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Technical Assessment of the Old, Mississippi, Atchafalaya, and Red (OMAR) Rivers: Mississippi River Multi-Dimensional Model

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Technical Assessment of the Old, Mississippi, Atchafalaya, and Red (OMAR) Rivers

Mississippi River Multi-Dimensional Model

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Abstract

This report is part of the (OMAR) Assessment (defined herein), intended to provide a comprehensive assessment of the interconnected Mississippi, Red, and Atchafalaya Rivers, and the potential results of various changes. This report details the multi-dimensional modeling efforts undertaken to characterize the hydrodynamic and morphodynamic response of the Mississippi River to both the existing configuration and to various proposed operational, dredging, and structural scenarios.

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Preface

The investigation documented in this report was conducted for the US Army Corps of Engineers, Mississippi Valley Division (MVD), as part of the Mississippi River and Tributaries Project, under Project Number 478534, and published through the Mississippi River Geomorphology and Potamology (MRG&P) Program. At the time of publication of this report, the MRG&P program director was Dr. James W. Lewis. The MVD commander was MG Diana M. Holland, and the MVD director of programs was Mr. Edward E. Belk.

The work was performed by the River and Estuarine Engineering Branch of the Flood and Storm Protection Division, US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory (ERDC-CHL). At the time of publication of this report, Mr. David P. May was chief of the River and Estuarine Engineering Branch, and Dr. Cary A. Talbot was chief of the Flood and Storm Protection Division. The deputy director of ERDC-CHL was Mr. Keith Flowers, and Dr. Ty V. Wamsley was the director.

The commander of ERDC was COL Christian Patterson, and the director was Dr. David W. Pittman.

1 Introduction

The US Army Corps of Engineers (USACE) conducted the Old River, Mississippi River, Atchafalaya River and Red River (OMAR) Assessment, under the authority of the Mississippi River and Tributaries (MR&T) Program (Investigations) to gain a more comprehensive technical understanding of the system and to develop pertinent information regarding its operation and management. The vision of the OMAR Assessment was a desire to maintain a sustainable sediment management plan for the interconnected river system and to sustain and maintain a viable MR&T system now and into the future.

The “Old River” in OMAR refers to the Old River Control Complex (ORCC), which consists of both the Old River Control Structure (ORCS) (consisting of three separate diversion structures: Overbank, Low Sill, and Auxiliary) and the Sidney A. Murray, Jr., Hydroelectric Plant (consisting of one diversion structure, the Hydropower Structure). Each of these structures is depicted in Figure 3.

Note that the ORCS is a federal project whereas the Hydropower Structure is a privately owned entity. This is the reason for the distinction in the definitions. The convention used throughout this report is to use ORCS to refer to the federally owned assets at ORCC, as distinguished from the Hydropower facility.

The OMAR Assessment accomplished the following:

- Evaluated operations at ORCC, with a focus on the Mississippi and Atchafalaya Rivers.
- Determined the current volume of sediment and water passing through ORCC, including potential adjustment to those volumes.
- Assessed if the operation of the structures at ORCC required an adjustment in flow and sediment, now and/or in the future, to maintain the authorized purpose of the ORCS, including, but not limited to, if necessary, an adjustment in the allocation of flow to the Sidney A. Murray, Jr., Hydroelectric Plant and its impact on, and capability for, sediment distribution.
- Provided an opportunity to gain a better understanding of the transport of water and sediment throughout the ORCC to inform

management options for addressing sediment deposition and flood risk on the Mississippi River, support water control operations, and evaluate how various operational changes at ORCC could impact the entire system.

- Ensured that any future adjustment to the current operation of the ORCC will be informed using the best available engineering and science.

Several charge questions were identified by the Executive Steering Council for the OMAR Assessment. The charge questions that the multi-dimensional model study, Mississippi River side (Task 4 of the OMAR Assessment) were to aid in answering were the following:

1. How much sediment is currently being diverted through the ORCC?
2. What are the impacts of sedimentation on the operation of the ORCC and the Morganza Structure?
3. How much sediment could be diverted by USACE operations (i.e., the ORCS) if the Hydroelectric Station were not operated?
4. How can water control operations be optimized to improve sediment transfer based on improved understanding of water flow and sediment transport in the system?
5. How much sediment must be diverted to bring the Mississippi River at the ORCC into dynamic equilibrium?
6. What are the long-term impacts (i.e., change in flowline) above and below the ORCC on the Mississippi River for the various operational and dredging management options evaluated? (The flowline is herein defined as the hydraulic grade line along the river corresponding to the project design flood.)
   a. Operational management options to be evaluated were based on technical operational constraints of the various structures and include scenarios that maintain the present 70/30 flow split as well as scenarios that modify the flow split.
   b. Dredging management options to be evaluated will include discharge downstream in the Mississippi River as well as discharge to bypass sediment to the Atchafalaya through the ORCC Outfall Channel and will consider continuous versus episodic dredging.
7. Are there potential structural solutions on either side of the ORCC that could facilitate sediment transport through the system?

This effort is a part of the overall OMAR Assessment. Table 1 lists the series of reports associated with the overall project, with this report listed in bold font.

Table 1. List of reports included in the overall project.

Vol.	Report Name	Description
1	Main Report	Summarizes the entire project assessment
2	Geomorphic Assessment	Analyzes the historic trends in hydrology, sedimentation, and channel geometry of the river reaches of interest
3	Channel Geometry Analysis	Analyzes the hydrographic surveys over the past 6 to 7 decades
4	Mississippi River HEC-6T Model	Evaluate the long-term and system-wide sedimentation effects on the Mississippi River
5	Atchafalaya River HEC-6T Model	Evaluate the long-term and system-wide sedimentation effects on the Old, Atchafalaya, and Red Rivers
6	**Mississippi River Multi-Dimensional Model**	Evaluate the short-term effects on the Mississippi River
7	Red and Atchafalaya Rivers AdH Model	Evaluate the short-term effects on the Old, Atchafalaya and Red Rivers
8	HEC-RAS Model	Investigate how water is stored in the Lower Red River floodplain
9	HEC-RAS BSTEM Analysis of the Atchafalaya River	Compare the relative impact of various scenarios on bank retreat in the upper portion of the Atchafalaya River

1.1 Background

This study has been preceded by multiple studies of the ORCC. The most recent of these was a study involving multiple disciplines, to investigate the influence of the ORCC on Mississippi River morphology and to investigate potential changes to operations that could be employed to increase the amount of sediment diverted (Heath et al. 2015). This report also includes a detailed discussion of previous studies of the ORCC and the conclusions associated with those studies.

1.2 Objective

The objective of this study is to perform multi-dimensional model analysis of the Mississippi River response to both existing ORCC operations and to various scenarios involving operational changes and other changes. This work was done in fulfillment of Task 6, as given in Table 1.

1.3 Approach

The Old River Complex Authorization in the Flood Control Act of 1945 mandates that the ORCS maintain a 70/30 split of flow (i.e., transfer 30% of the *latitude* flow [i.e., the combined Mississippi River and Red River flows] to the Atchafalaya River). Any changes to these authorized proportions require a technical assessment of the effects of the alteration to the hydrodynamic and sediment behavior of the Mississippi River and the ORCC. The OMAR Assessment technical team recommended that the analysis consider a High (2008), a Typical (2013), and a Low (2012) water year (WY). Further, the team recommended that the WYs should be simulated independently such that determinations can be made for every alternative under consideration for each WY analyzed. The technical team selected these WYs based on several factors including annual water and sediment yield, hydrograph shape, and operations at the ORCC. The recommended years span the normal range of the estimated annual sand yields at Tarbert Landing and have relatively typical hydrographs.

The technical team used data from multiple years along with steady state simulations for the validation of the Adaptive Hydraulics (AdH) model. Details of these data are discussed in the report.

1.4 Scope

The technical work presented in this report includes a discussion of the numerical model, a review of the efforts used to validate the model for hydrodynamics and sediment transport, and a detailed analysis of multiple operational, dredging, and structural scenarios at the ORCC. The conclusions address the charge questions presented in the introduction, and how the results of the scenario analysis can inform them.

2 Adaptive Hydraulics (AdH) Hydrodynamic and Sediment Modeling and Validation

2.1 Model description

2.1.1 Adaptive Hydraulics (AdH) and SEDLIB

AdH is a finite element model that is capable of simulating three-dimensional (3D) Navier Stokes equations, two-dimensional (2D) and 3D shallow water equations, and groundwater equations. AdH can be used in a serial or multiprocessor mode on personal computers, UNIX, Silicon Graphics, and CRAY operating systems. For this study, AdH is applied in 2D shallow water depth-averaged mode.

The adaptive aspect of AdH is its ability to dynamically refine the mesh in areas where more resolution is needed at certain times due to changes in the flow and/or transport conditions. AdH can simulate the transport of conservative constituents, such as dye clouds, as well as sediment that is coupled to bed and hydrodynamic influences. The ability of AdH to allow the domain to wet and dry as the river stage changes is important in accurately simulating the Mississippi River as it can possess vastly different flow rates and water levels.

SEDLIB is a sediment transport library developed at the US Army Engineer Research and Development Center (ERDC) (Brown 2012a,b). It is capable of solving problems consisting of multiple grain sizes, cohesive and noncohesive sediment types, and multiple bed layers. SEDLIB calculates erosion and deposition processes simultaneously and simulates such bed processes as armoring, consolidation, and discrete depositional strata evolution.

