed}^2 + S_{fp}^2 + S_{dredgelocs}^2}$$

For bed elevation dependent features (revetments, levee toes, etc.):

$$S_{t,bed} = \sqrt{S_{beddeg}^2 + S_{Qseries}^2 + S_{sed}^2 + S_{fp}^2 + S_{dredgelocs}^2 + S_{temp}^2}$$

where

S_t represents the total standard deviation of the uncertainty including both model uncertainty and boundary condition variability in the water surface or bed.

Sws_{deg} represents the standard error of estimate for the minimum water surface elevation in a given year. As described earlier in this appendix, the standard errors at the St. Joseph and Kansas City gages, giving an equal weight to the calibration time period and the single-year verification time period with the updated model, are 0.57 ft and 0.56 ft, respectively. For purposes of computing a composite standard deviation, 0.57 ft is used everywhere. Note that this parameter integrates uncertainties in model parameters (such as Manning 'n' values, bathymetry, flow/load relationship, bed gradations, and transport function) into a single standard deviation.

S_{beddeg} represents the standard error of estimate for bed elevation predictions, adjusted to account for natural bed fluctuations. Changes in bed elevations between 2008 and 2009, years without major flooding, provide an estimate of natural variability (USACE 2015). The model bed uncertainty can be computed using the following equation:

$$S_{beddeg} = \sqrt{R^2_{Model-Measured} - R^2_{2008-2009}}$$

where $R_{model\text{-}measured}$ = the average bed residual between the modeled and measured bed elevation change from 1994 to 2009; and $R_{2008\text{-}2009}$ = the average absolute bed elevation change between measured cross sections in 2008 and 2009. $R_{model\text{-}measured}$ = 2.00 and $R_{2008\text{-}2009}$ = 1.29, yielding S_{beddeg} = 1.53. Note that this parameter integrates uncertainties in model parameters (such as Manning 'n' values, bathymetry, flow/load relationship, bed gradations, and transport function) into a single standard deviation.

$S_{Qseries}$ represents the standard deviation of degradation predictions due to uncertainty in the next 50 years of daily flows which may differ from the base case. This is not hydrologic uncertainty as described in EM 1619; the historical record is assumed to completely describe the flow probability without uncertainty. Five series of 50 years of flow are synthesized based on a Monte Carlo analysis with 999 potential 50-years of flows. How this was done is explained in Section 10 below. The range of these projections is divided by 4 to yield $S_{Qseries}$.

S_{sed} represents the standard deviation of degradation predictions due to the future flow/load relationship departing from the average relationship over the calibration period. The sediment load is increased to +10% and decreased to -20% over 50 years to provide a range of flow/load conditions. The range of these projections is divided by 4 to yield S_{sed}.

S_{fp} represents the standard deviation of degradation predictions due to uncertainty in the volume of floodplain deposition. The floodplain deposition included in the model was varied from 50% to 150% of the base case. The range of these projections is divided by 4 to yield S_{fp}.

$S_{dredgelocs}$ represents the standard deviation of degradation predictions due to changes in the locations of dredging within each authorized dredging reach. Three scenarios were considered: the 2013 locations, the 2014 locations, and the base case which is an average of all locations from 2010 to 2015. The range of these projections is divided by 4 to yield $S_{dredgelocs}$.

S_{temp} represents the additional bed elevation uncertainty in the future bed elevation projection due to temporary bed degradation that may be higher or lower than the average during those years when flows exceed 220,000 cfs. As explained earlier in this document, based on 2,125 paired bathymetric measurements taken in 2009, November of 2011, and 2014 (during, immediately after, and three years after the 2011 flood), the standard deviation of temporary degradation = 0.86 ft. This uncertainty is included in the years that sufficiently high floods occur to induce the temporary degradation (model years 12, 16, 17, 23, 44, 45, and 50.)

10. Uncertainty due to Future Flow Series

A series of flows (and associated sediment) with a 50% probability of exceedance for the cumulative volume of transported bed material at the end of 5, 10, 25, and 50 years was used as the base case. However, degradation projections for 50-year series of flows that transport more or less sediment are also relevant for understanding potential future bed and low water surface elevations. The procedure used to develop the FWOP base case was followed to develop four additional flow series scenarios to represent a reasonable range of potential future flow series. These scenarios have the following exceedance probabilities for cumulative volume of bed material transported: 1%, 25%, 75%, and 99 (see Figure 16). These flow scenarios were developed from the Monte Carlo analysis of 999 potential 50-years of flow following a similar procedure as described in the FWOP base case. Table 6 lists the flow years that comprise each flow series. Figure 17 presents the curves for cumulative volume of bed material transported for the statistically-defined scenarios plotted with the curves for the first 240 of 999 random flow scenarios.

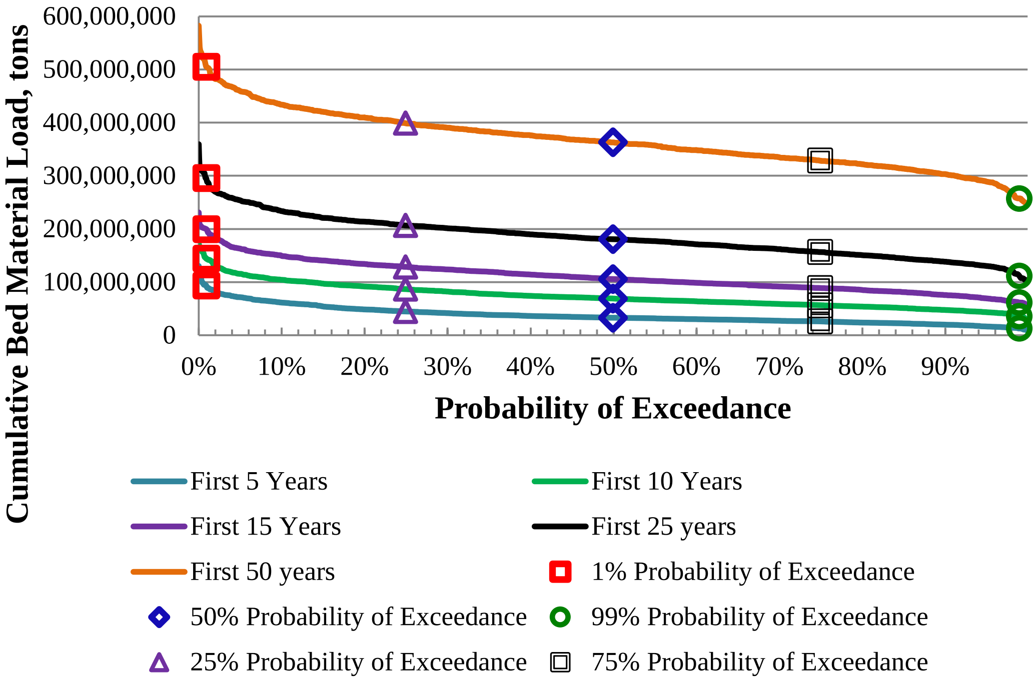

Figure 16. Cumulative volume of bed material transported with percent exceedance probability