The SEDLIB library system is designed to link to any appropriate hydrodynamic code. The hydrodynamic code must be capable of performing advection diffusion calculations for a constituent. SEDLIB interacts with the parent code by providing sources and sinks to the advection diffusion solver in the parent code. The solver is then used to calculate bedload and suspended load transport for each grain class. The sources and sinks are passed to the parent code via an explicit bed sediment flux for each grain class.

These tools have been developed at the ERDC Coastal and Hydraulics Laboratory (CHL) and have been used to model sediment transport in such varied environments as the Mississippi River, tidal conditions in southern California, and vessel traffic in the Houston Ship Channel.

2.1.2 AdH/SEDLIB contributions to the study

The AdH/SEDLIB sediment model contributes several important capabilities to the current study, including the following:

- Quasi-3D flow and transport formulations, which use analytical and semi-empirical methods to approximate the 3D character of the flow and sediment transport phenomena (Brown 2008, 2012a).
- The ability to model the impact of helical flow through a river bendway on the water velocity, and the suspended load and bedload sediment transport, by utilizing the bendway vorticity transport algorithm given by Bernard (1992).
- The SEDLIB module is equipped to simulate multi-grain class suspended load and bedload sediment transport phenomena. It is also equipped to handle generalized multi-grain class bed processes, including armoring, sorting, erosion to a solid boundary, and the storage of discrete depositional strata.
- The unstructured model mesh employed by AdH permits very high resolution in areas of interest and high-fidelity resolution of shoreline geometry.

2.2 Model application history

The model application developed for this study has a long history of development for several studies. This history is briefly recounted here.

- The original AdH/SEDLIB model was developed for a study of the ORCC (Heath et al. 2015). This study focused on an analysis of the existing operations and included some scenario analyses to investigate the potential for changes to operations. The Optimization scenario discussed in the 2015 report was adopted as an aspirational operational scenario for the ORCC. The model domain extended from Red River Landing to The Homochitto River.

- The model was next used in support of the Mississippi River Hydrodynamic and Delta Management study (Brown et al. 2018). For this study, the model domain was extended down to the Gulf of Mexico.
- The model was then used in support of a morphologic study of the Mississippi River from Natchez to Baton Rouge (Leech et al. 2018). For this study, the model was truncated downstream to have a boundary at Baton Rouge and extended upstream to Natchez.
- The model was then used in 2018 for a further study of the ORCC. These results have not been previously published.
- Finally, the model is being used again for the present study.

For each of these efforts, separate validation efforts were undertaken. The details of these efforts can be obtained from those reports. The efforts for the unpublished 2018 study and the present effort are documented in this report. Note that the model configuration for the 2018 effort was used for the present effort, so the verification results are germane to this study.

2.3 Model creation

The AdH model used for this effort covered a reach of the Mississippi River from Natchez, MS, to Baton Rouge, LA, and included the main channel and the batture between the main line levees. Figure 1 and Figure 2 show the study extents, with important features identified and contours of model bathymetry/topography. Figure 3 and Figure 4 show the study focus area, with important features identified and contours of model bathymetry/topography. Water flow is schematically depicted in Figure 3 with blue arrows to illustrate how the ORCC structures divert flow. The element mesh resolution is shown in Figure 4.

The model bathymetry was established using Mississippi River channel condition surveys and airborne lidar data. The model vertical and horizontal datum were NAVD88 and Louisiana State Plane South Meters, respectively.

Figure 1. Study area extents with important features identified.

Figure 2. Study extents with mesh bathymetry/topography.

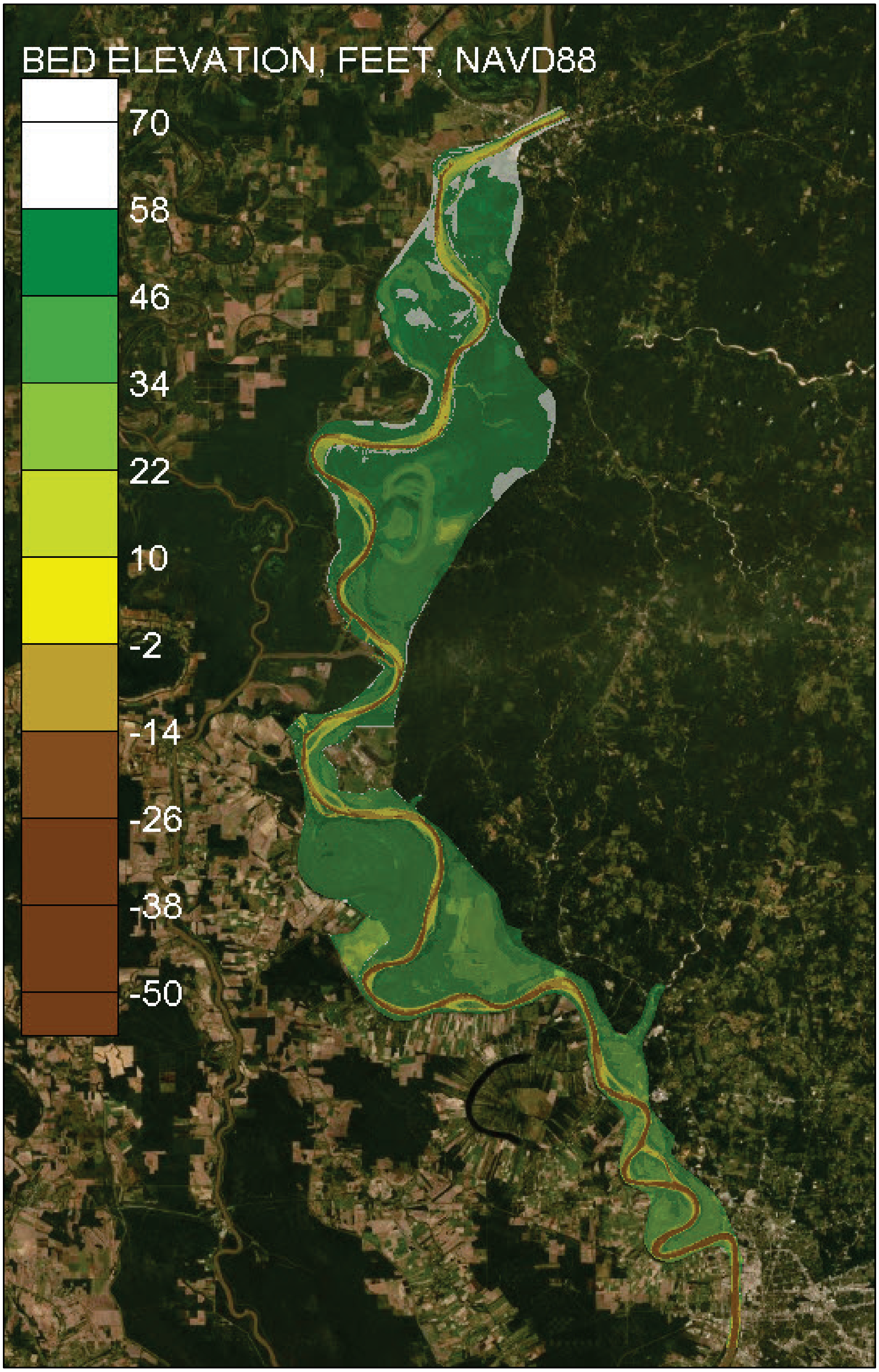


Figure 3. Study focus area with important features identified.

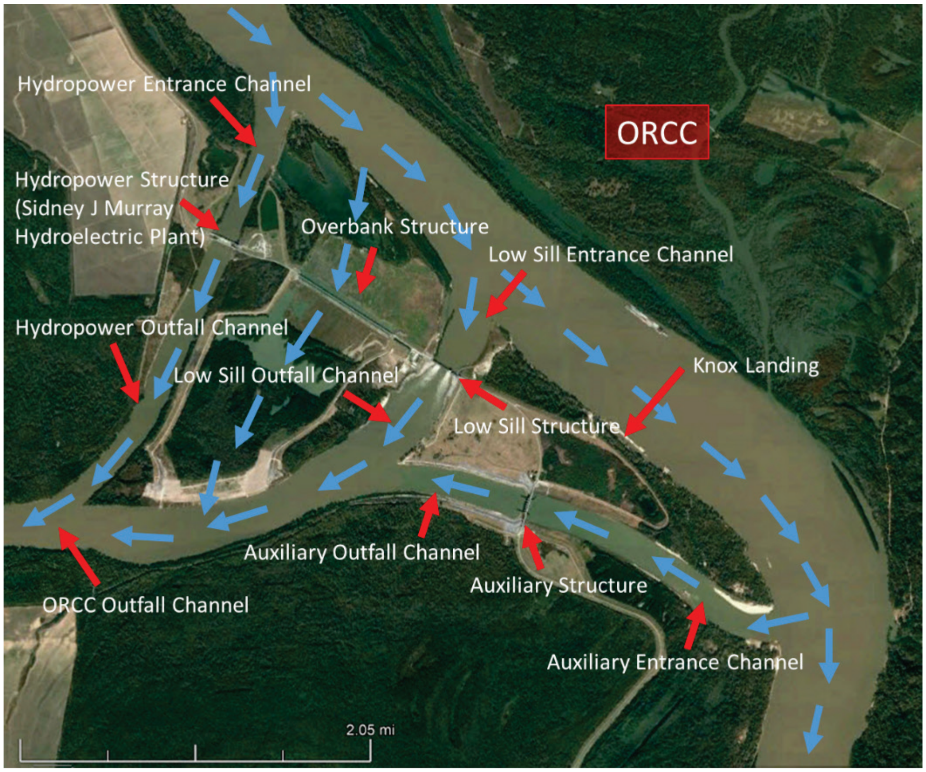
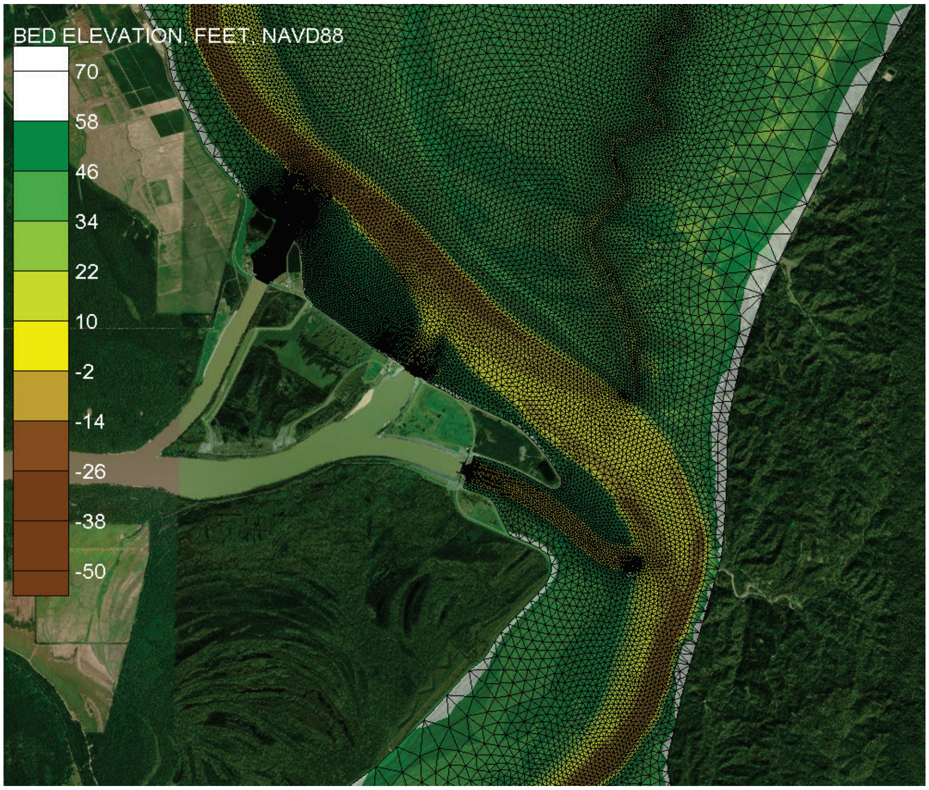


Figure 4. Study focus area with mesh bathymetry/topography and element resolution.



The mesh consisted of approximately 290,000 nodes and 590,000 elements covering an area of approximately 330,000 acres(1,2) (1,338 km^2). The area covered by the mesh included regions from open water to densely vegetated wooded areas, therefore the model parameters such as friction and eddy viscosity were specified using 18 material/region types (Table 2). The friction values given in Table 2 were calibrated and validated using methods described in Heath et al. (2015) and Leech et al. (2018).

Table 2. Model parameters.

Material	Type	Friction Type	Eddy Viscosity Type	Eddy Viscosity Coefficient or Value	Adaptive Levels
1	Mississippi River Channel	Manning 0.027	Rodi (Isotropic)	0.5	2
2	Dikes	Manning 0.035	Rodi (Isotropic)	0.5	2
3	Revetments	Manning 0.026	Rodi (Isotropic)	0.5	2
4	River Islands	Woody Vegetation	Rodi (Isotropic)	0.5	2
5	Lakes	Manning 0.02	Rodi (Isotropic)	0.5	0
6	Overbank Areas	Woody Vegetation	Rodi (Isotropic)	0.5	0
7	Forebay	Manning 0.02	Rodi (Isotropic)	0.5	0
8	Natchez Reach Overbank	Unsubmerged Vegetated	Rodi (Isotropic)	0.5	0
9	Natchez Reach Channel	Manning 0.026	Rodi (Isotropic)	0.5	0
10	Lower Reach	Woody Vegetation	Rodi (Isotropic)	0.5	0
11	ORCC Channels	Manning 0.026	Rodi (Isotropic)	0.5	2
12	ORCC Structures	Manning 0.026	Specified EV (for stability)	2.0	0

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[1] For a full list of the spelled-out forms of the units of measure used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office 2016), 248-52, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

[2] For a full list of the unit conversions used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office 2016), 345-7, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

Table 2. (cont.) Model parameters.

Material	Type	Friction Type	Eddy Viscosity Type	Eddy Viscosity Coefficient or Value	Adaptive Levels
13	Angola Levees	Manning 0.026	Rodi (Isotropic)	0.5	0
14	Buffalo River	Manning 0.027	Rodi (Isotropic)	0.5	0
15	MS Channel near ORCC	Manning 0.027	Rodi (Isotropic)	0.5	2
16	Dikes near ORCC	Manning 0.035	Rodi (Isotropic)	0.5	2
17	Revetments near ORCC	Manning 0.026	Rodi (Isotropic)	0.5	2
18	Islands near ORCC	Woody Vegetation	Rodi (Isotropic)	0.5	2

A trial-and-error process was followed to determine an adaption level for the material regions. A trial-and-error process was also followed to arrive at a converged time step of 300 sec. This time-step is the largest time-step for which the morphologic solution does not demonstrate significant sensitivity to the time-step size.

Sediment properties were specified using observed grain sizes from the US Geological Survey (USGS) as well as ERDC data collection efforts. Since the focus of this study was the morphological response of the Mississippi and Atchafalaya Rivers to the presence and/or changes to the ORCC, it was decided to simulate only those grain classes that comprise the bed material load. This is because grain size sampling in the study area indicates that sand size classes dominate the bed material, with silt and clay classes only occurring in quiescent areas behind obstructions, or at the highest elevation of sand bars, or in the batture. Hence, there are no silts or clays specified for the modeling effort. The selected sediment classes and their properties are presented in Table 3.

Table 3. Sediment grain size descriptions.

Sediment Number	Sediment Type	Characteristic Grain Diameter (mm)	Sediment Specific Gravity	Porosity of Bed Material
1	Very Fine Sand (VFS)	.088	2.65	0.35
2	Fine Sand (FS)	.177	2.65	0.35
3	Medium Sand (MS)	.354	2.65	0.35
4	Coarse Sand (CS)	.707	2.65	0.35
5	Very Coarse Sand (VCS)	1.41	2.65	0.35
6	Very Fine Gravel (VFG)	2.83	2.65	0.35
7	Fine Gravel (FG)	5.66	2.65	0.35

The sediment model was initialized using four sediment layers with varying proportions of the sediment classes. These initial bed gradations were selected to be consistent with bed samples taken in the river. The bed gradations were assigned by elevation (i.e., the initial layers were assigned an elevation that represented the bottom elevation of the layer). The local bed elevation at each node was then used to determine the local thickness of each bed layer. The initial elevations of the bottom of each layer in the main channel, and the initial gradations in the main channel, are given in Table 4. Note that the layers are numbered from deepest to shallowest layer (i.e., layer 4 is the layer at the bed surface; layer 1 is the layer just above bedrock). Note also that an elevation of 1000 m is specified for any layer that is initialized with zero thickness (if the elevation of the floor is higher than the elevation of the bed surface, the layer thickness is initialized to 0).

Table 4. Initial bed layer specification for the main channel.

Layer	Elevation of the Layer Floor (ft, NAVD88)	Grain Fractions						
		VFS	FS	MS	CS	VCS	VFG	FG
1	-40	0	0	0	0.1	0.3	0.3	0.3
2	-30	0	0.1	0.6	0.25	0.03	0.01	0.01
3	-5	0.04	0.1	0.63	0.22	0.01	0	0
4	1000	1	0	0	0	0	0	0

Using these initial estimates of the bed gradations, the model was subjected to an initialization simulation. This initialization simulation allowed the model to sort and armor the bed material, without permitting morphologic change. Once this initialization simulation was complete, the model was applied to verification and production simulations using the sediment bed generated from the initialization simulation.

The sand transport was modeled using the following transport relations:

- Bedload transport — van Rijn (1984), modified for multiple grain classes by Kleinhans and van Rijn (2002)
- Suspended Load — Wright and Parker (2004)
- Hiding factor — Egiazaroff (1965).

The model boundary conditions consisted of the following:

- Mississippi River upstream inflow boundary at Natchez (USACE, Vicksburg District)
- Mississippi River downstream stage boundary at Baton Rouge (Source: USGS)
- Specified outflows at all ORCC structures. (Source: USACE, New Orleans District).

The inflowing sediment load for all grain classes was prescribed using an equilibrium boundary condition. This boundary condition assumes that equilibrium conditions exist at the boundary location and provides the sediment concentration necessary to maintain that equilibrium. Hence, the inflowing sediment is a function of the river discharge and the local bed gradation at each time-step.

2.4 Model revalidation

The model has been previously validated for several studies. Some adjustment and revalidation were performed for this study. This revalidation includes the work done in 2018 that was not previously published.

2.4.1 Hydrodynamic revalidation

The hydrodynamics were revalidated against observed stages at three locations along the Mississippi River for the WY 2016 river hydrograph. Model recalibration was performed primarily by adjustment of riverbed roughness parameters.

Independent adjustment of the floodplain (vegetative) roughness coefficients was then undertaken by calibration of the floodplain roughness to match observations of the fraction of river discharge passing through the floodplain during high flows. This is described in more detail below.

Figure 5 and Figure 6 present the Mississippi River inflow and the ORCC outflows for WY 2016. The model was simulated using the roughness parameters presented in Table 2.

Figure 5. 2016 Mississippi River inflow.