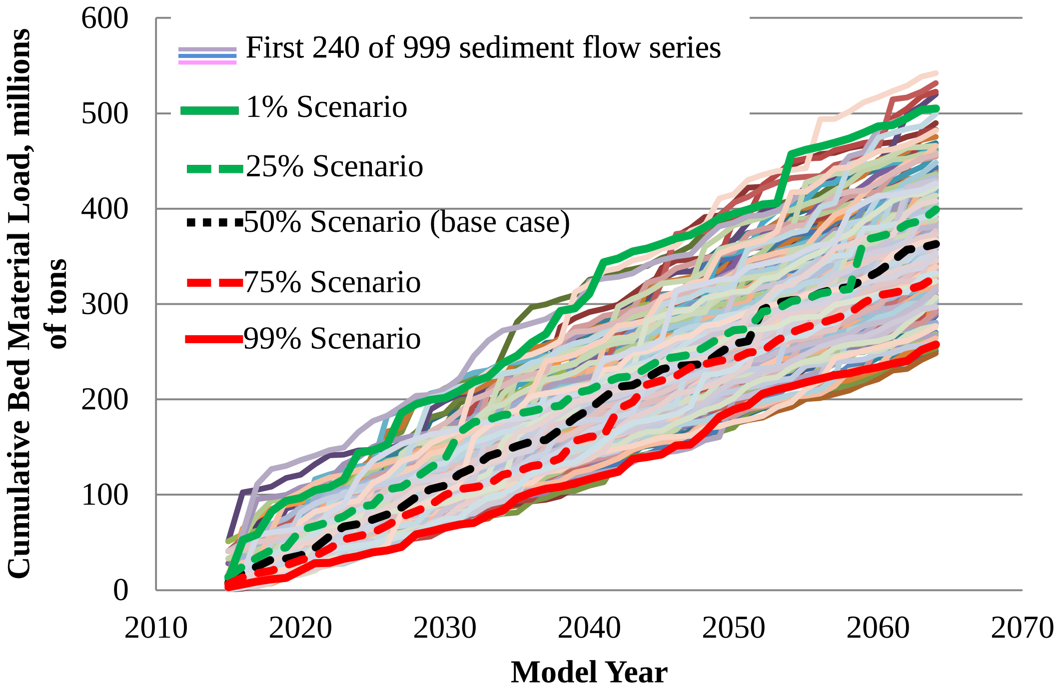

Figure 17. Cumulative volume of bed material transported over time for various flow series

Table 6. Series of flow/sediment years used in sensitivity analysis

Model Year	1%	25%	50% (base case)	75%	99%	Model Year	1%	25%	50% (base case)	75%	99%
1	1987	1984	1900	1972	1969	26	1996	1907	1979	1923	1962
2	2011	2009	2009	2002	1907	27	1952	1921	1997	1937	1922
3	1924	2008	1972	1962	1965	28	1931	1943	1917	1916	1967
4	1985	1903	1900	1992	1958	29	1908	1934	1956	1921	1909
5	2009	1992	1939	1929	1934	30	1902	1979	1970	1988	2007
6	1907	1988	1933	1959	1910	31	1959	1953	1979	1949	1955
7	1930	1914	1950	1923	1900	32	1943	2007	1927	1962	2008
8	2005	1978	1997	1966	1941	33	1991	1992	1935	1953	1935
9	1910	1951	1961	1983	1976	34	1945	1970	1956	2005	1904
10	1916	1983	1955	1926	1965	35	1953	1953	1917	1915	1974
11	1992	1958	1973	1914	1931	36	1919	1903	1953	1942	1908
12	1924	1974	1925	1908	1964	37	1977	1934	1901	2002	1973
13	1952	1965	1921	1948	2006	38	1981	1988	1952	1942	1975
14	1948	1983	1918	1924	1904	39	1912	1989	2002	1999	1976
15	1919	2009	1945	1906	2005	40	1994	1968	1954	1968	2005
16	2007	1945	1960	1961	1936	41	1949	1990	1938	1924	1977
17	1921	1916	1997	1986	1915	42	2006	1943	1921	1922	1922
18	1953	2009	2002	2004	1912	43	1931	1958	1967	1978	2006
19	1995	1990	1980	1958	1903	44	1913	1932	1947	1924	1932
20	1984	1944	1981	1961	1973	45	1924	1994	1930	2009	1936
21	1930	1957	1995	1901	1904	46	1986	1907	1966	1910	1982
22	1984	1969	1973	1911	1929	47	1942	1949	1917	1958	1914
23	1979	1936	1942	1990	1931	48	1921	1948	1975	1902	1927
24	1985	2007	1917	2010	1964	49	1905	2001	2007	1919	1917
25	1965	1904	1975	1988	2006	50	1956	1980	1922	1948	1943

Figure 18 compares projected bed elevation change at the end of simulation under the five different flow scenarios listed in Table 5. All other parameters are as specified in Table 4. As risk and uncertainty automation tools are not available for HEC-RAS sediment modeling, each flow of the five scenarios was manually parameterized and run.

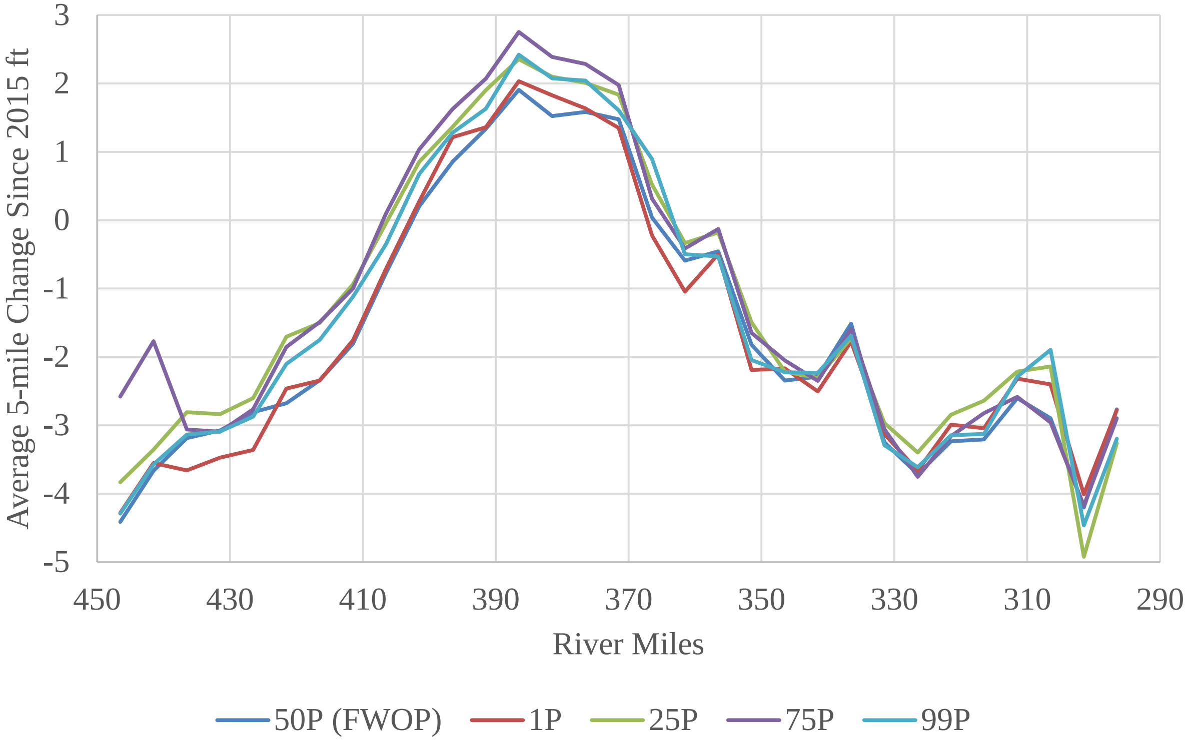

Figure 18. Bed degradation projections under five flow scenarios as of 2065

As seen in Figure 18, all scenarios follow the same basic trend, but the magnitude of future degradation depends on the flow series used. The relative rankings do not predict the amount of bed material computed a priori for each scenario. Rather, the scenario resulting in the most or least degradation differs depending on the location. $S_{Qseries}$ = the range from the highest to lowest of the degradation projections divided by 4, as indicated by Equation 5-7 in EM1619. $S_{Qseries}$ varies both spatially and temporally. The spatial distribution is given by the range of model outputs for each location and is computed in 5-mile increments. The temporal trend is simplified by assuming that $S_{Qseries}$ grows linearly to the maximum value by year 50.