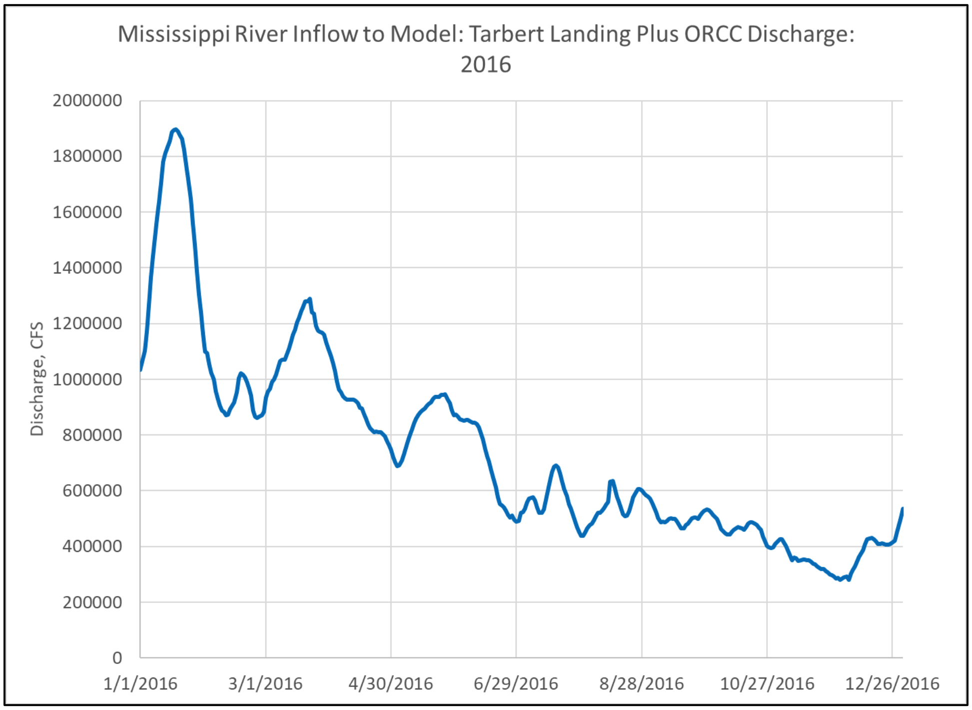
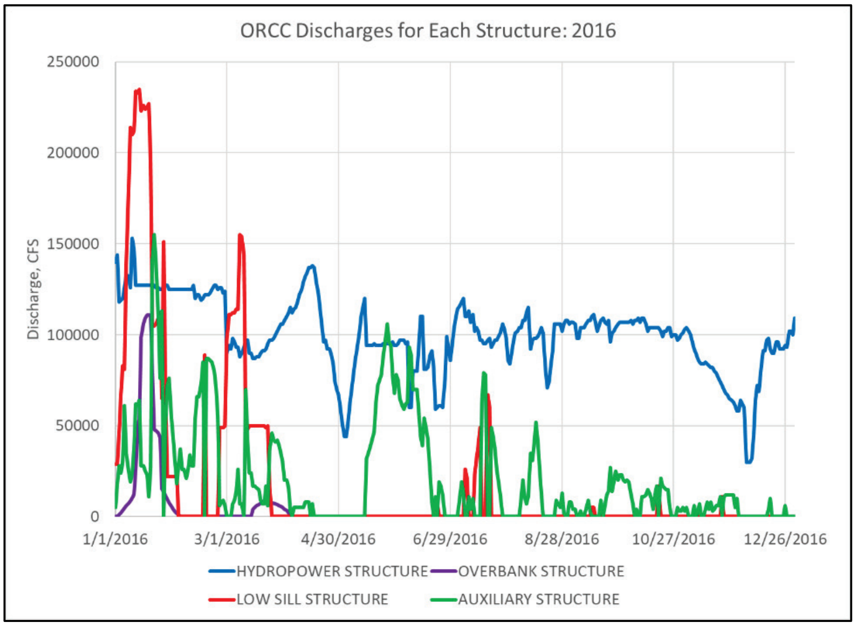


Figure 6. 2016 ORCC Outflows.



Simulated water surface elevations were compared to those at Knox Landing, Red River Landing, and St. Francisville (Figure 1 and Figure 3). Figure 7 through Figure 9 present these comparisons. Note that the model results closely follow the water surface observed. Table 5 presents a statistical analysis for a representative observation gage: the Knox Landing location.

Figure 7. Comparison of observed and modeled water surface elevation at Knox Landing.

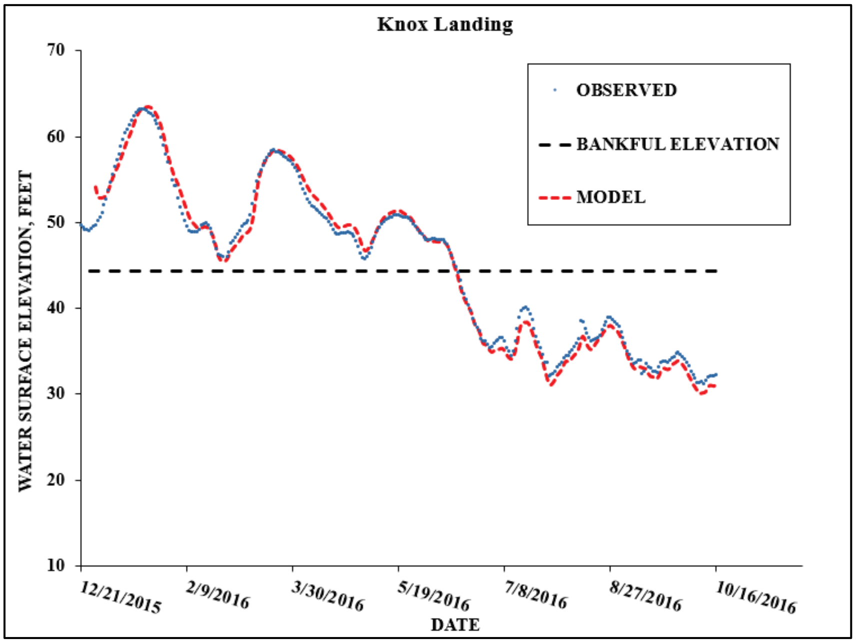


Figure 8. Comparison of observed and modeled water surface elevation at Red River Landing.

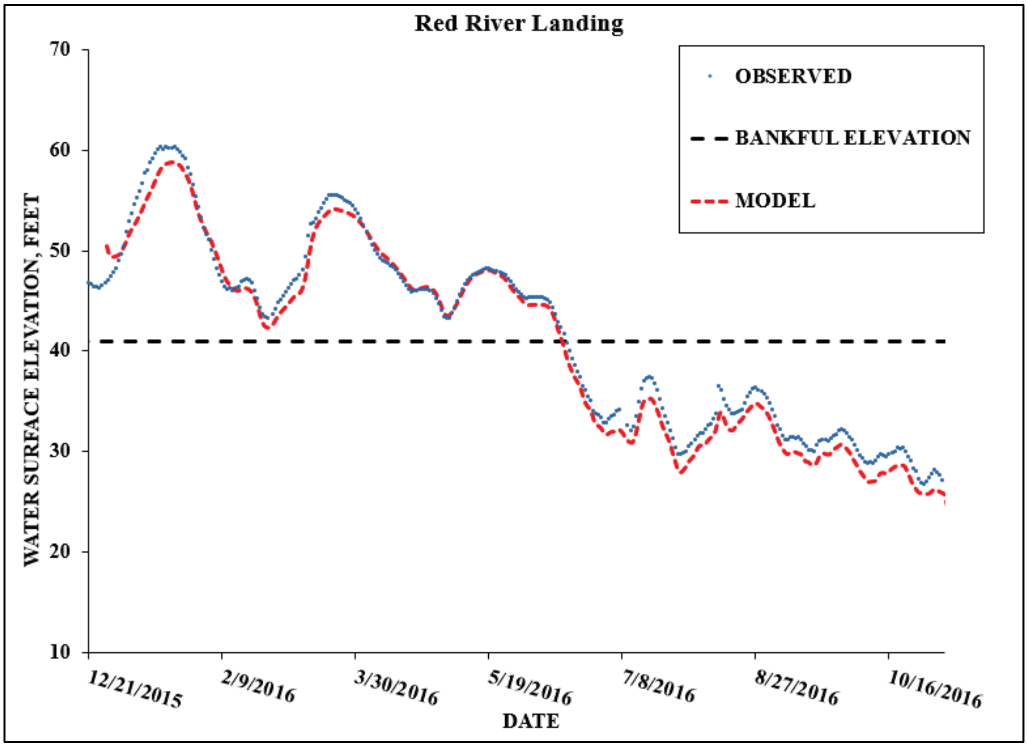


Figure 9. Comparison of observed and modeled water surface elevation at St. Francisville.