11. Uncertainty in the Flow/Load Relationship

The Future Without Project base case projection assumes the relationship between flow and incoming sediment load between 1994 and 2009 continues to be valid over the next 50 years. This relationship was developed as a long-term average relationship and was an important calibration parameter. In some years, the actual annual sediment load may be higher or lower than the calibrated relationship, which would lead to an over- or under-estimation of bed elevations. Likewise, the daily sediment load on any given day may be higher or lower than the average, calibrated relationship. The uncertainty in bed elevations caused by these deviation from the calibrated flow/load relationship is reflected in the standard deviation of error, S_{beddeg} and S_{wsdeg} and need not be included again.

However, it is possible for the flow/load relationship to experience a systemic shift or trend. Analysis by David Heimann at USGS (Heimann 2016) suggests that the Missouri River has been experiencing an overall decreasing trend in sediment transport beginning with the construction of major dams. Recent data, however, indicates that the trend may have stopped. Figure 19 plots flow vs sediment concentration at the St. Joseph Gage for 2004 to 2015. As expected, higher flows generate a higher concentration of suspended sediments. Figure 20 displays the ratio of the measured concentration to the best-fit line in Figure 19 to examine if there is a trend with time independent of the flow rate. As seen, the recent data is essentially flat. An exponential trend line fit through the data and extrapolated for 50 years suggests a potential for a 6% decrease in sediment concentration by the end of 50 years.

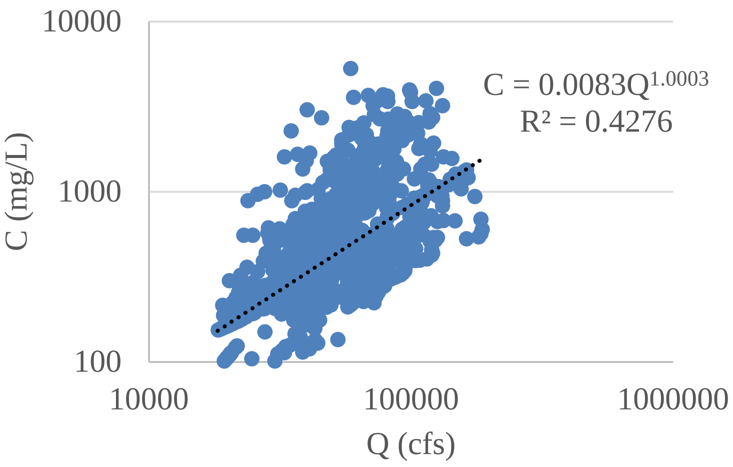

Figure 19. Flow vs. concentration at the St. Joseph Gage, 2004 to 2014

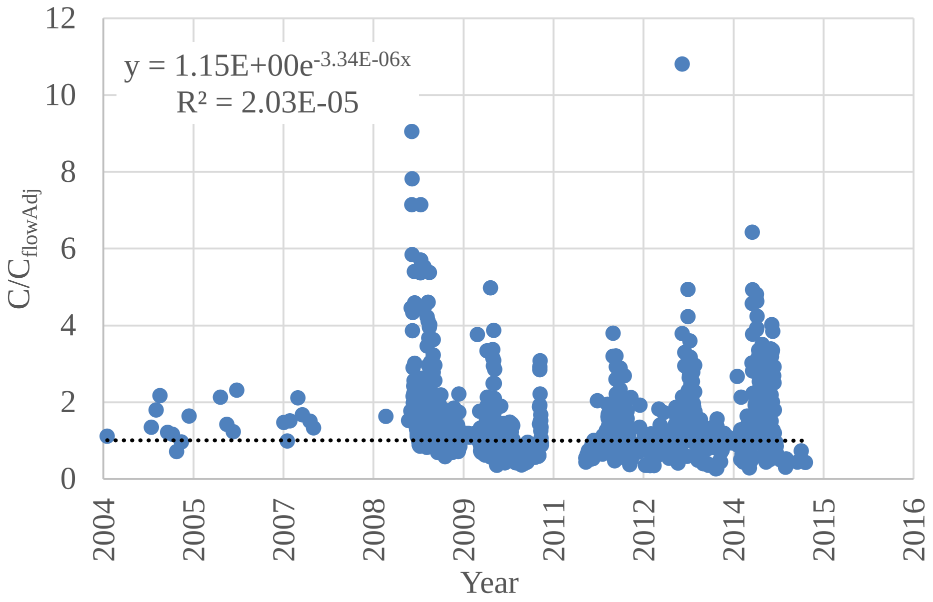

Figure 20. Flow-adjusted Concentration Ratio over Time

Historic data does not support an increase in the sediment load over time. However, climate change, sediment bypass on upstream dams, or other unknown factors could increase the sediment load.

As a conservative estimate, the sediment load was gradually varied to achieve a 20% decrease or 10% increase in sediment loads achieved by the end of the 50-year simulation (a 10% decrease and 5% increase on average.) As indicated in Figure 21, physical changes in the flow/load relationship can have large effects on the rate of degradation. S_{sed} = the range from the highest to lowest of the degradation projections divided by 4, as indicated by Equation 5-7 in EM1619. S_{sed} varies both spatially and temporally. The spatial distribution is given by the range of model outputs for each location and is computed in 5-mile increments. The temporal trend is simplified by assuming that S_{sed} grows linearly to the maximum value by year 50.

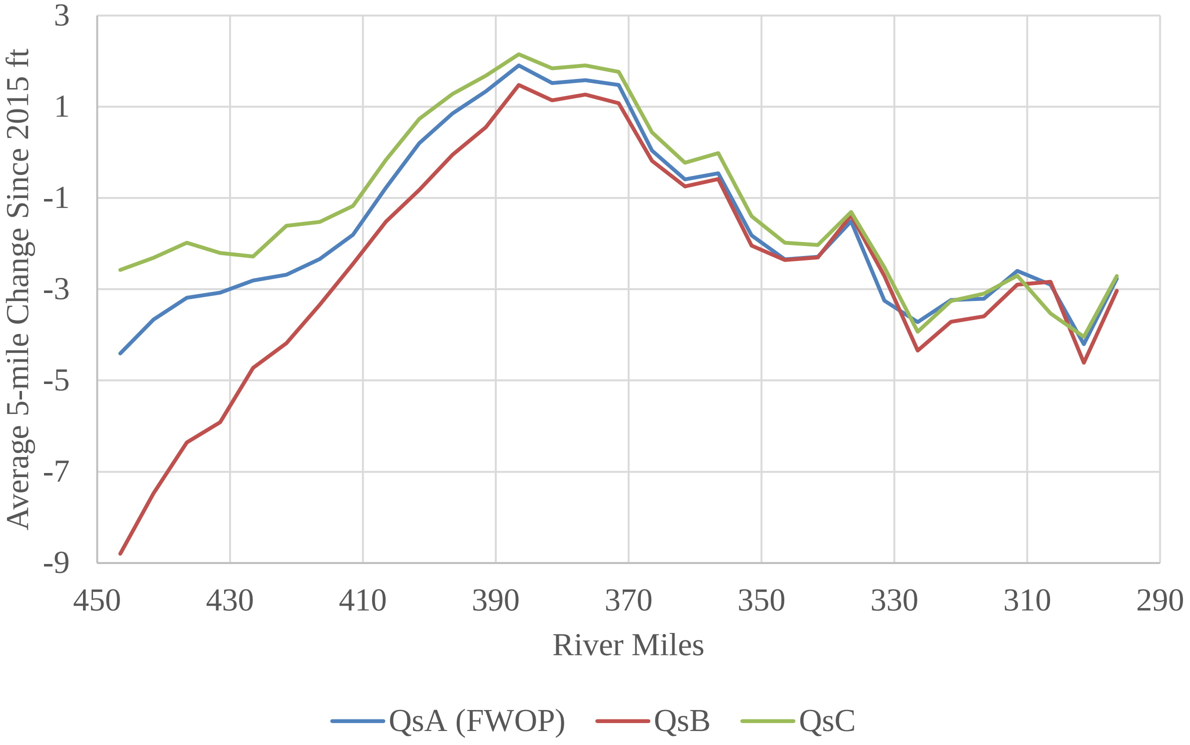

Figure 21. Bed degradation projections under three sediment load scenarios

12. Sensitivity to Floodplain Deposition

As explained in the Model Calibration appendix, sediment loss due to floodplain deposition during the 2011 event was included as 2 ft times the planimetric area of sand deposition based on a USGS report (Alexander et. al, 2013). In the report, the 2 ft deposition depth was stated as a reasonable minimum detection threshold for area of deposition. Uncertainty exists in the areal extent of deposition, the depth of deposition, the size gradation of deposition, and in the similarity of future floodplain deposition events to the 2011 floodplain deposition. As a surrogate for these sources of uncertainty, the volume of floodplain deposition was increased to 150% and decreased to 50% of the amount included in the base case, which equates to from 2 to 6% of the incoming sediment load at St. Joseph. The locations and timing (during high flows) were identical as the base case, with only the volume of floodplain deposition varying. The results of this sensitivity analysis indicate that the future bed degradation levels are relatively insensitive to variations in floodplain deposition between 50 and 150% (see Figure 22).

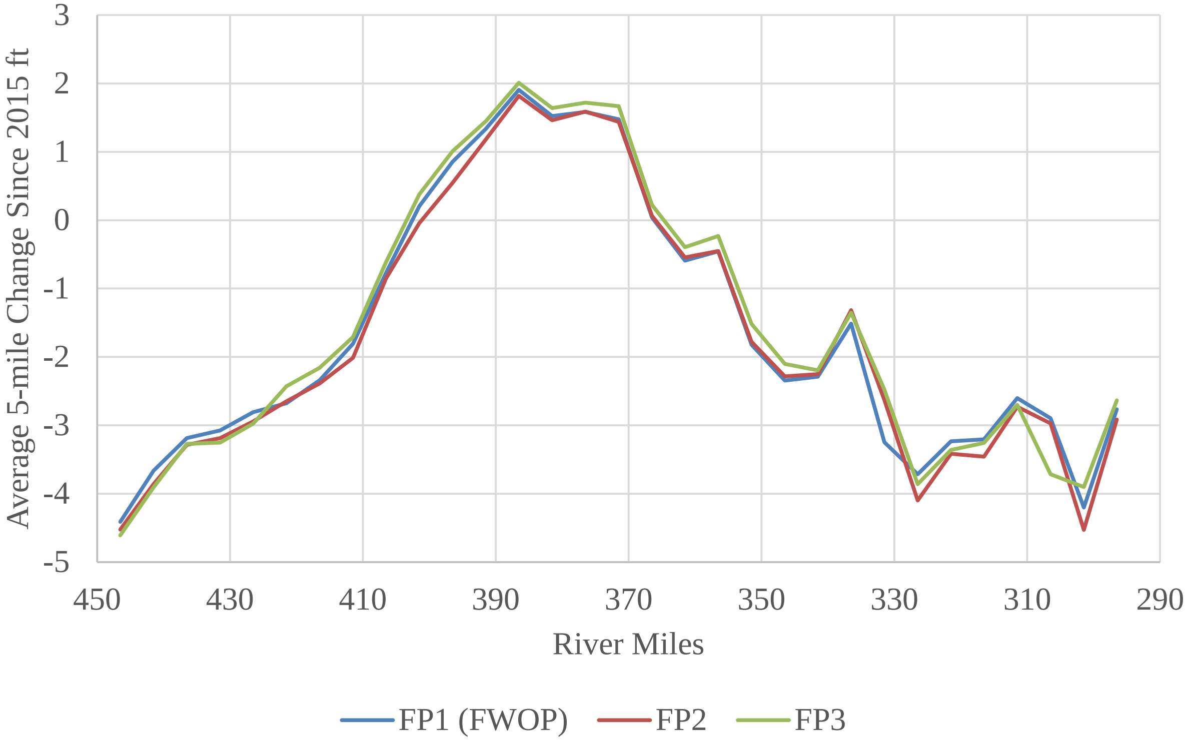

Figure 22. Bed degradation projections under three floodplain deposition scenarios

Two additional formulations for approximating future floodplain deposition were also tested which scale by sediment load on the days with flow above the threshold. The first scales the 2011 deposition amount by the total suspended load (computed via a long-term rating curve) for days with flow above the threshold. The total floodplain deposition over 50-years using this method summed to 4.5 million tons, which is 81% of the modeled method and within the +/-50% tested in the sensitivity analysis. Another method tested was 100% of the suspended sand load for days above the flow threshold. This equates to 105% of the modeled method, which is within the +- 50% tested in the sensitivity analysis. While the floodplain deposition parameter is highly uncertain and is important for modeling individual flood events, long-term results are highly insensitive to the range of floodplain deposition events likely to occur. S_{fp} is assumed constant in time and set to the end-of-simulation value.

13. Sensitivity to Dredging

The Missouri River Bed Degradation Reconnaissance Report (USACE 2009) and the Missouri River Dredging Environmental Impact Statement (USACE 2011) identify commercial sand and gravel extraction (commercial dredging) of the Missouri River as a significant contributor to bed degradation. Moreover, a sediment budget analysis using measured bed change from bathymetric surveys indicates that the Missouri River would have been rebounding following the 1993 flood rather than degrading, were in not for the high level of dredging (USACE 2015b).

Commercial dredging was included in the calibration period at historic levels as described in the Model Calibration Appendix. Commercial dredging for the FWOP base case is based on the December 2015 permitted level of commercial dredging. However, actual levels of commercial dredging in the future will depend on a myriad of factors including future local demand for construction materials, competition from alternate sources such as floodplain pit mines, regulatory actions, judicial actions, and the business decisions of the owners and operators of a small number of commercial dredging companies.