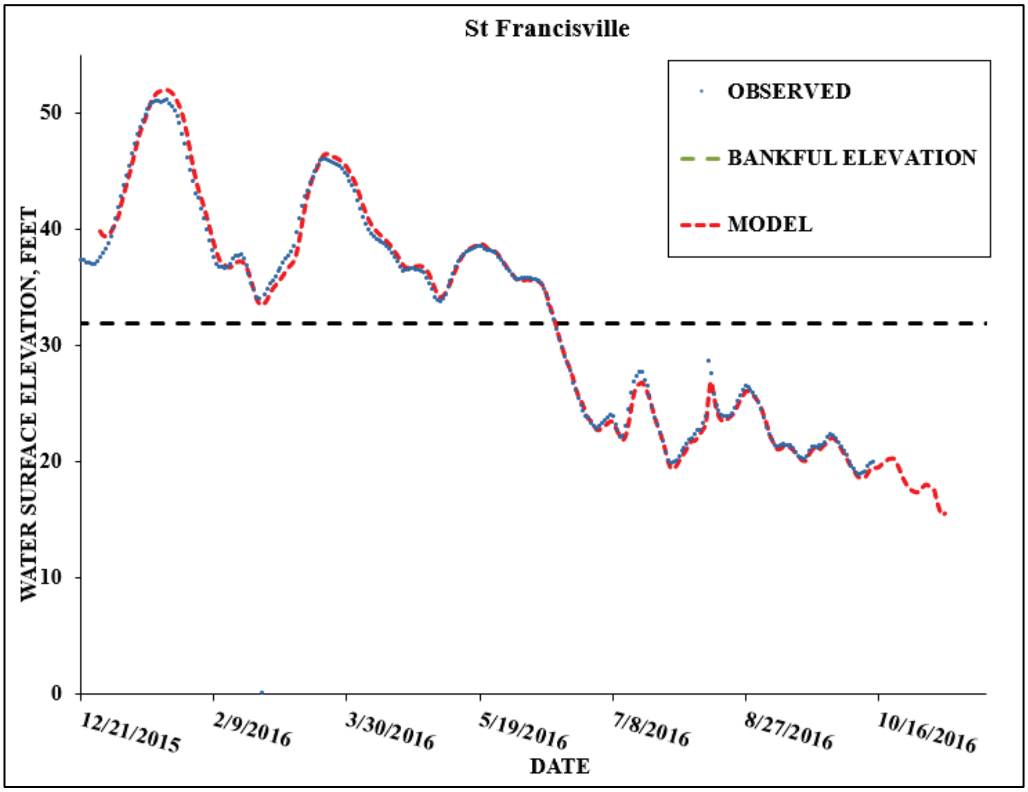


Table 5. Goodness of fit statistics for Knox Landing (RMSE = root mean square error).

Goodness of Fit	Value
RMSE	0.13 m
Willmott Index of Agreement	0.96
Correlation Coefficient	0.93

The independent calibration for the floodplain roughness at Morgan's Bend (Figure 1) is depicted in Figure 10 and Figure 11. The floodplain roughness is calibrated by adjusting the estimated number of trees per unit area. Figure 10 depicts the simulated velocities, showing the bypassing of the river channel through the batture. Figure 11 depicts the modeled and observed river channel discharge for two different days in 2016 as the river was rapidly rising and the floodplain was taking on more water.

Note that the discharge that is not accounted for in the river channel transect (the red transect in Figure 10) necessarily bypasses the river channel and flows over the floodplain to rejoin the river downstream of the bend. Hence, the observed discharge passing though the floodplain can be calculated and compared to the simulated values (Figure 11).

Figure 10. Modeled velocities at Morgan's Bend, with simulated flux observation transect lines shown (green transect is levee-to-levee; red transect is river channel only).

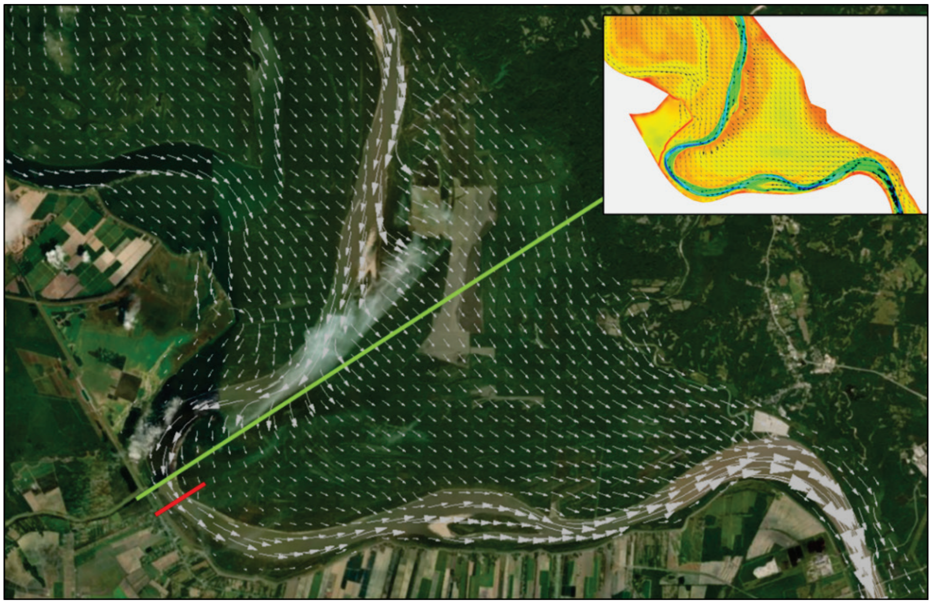
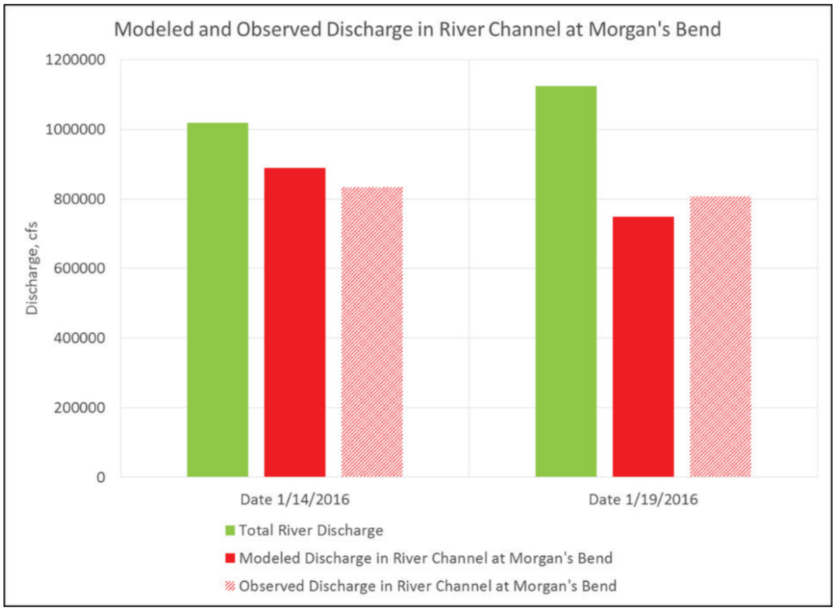


Figure 11. Modeled and observed river channel discharge at Morgan's Bend.



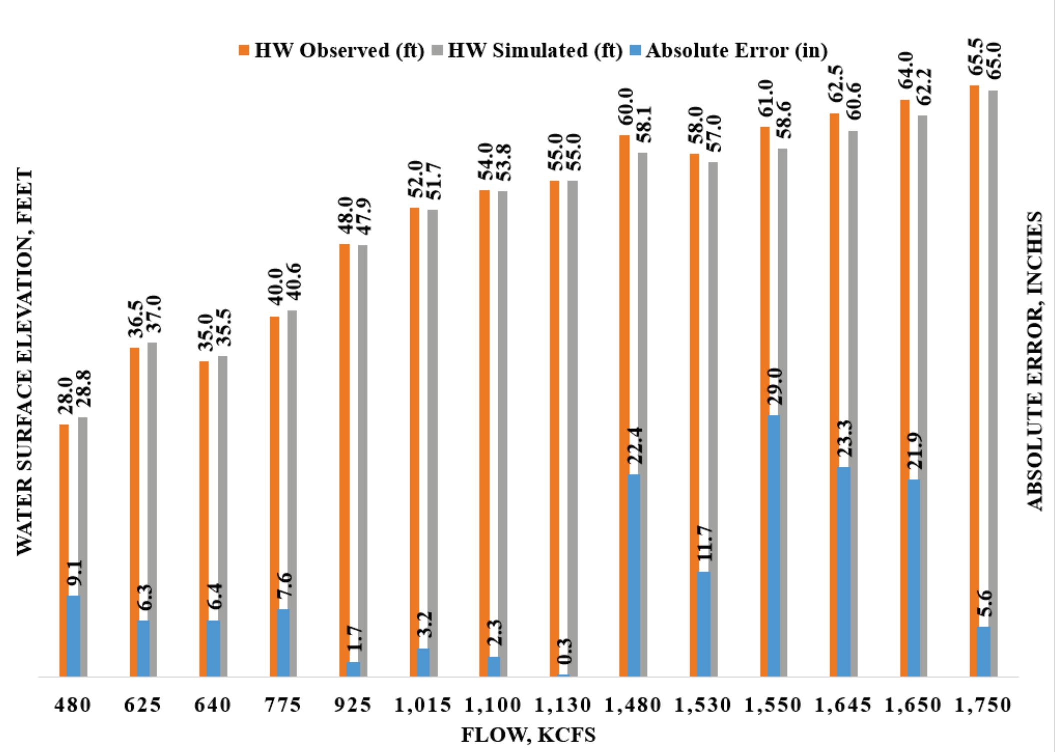
In addition to the 2016 validation, simulated water surface elevations were also compared to those observed at the Low Sill Structure for a series of steady state flows (Table 6).

Table 6. Low Sill Structure observed water surface elevation.

Mississippi River Flow, cfs	Water Surface Elevation, ft, NAVD88
479997	27.89
624999	36.42
640008	35.10
775016	40.03
924997	47.90
1015014	51.84
1100017	54.13
1129999	55.12
1480002	60.04
1530008	58.07
1549961	61.02
1644992	62.66
1650007	63.98
1749983	65.62

Figure 12 graphically illustrates the comparison of the model reproduced water surface elevations with those observed.