In this appendix, sensitivity to commercial dredging is assessed three ways, (1) The calibration time period (1994 to 2014) is re-run with the dredging set to zero, (2) The 50-year projection period is run with dredging levels set to multiples of the December 2015 permitted levels (0, 50%, 100%, and 150%), and (3) The future locations of dredging are varied.

Effect of Dredging During the Calibration Period (1994 – 2014)

As an initial assessment of the impact of commercial dredging on bed elevations in the Missouri River, the calibration model was re-run with all dredging set to zero (including both commercial dredging and Corps of Engineers dredging for the L385 levee). The results of this model run were compared to the calibration run which included dredging to isolate the effects that sand and gravel dredging has had on bed degradation since 1994. The results of this analysis are shown in Figure 23.

As seen in Figure 23, the sand and gravel dredging from 1994 to 2014 for River Miles 293 to 449 caused substantial additional degradation when compared to the zero-dredging model run. With dredging, the total degradation equaled 40.3 million tons, compared to 13.4 million tons of bed recovery without dredging. Thus, 60.8 million tons of dredging induced 53.7 million tons of degradation compared to the “no dredging” scenario. Stated differently, 1 ton of dredging extracted resulted in 0.88 tons of persistent bed loss compared to the “no dredging” scenario. The Model No Dredging line in Figure 23 indicates aggradation rather than degradation from River Mile 387 to 330, which encompasses Kansas City. This modeling suggests that in the absence of dredging, Kansas City would not have degraded over this time period, notwithstanding the historic flood of 2011. This agrees with the sediment budget analysis provided in USACE (2015) which concluded that the river would have been in a recovery phase post-1993 flood were in not for the level of dredging that occurred. Figure 23 indicates that slight degradation would still have occurred from the Platte River confluence (River Mile 391) upstream due to the effects of the 2011 flood and upstream migration of the headcut that had formed prior 1994.

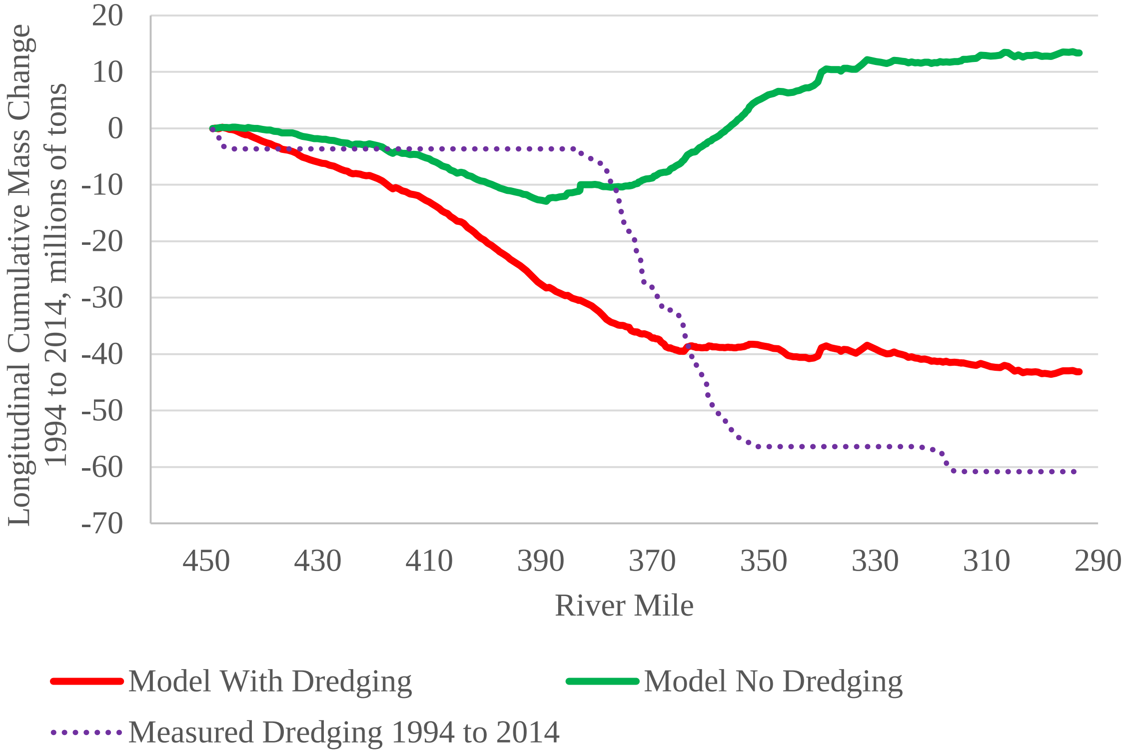

Figure 23. Effects of Sand and Gravel Dredging from Aug 1, 1994 to 29 July, 2014 on Longitudinal Cumulative Mass Change

Figure 24 presents model output for mean effective invert change from 1994 to 2014, with and without dredging. Each point on Figure 24 represents the bed elevation change at a model cross section. The bed recovery seen in the "Model Without Dredging" scenario is roughly equal to the amount of bed degradation observed between 1987 and 1994. This suggests that in the absence of dredging, the river would have recovered to approximately pre-1993 flood levels in Kansas City by 2014.

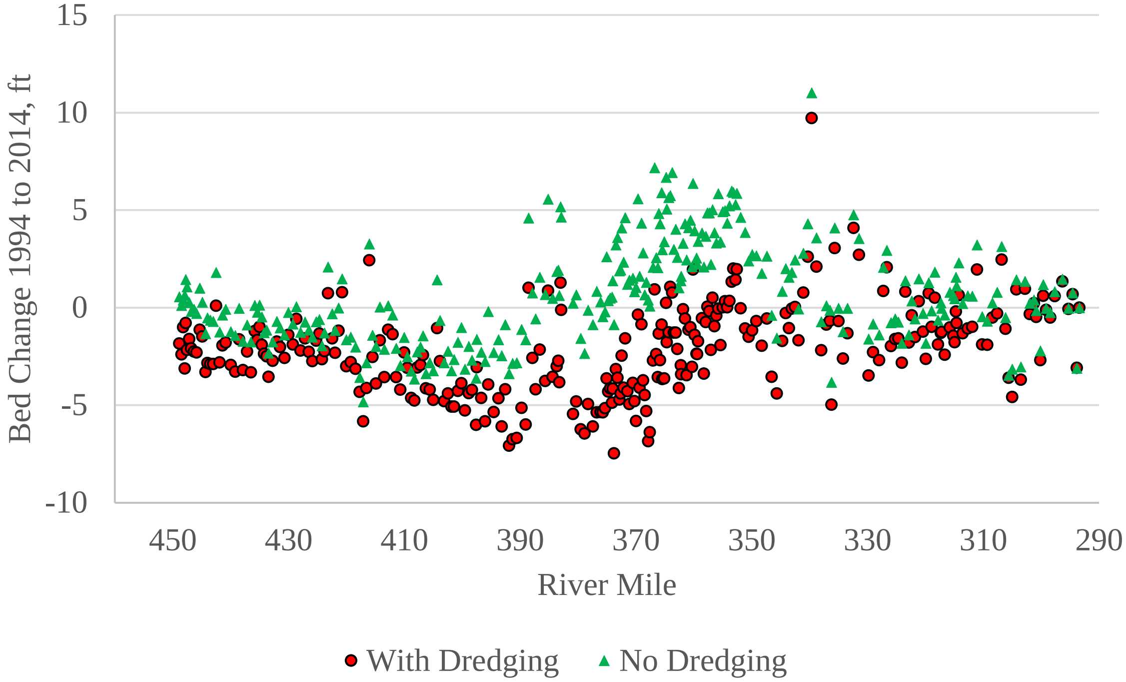

Figure 24. Effects of Sand and Gravel Dredging from Aug 1, 1994 to 29 July, 2014 on Bed Elevations

Effect of Dredging During the Projection Period (2015 – 2065)

The effect that dredging has on future projections (2015 to 2065) was assessed by running forward the updated model (bathymetry and dike elevation updates as described in this document) under four different dredging conditions. The dredging conditions modeled for this analysis include the permitted level as of December 2015, 150% of the permitted level, 50% of the permitted level, and a "No Dredging" scenario. The reach limits are those defined in the 2011 dredging EIS (USACE 2011). The distribution of dredging within each dredging reach was assigned according to historic locations of dredging from 2010 to 2015, as described earlier in this appendix. Note that in the Waverly reach, dredging included in the model is slightly less than the full permitted allotment because some of the Waverly reach dredging historically occurs outside of the model domain. All dredging for the St. Joseph and Kansas City reaches were assumed to occur within the model domain.

Table 7. Dredging Amounts (tons/year) Used in Dredging Sensitivity Analysis

EIS Dredging Reach	150% of Base Case	Base Case (Dec 2015 Permitted Dredging)	50% of Base Case	No Dredging
St. Joseph (RM 391 to 498)	495,000	330,000	165,000	0
Kansas City (RM 357 to 391)	810,000	540,000	270,000	0
Waverly (RM 250 to 357)	2,595,647	1,730,431	865,216	0

Figure 25 presents the bed degradation under the four different dredging conditions at the end of 50 years. The level of commercial dredging has a significant impact on the magnitude of bed change over every 5-mile reach. The differences between the 150% of base case and No Dredging levels range from 2.9 to 8.9 ft, with an average difference of 5.7 ft. A comparison between Figure 25 and Figure 13 indicates that the level of bed recovery seen in Kansas City in the “No Dredging” scenario is slightly less than the level of degradation experienced from 1987 to 2014. This suggests that even in the absence of future dredging, the river bed in Kansas City will recover, but will not have fully attained pre-1993 levels by the end of 50 years.

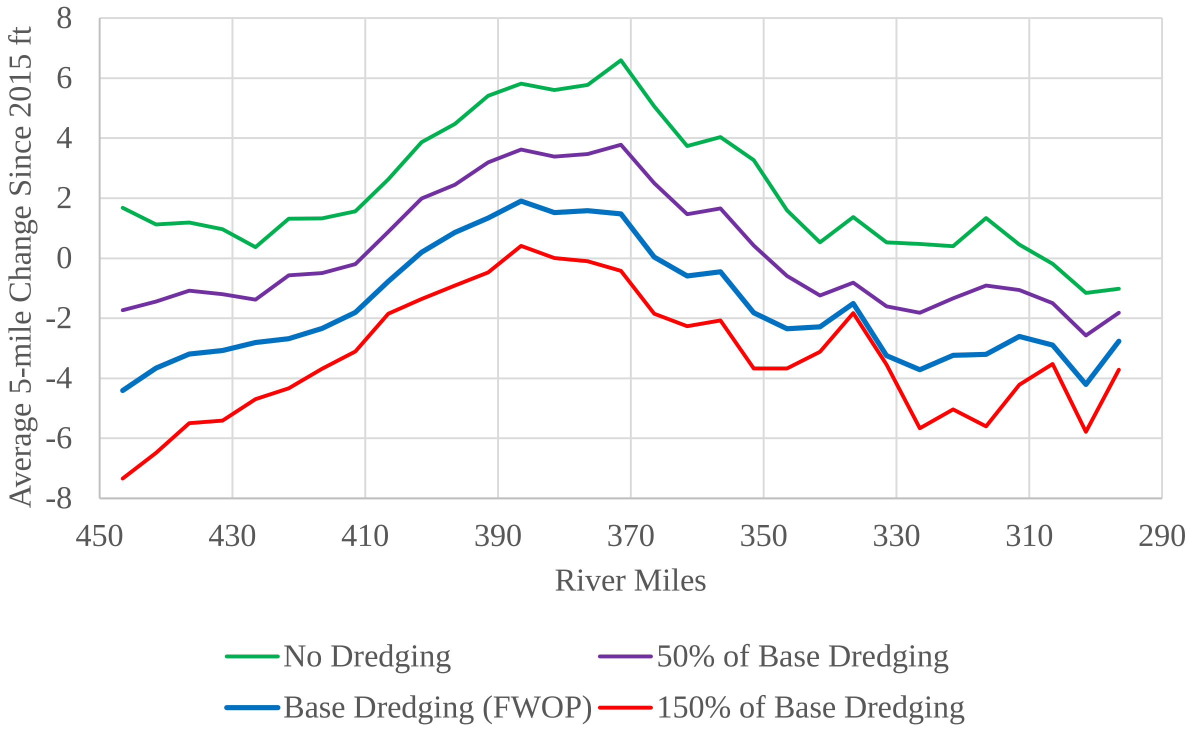

Figure 25. Bed degradation projections under four dredging scenarios

Figure 26 plots the total mass of bed material change compared to the mass of bed material extraction via dredging. As seen, there is a strong relationship between the volume of material extracted and the bed change. The only difference among the model runs is the level of dredging, indicating a causal relationship between dredging and degradation. This analysis suggests that without dredging, the reach of the river included in the model domain (St. Joseph to Waverly) would recover at a rate of approximately 1,200,000 tons/year. Figure 26 suggests that a dredging level around 1.5 million tons/year would result in no net bed change overall. A dredging level at slightly higher than the “No Dredging” recovery rate is possible due to geomorphic feedbacks. While most of the dredging translates directly into bed degradation, some of it translates into less transport out of the model reach at Waverly, MO. Figure 25 indicates that 1.5 million tons/year (between the 50% and the Base Case) would still induce degradation near St. Joseph, MO compared to both the existing condition and the “No Dredging” future condition. The strongly-causal relationship between dredging and degradation highlights the need to include dredging restrictions in formulating alternatives for slowing or stopping degradation, rather than just in the computation of uncertainty.

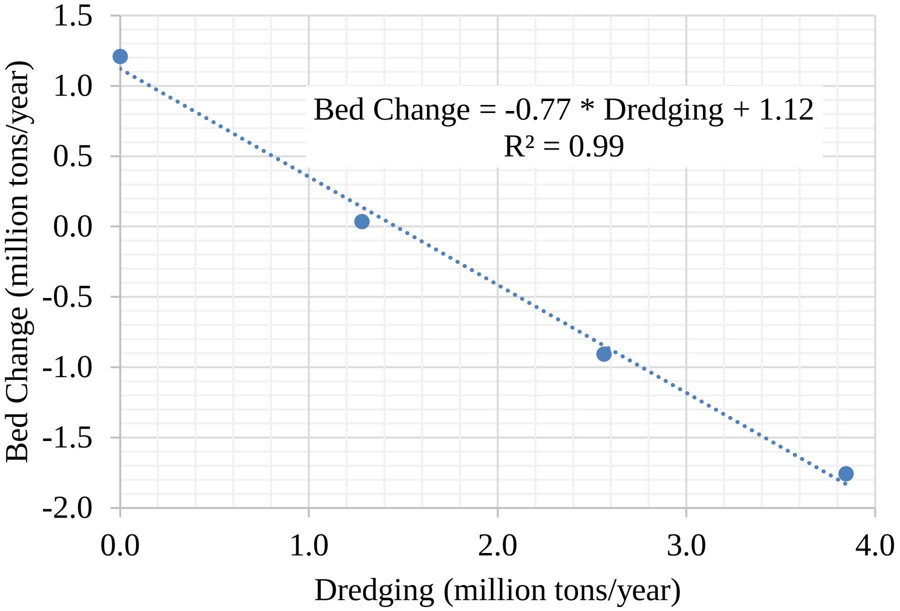

Figure 26. Relationship between dredging and degradation between St. Joseph and Waverly, MO. Relative magnitudes among dredging reaches correspond to the December 2015 permitted amount and recent historical locations of dredging.