Figure 12. Comparison of observed and model water surface elevations.



2.4.2 Sediment transport revalidation

Adjustments to the existing sediment calibration were performed using the sediment data collected by ERDC during WY2010. These data included suspended sediment and bedload sediment flux data at multiple locations at the ORCC. Figure 13 through Figure 18 depict the simulated and observed fluxes, together with an inset map of the cross section associated with each plot (the relevant cross section is highlighted in red). Adjustments to the existing calibration was accomplished via subtle changes in the modeled bed gradation.

The fluxes agree with observation reasonably well, with the notable exception of the July 2010 data. At each cross section in July 2010, the model overpredicts the observed sand load, both for suspended bed material load and for bedload.

The reason for this appears to be the armoring of the sediment bed in the observed data. The hydrograph in 2010 was persistently high for a long duration, and by July it appears that much of the sand available for transport (especially fine sand and medium sand) had been winnowed from the bed, with only coarser classes remaining.

This can be deduced by comparing the percentage sand in the suspended samples for March 4 (38%) to the percentage sand in the suspended samples for July 1 (9%). Both observations were taken at nearly the same river discharge rate, and yet the sand fraction is much lower in July than in March.

The inability of the model to match this trend, therefore, suggests that the model initialization resulted in a sediment bed with relatively greater stores of fine and medium sand available for transport than were available in the Mississippi River in 2010.

However, the fact that these same trends do not appear in the comparisons to the 2008 data (see below) suggests that this is not a persistent problem with the model.

Figure 13. Comparison of modeled and observed sediment fluxes. 2010 hydrograph: Mississippi River upstream of Hydropower.

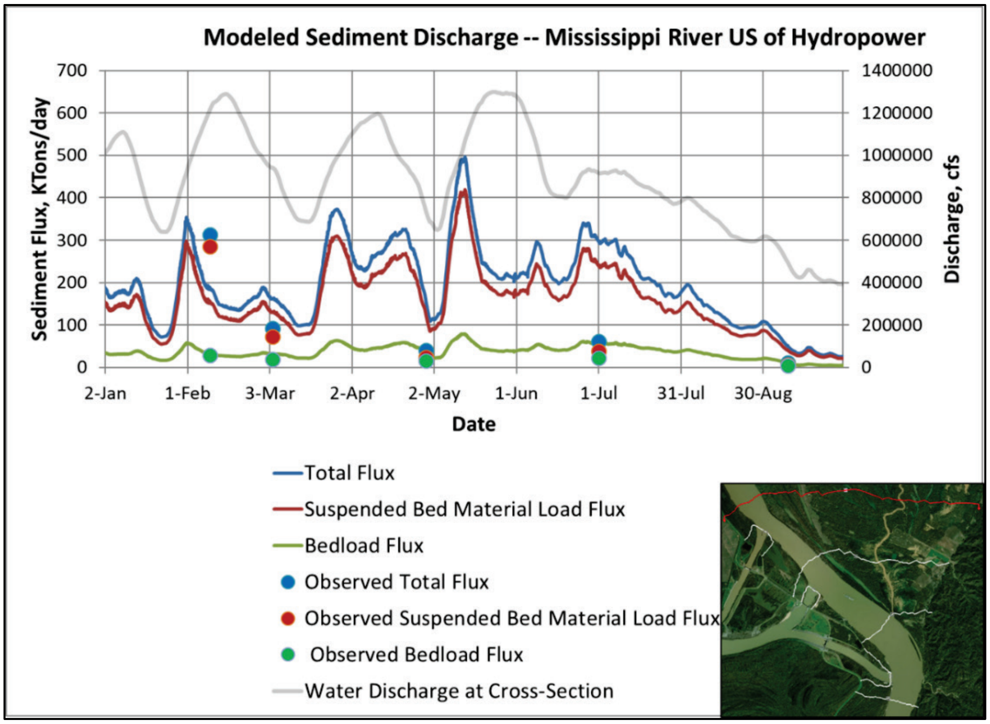


Figure 14. Comparison of modeled and observed sediment fluxes: 2010 hydrograph: Mississippi River downstream of Hydropower.

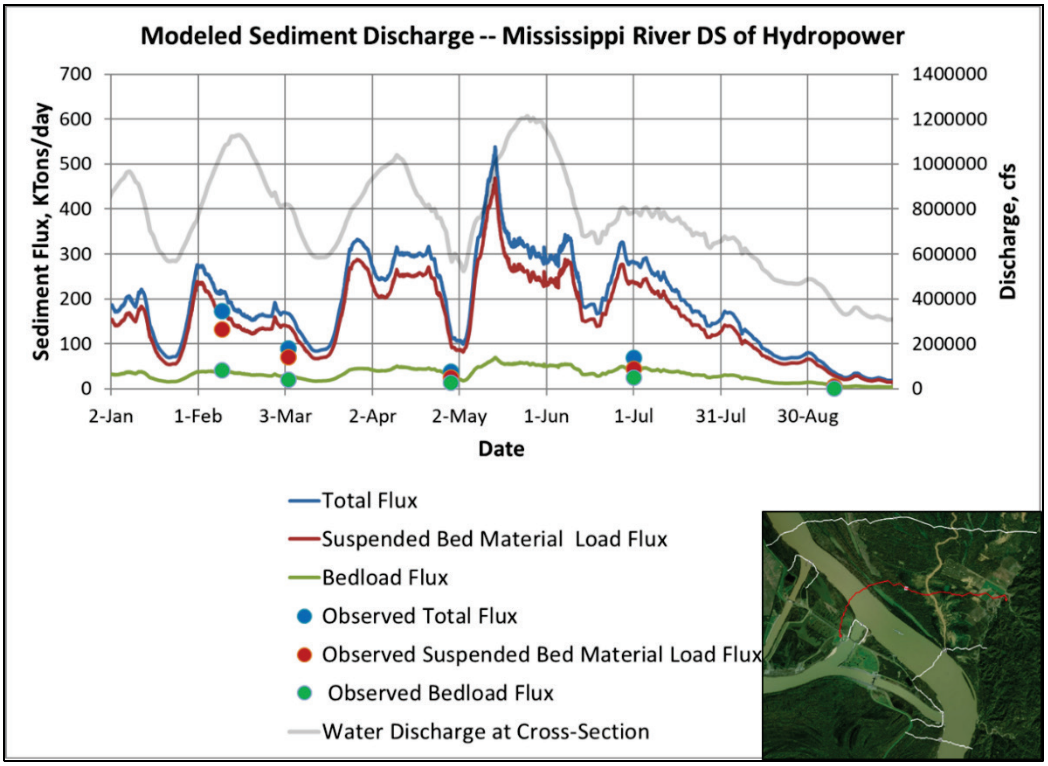


Figure 15. Comparison of modeled and observed sediment fluxes: 2010 hydrograph: Mississippi River downstream of Auxiliary entrance channel.

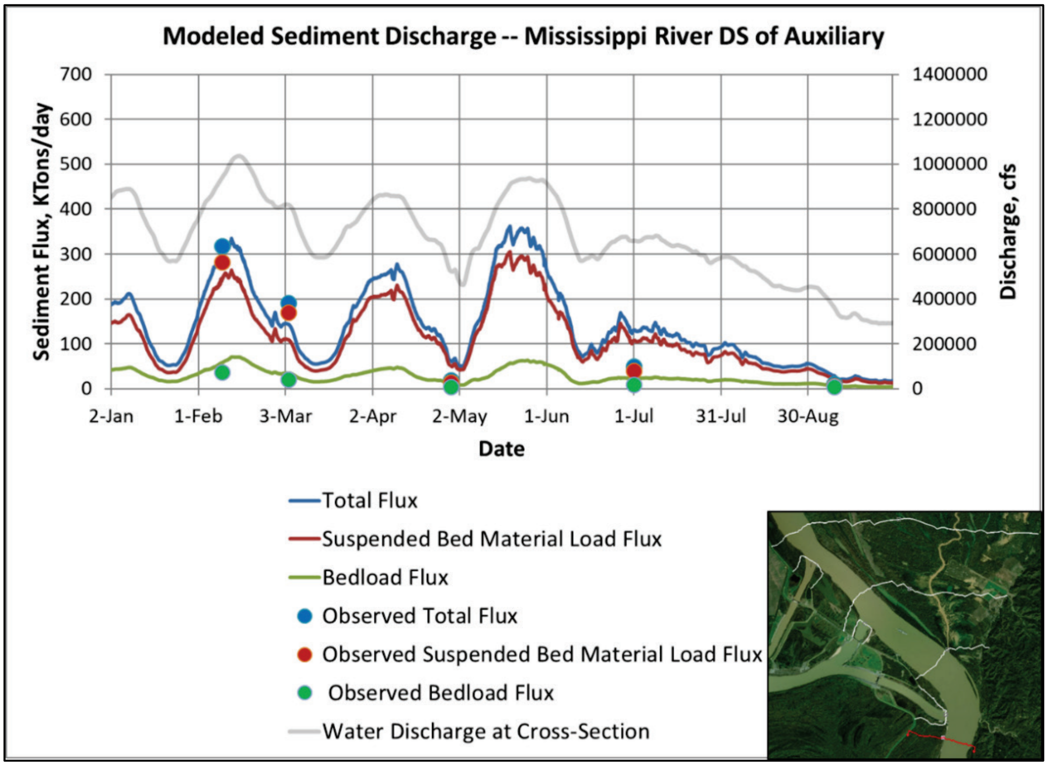


Figure 16. Comparison of modeled and observed sediment fluxes: 2010 hydrograph: Hydropower channel.