Effect of Dredging Locations During the Projection Period (2015 – 2065)

In the preceding analyses, the dredging was spatially distributed in each dredging reach according to the locations of dredging from 2010 to 2015. This results in a slightly more distributed (i.e. less concentrated) dredging pattern than in any specific year, but a more representative distribution over 50 years. Restrictions in the dredging permits, including no-dredge buffers around infrastructure and concentration limits as well as the economic incentive to minimize transport distance to the dredgers' unloading facilities limit the variability from year to year.

Two additional model runs demonstrate the sensitivity and compute additional uncertainty due to the within-reach distribution of dredging. These runs include dredging with the spatial distribution of a specific year (2013 and 2014, respectively) repeated each year in the 50-year scenario. The volume of dredging in each dredging reach is equivalent in both runs, but the distribution of dredging within the reach varies. As seen in Figure 27, the variability in the output is greatest towards the downstream end of the model, which corresponds to the Waverly dredging reach. More than one company operates in the Waverly reach, which results in greater inter-annual variability. $S_{dredgelocs}$ = the range / 4 for each five mile reach. This within-reach variability is included in the propagated uncertainty.

Figure 27. Bed degradation projections under within-reach spatial distributions of dredging

14. Composite Standard Deviation

Table 8 presents the individual standard deviations at the end of 50 years. S_{deg} is constant in time, S_{temp} is included in flood years, and $S_{Qseries}$, S_{sed} , and $S_{dredgelocs}$ are assumed to grow linearly to the maximum values presented in Table 8. The $S_{t,\ bed}$ and $St,_{wse}$ values are added or subtracted to the base case to create the *less degradation* and *more degradation* scenarios.

Boundary condition uncertainty, particularly changes in the sediment loading, most affect the upstream end of the model. For example, if less sediment enters the model the relatively clear water satisfies its excess capacity by degrading the bed upstream. This excess sediment adds to the sediment load downstream, which partially offsets the decrease in sediment load and mutes differences among sensitivity testing model runs. Furthermore, the most downstream cross section in the model has a fixed elevation which may dampen the differences among sensitivity runs downstream. $S_{t,\ bed}$ is larger than $St,_{wse}$ because it includes S_{temp} and because it includes S_{beddeg} instead of $S_{deg,wsdeg}$.

Table 8. Uncertainty Components at the End of 50 Years

US	DS	S_{wsdeg}	S_{beddeg}	$S_{Qseries}$	S_{sed}	$S_{dredgelocs}$	S_{temp}	$S_{t,bed}$	$S_{t,wse}$
449	444	0.57	1.46	0.66	1.62	0.04	0.86	2.72	1.72
444	439	0.57	1.46	0.54	1.37	0.05	0.86	2.49	1.49
439	434	0.57	1.46	0.45	1.13	0.05	0.86	2.21	1.25
434	429	0.57	1.46	0.47	0.97	0.04	0.86	2.09	1.10
429	424	0.57	1.46	0.46	0.76	0.06	0.86	1.82	0.86
424	419	0.57	1.46	0.52	0.76	0.06	0.86	1.72	0.89
419	414	0.57	1.46	0.42	0.57	0.06	0.86	1.63	0.76
414	409	0.57	1.46	0.37	0.46	0.13	0.86	1.58	0.69
409	404	0.57	1.46	0.32	0.49	0.06	0.86	1.59	0.70
404	399	0.57	1.46	0.31	0.30	0.04	0.86	1.63	0.72
399	394	0.57	1.46	0.24	0.35	0.03	0.86	1.61	0.69
394	389	0.57	1.46	0.28	0.45	0.03	0.86	1.59	0.66
389	384	0.57	1.46	0.28	0.36	0.05	0.86	1.56	0.63
384	379	0.57	1.46	0.22	0.32	0.06	0.86	1.56	0.63
379	374	0.57	1.46	0.25	0.32	0.04	0.86	1.55	0.62
374	369	0.57	1.46	0.22	0.36	0.08	0.86	1.55	0.62
369	364	0.57	1.28	0.28	0.35	0.15	0.86	1.57	0.67
364	359	0.57	1.28	0.23	0.26	0.09	0.86	1.54	0.61
359	354	0.57	1.28	0.13	0.20	0.06	0.86	1.54	0.60
354	349	0.57	1.28	0.20	0.21	0.04	0.86	1.55	0.62
349	344	0.57	1.28	0.10	0.14	0.04	0.86	1.53	0.58
344	339	0.57	1.28	0.03	0.17	0.05	0.86	1.53	0.58
339	334	0.57	1.28	0.35	0.30	0.23	0.86	1.54	0.58
334	329	0.57	1.28	0.35	0.18	0.06	0.86	1.58	0.64
329	324	0.57	1.28	0.11	0.24	0.12	0.86	1.57	0.60
324	319	0.57	1.28	0.13	0.29	0.15	0.86	1.56	0.61
319	314	0.57	1.28	0.24	0.32	0.21	0.86	1.56	0.63
314	309	0.57	1.28	0.16	0.38	0.17	0.86	1.55	0.60
309	304	0.57	1.28	0.23	0.16	0.20	0.86	1.58	0.67
304	299	0.57	1.28	0.15	0.11	0.11	0.86	1.58	0.65
299	294	0.57	1.28	0.07	0.24	0.11	0.86	1.55	0.60

15. Output to Economic Model

Output to the economic model includes a base case, *less degradation*, and *more degradation* estimate at each infrastructure feature, for both the bed and the low water surface, for each year from 2015 to 2065. The same uncertainty is used for all the alternatives as was computed for the FWOP, a simplification that is more accurate for the alternatives with channel mining restrictions and BSNP changes (Alts 1A, 1B, 1C, 4A, 4B, and 4C), but less accurate for the alternatives with grade control (5A, 5B, 5C).

For the water surface elevation, the base case = the minimum model elevation for each year interpolated from the two bounding cross sections. The *more degradation* scenario = the base case - $S_{t,ws}$ at the infrastructure location for the year. The *less degradation* scenario = the base case + $S_{t,ws}$ at the infrastructure location for the year.

For bed elevations, the base case = the minimum bed elevation output for each year interpolated from the two bounding cross sections. The *more degradation scenario* = the base case - $S_{t,bed}$. The *less degradation scenario* = the base case + $S_{t,bed}$. An additional offset for flood-related degradation is subtracted from the base case in years when flow at Kansas City exceeds 220 kcfs. The *more degradation* scenario includes this offset in every year (high flows could happen in any year, not just the years included in the FWOP) and the *less degradation* scenario does not include the offset in any year.