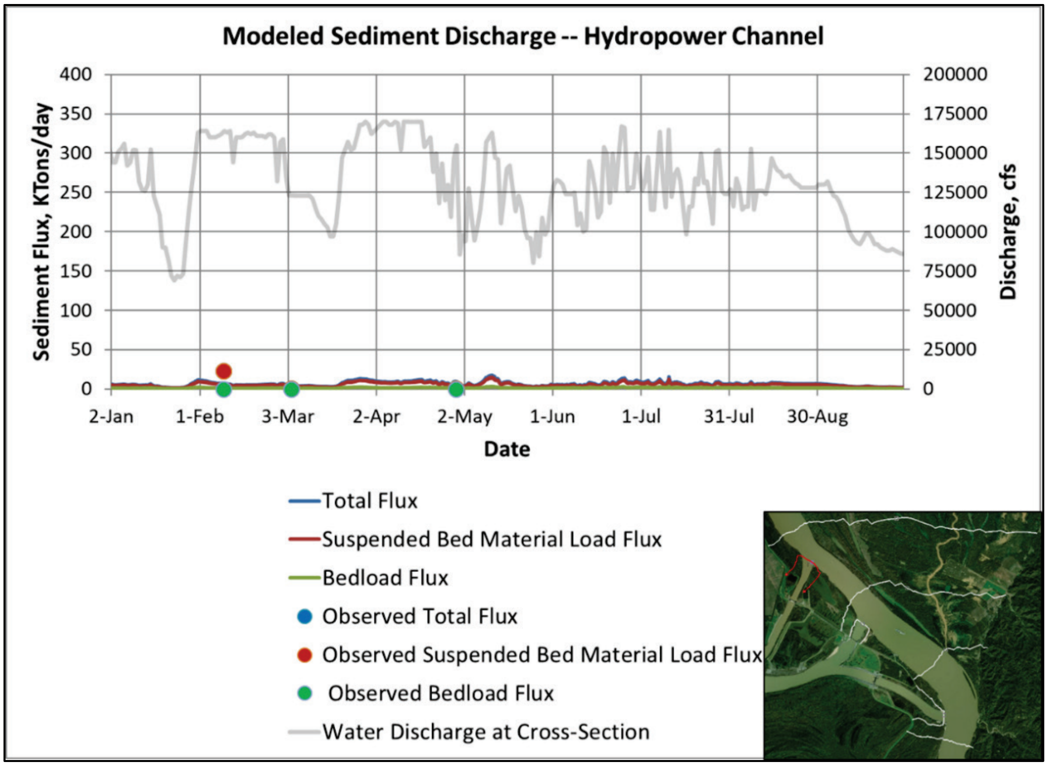


Figure 17. Comparison of modeled and observed sediment fluxes: 2010 hydrograph: Low Sill channel.

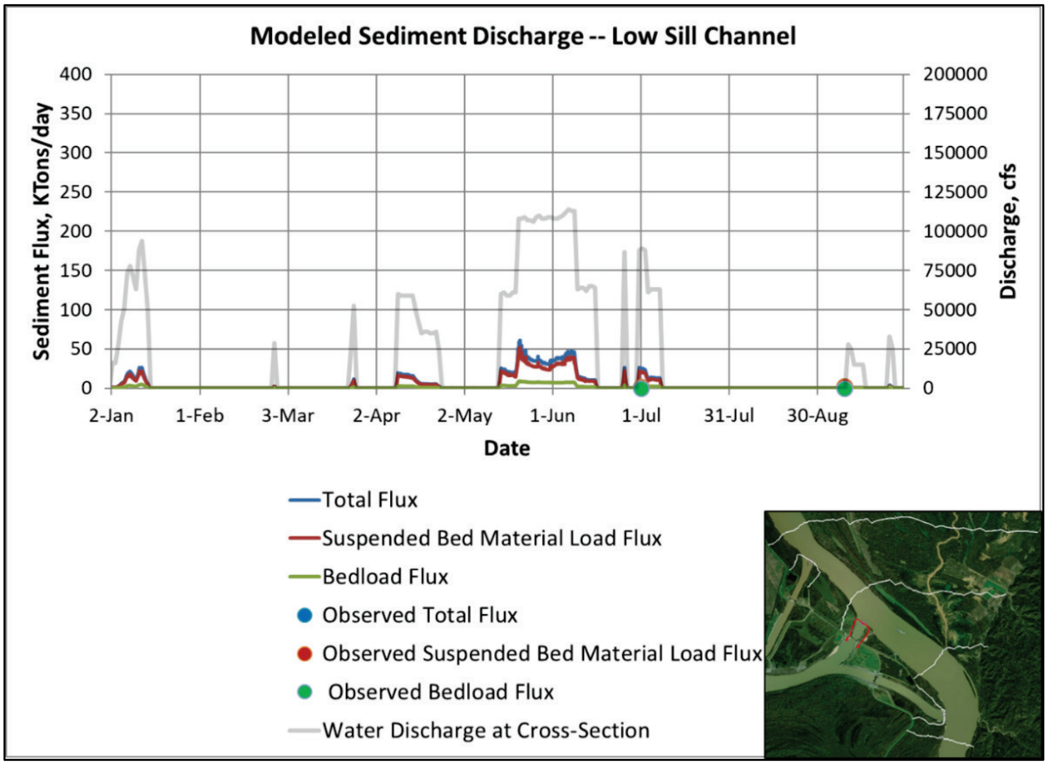
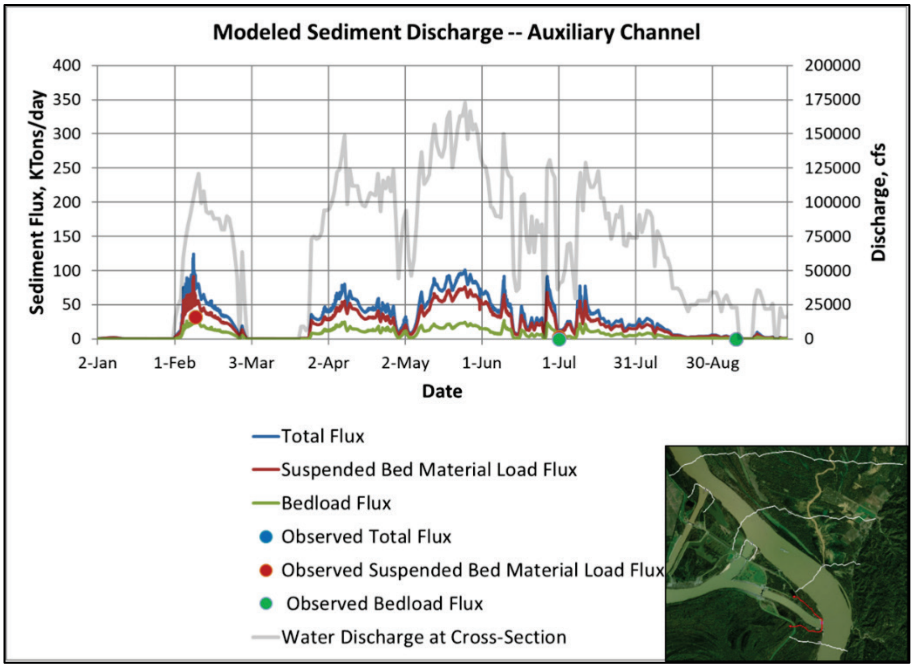


Figure 18. Comparison of modeled and observed sediment fluxes: 2010 hydrograph: Auxiliary entrance channel.



The sediment transport simulation was validated against USGS observations of suspended sand flux at Tarbert Landing. This was simulated for WY 2008. The results are given in Figure 19. Quantitative statistics for the 2008 comparisons are given in Table 7.

Figure 19. Comparison of modeled and observed (USGS) sediment fluxes: 2008 hydrograph: Tarbert Landing.