Figure 28 shows the output provided to the economic model for the bed-dependent feature at RM 352.7. Similar output is provided for each bed-dependent infrastructure feature of interest and at even river miles (for computing the effects on BSNP revetments).

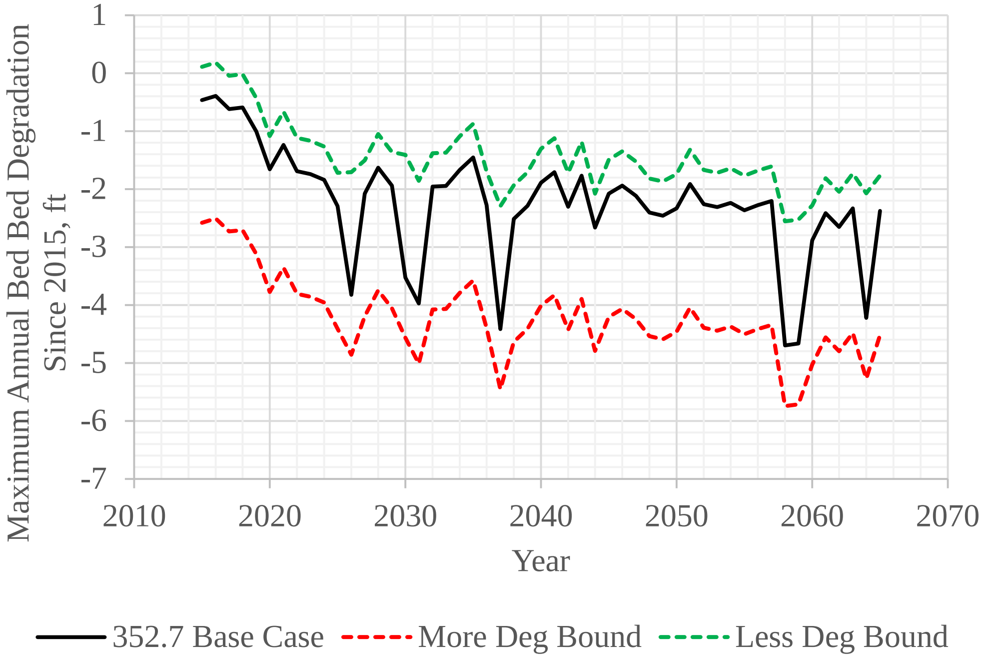

Figure 28. Bed elevation projection at RM 352.7

Figure 29 shows the output provided to the economic model for the water-dependent feature at RM 425.71. Similar output is provided for each water-dependent infrastructure feature of interest, at even river miles (for computing the effects on BSNP dike lowering) and at the mouth of each tributary.

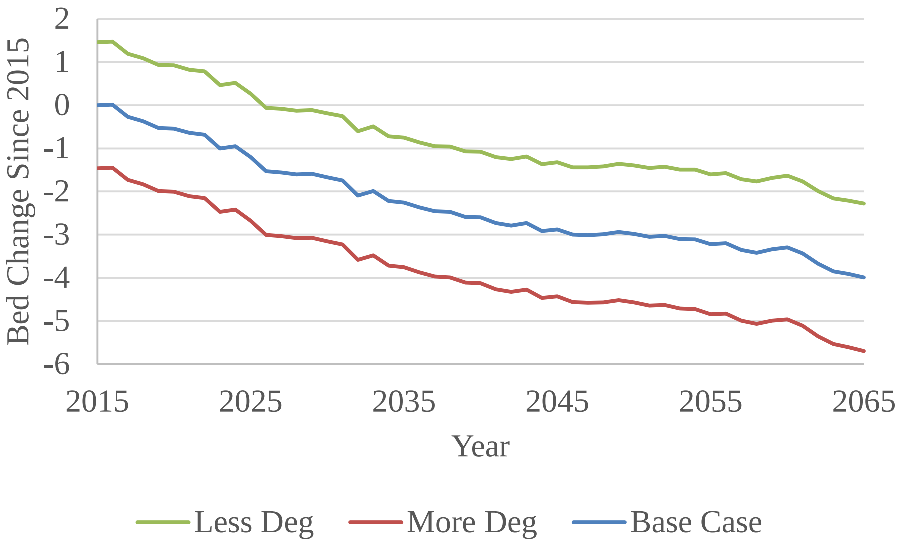

Figure 29. Water surface elevation change projection at RM 425.71

16. Conclusion

This technical appendix documented the development of Future Without Project bed and water surface projections, including a base case plus *less degradation* and *more degradation* scenarios. Channel bathymetry and structure heights were updated to 2014 conditions. For the base case, the future hydrologic input was developed based on the 50% sediment exceedence probability at Kansas City and the sediment rating curve was as calibrated from 1994 to 2014. The future dredging condition was set to the December 2015 permitted levels with the locations of dredging corresponding to the 2010 to 2015 locations. Floodplain deposition in the projection time period was scaled from deposition during the 2011 flood event.

Long-term degradation was found to be very sensitive to the level of commercial sand and gravel dredging (channel mining). The model indicates that without dredging, the Missouri River in Kansas City would have recovered to approximately pre-1993 flood levels, rather than degrading from 1994 to 2014. Moreover, the future bed elevations depend, in large measure, on the level of commercial dredging. As commercial dredging is a human action permitted by the Corps of

Engineers, changes to allowable sand and gravel extraction are included in the project alternatives rather than in the uncertainty analysis.

A standard deviation of uncertainty was computed for the bed and water surface by combining model uncertainty (computed via the root mean square of the error) and boundary condition uncertainties (computed from the sensitivity analysis). Output to the economic model for bed elevation includes the base case model projection plus an adjustment to account for temporary, flood-related degradation in years with flows above 220 kcfs. L*ess degradation* and *more degradation* scenarios were computed by adding or subtracting the combined standard deviation to the base case.

17. References

Alexander, J.S., Jacobson, R.B., and Rus, D.L. (2013), Sediment transport and deposition in the lower Missouri River during the 2011 flood: U.S. Geological Survey Professional Paper 1798–F, 27 p., http://dx.doi.org/10.3133/pp1798f.

USACE (2009). Missouri River Bed Degradation Reconnaissance Study Section 905(b) (Water Resources Development Act of 1986) Analysis. U.S. Army Corps of Engineers, Kansas City District. Kansas City, MO.

USACE. (2011a). *Record of Decision for Authorization of Commercial Sand and Gravel Dredging on the Lower Missouri River.*

USACE. (2011b). *Final Environmental Impact Statement for Missouri River Commercial Dredging.*

USACE. (2013). Technical Report - Hydrologic Statistics, September 2013. Missouri River Basin Water Management Division, Omaha, Nebraska. http://www.nwd-mr.usace.army.mil/rcc/reports/pdfs/MRBWMTechReport-HydrologicStatistics_September2013.pdf .

USACE (2015a). Missouri River Bed and Water Surface Changes between 2009 and 2014 as They Relate to Renewal of Commercial Dredging Permits under Section 404 of Clean Water Act and Section 10 of the Rivers and Harbors Act (Section 404/10 Permits). Memorandum for CENWK-OR-R. July 14, 2015. U.S. Army Corps of Engineers, Kansas City District.

USACE (2015b). A Sediment Budget Approach to Stable Dredging Levels on the Lower Missouri River, 1994 to 2014. Memorandum for CENWK-OR-R. October 2, 2015. U.S. Army Corps of Engineers, Kansas City District.