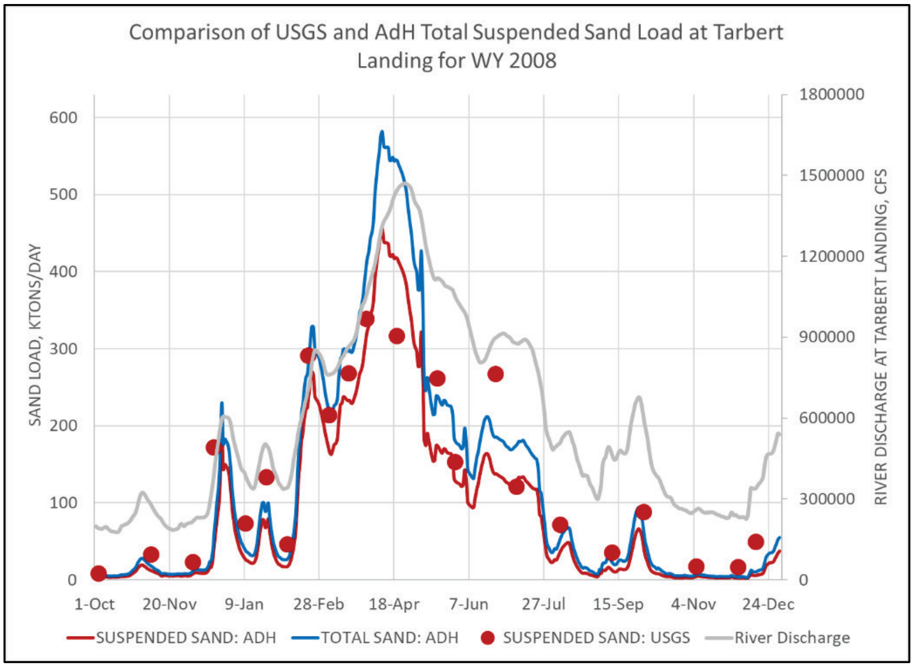
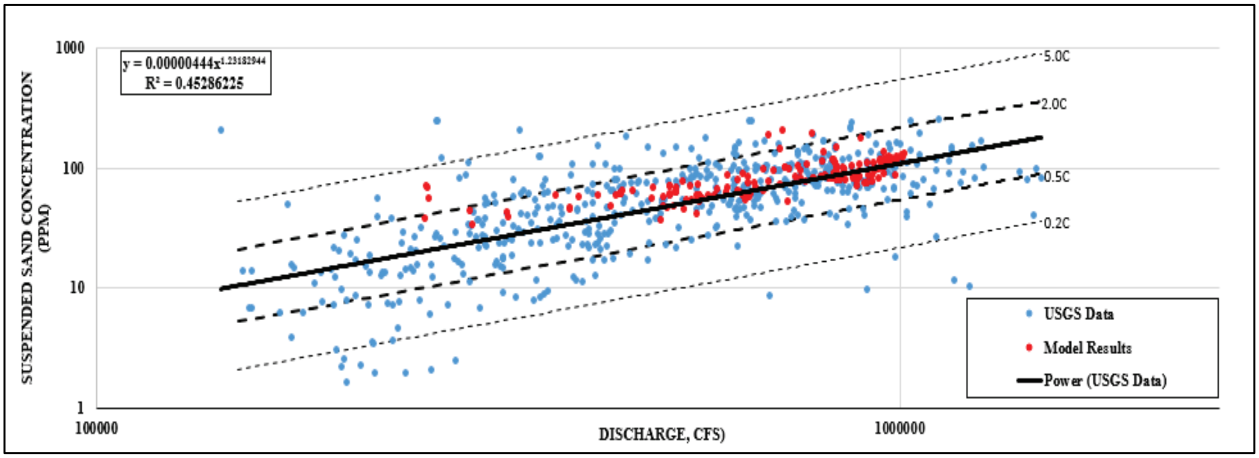


Table 7. Statistical analysis for model-computed vs. USGS reported suspended sand concentration.

Model-Mean (Ktons/day)	Field-Mean (Ktons/day)	Bias (Ktons/day)	RMSE (Ktons/day)	Normalized RMSE	Correlation-Coefficient	Willmott-Index of Agreement
101.1	135.8	34.7	56.8	0.419	0.919	0.935

In addition to the comparisons presented above, the USGS has collected spot and instantaneous suspended sediment concentrations across several flow conditions. The model was executed for several WYs from 2008 to 2017, and the model results from these runs were compared to USGS reported concentrations. These are presented in Figure 20, including the confidence banding of the results. The model accurately captures the suspended sand concentration across a wide range of flows.

Figure 20. Discharge vs. suspended sand concentration.



3 Theoretical Considerations

This chapter provides an overview of the theoretical considerations that can be applied to inform the more detailed, quantitative results that are obtained from the numerical analysis. These considerations are taken from fundamental hydraulic and geomorphic principles.

The sources of the methods discussed in this chapter are developed in detail in two CHL technical notes (Letter et al. 2008; Brown et al. 2013). These technical notes apply fundamental hydraulic and geomorphic principles to analyze the riverside effects of sediment diversions, assuming greatly simplified river and diversion conditions. An overview of these basic theoretical principles is given below. Then, these principles are applied to the specific conditions associated with the ORCC to develop insights into the expected geomorphic response to the operation of the ORCC.

3.1 Sediment diversion basics

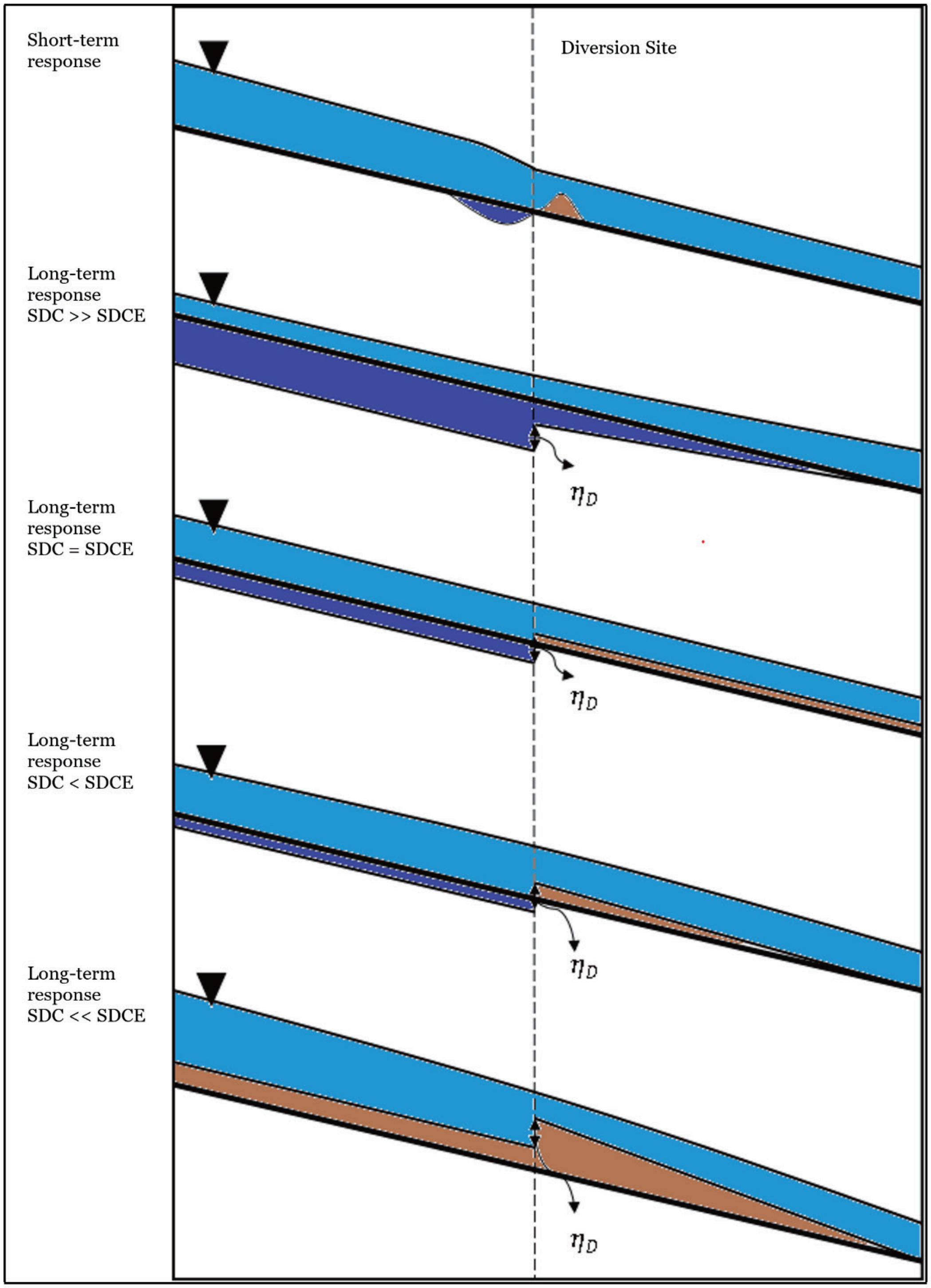
A detailed analysis, complete with equations, of the theoretical response of a river to the introduction of a water diversion is given in Brown et al. (2013). The primary conclusions of the analysis are as follows:

- When a diversion is initially opened, it induces a drawdown in the river upstream of the diversion. This accelerates the flow just upstream of the diversion, eroding the bed and supersaturating the river with sediment.
- Because of this initial increase in the sediment load from the upstream reach, for all practical purposes it is not feasible to design a diversion that will inhibit the initial deposition in the river downstream of the diversion. There will always be some transfer of bed material in the river from upstream to downstream of the diversion. This process will persist until the local river morphology has adjusted to the presence of the diversion.
- As time progresses, the river upstream of the diversion site adjusts to the drawdown induced by the diversion (by scouring and armoring the bed), and the river sediment load reduces to the equilibrium value.
- In the long term, a new sediment equilibrium is established in the river upstream and downstream of the diversion.
- The morphologic changes required to establish this equilibrium are dependent on the ratio of concentration of the sediment diverted,

relative to the concentration of the sediment in the river upstream of the diversion. This ratio is called the sediment diversion efficiency in Heath et al. (2015), but in this report, it is referred to as the sediment diversion coefficient (SDC) (a detailed discussion of the SDC is given in Section 4.1.2).

- The expected qualitative trends in river morphology are a function of the relationship between the SDC for the diversion and the SDC equilibrium value (SDCE). The SCDE (first introduced in Letter et al. [2008]) is the value of the SDC for which there is no change in the slope of the energy grade line in the river downstream of the diversion (for uniform flow, the water surface slope) after the introduction of the diversion. The qualitative trends are given as follows (these are also illustrated in Figure 21):
    - If SDC >> SDCE, there is likely to be downstream erosion and significant upstream channel degradation.
    - If SDC = SDCE, there is likely to be mild downstream deposition and moderate upstream channel degradation.
    - If SDC < SDCE, there is likely to be moderate downstream deposition and mild upstream channel degradation.
    - If SDC << SDCE, there is likely to be significant downstream deposition and upstream deposition.
- The quantitative trends are dependent on specific diversion characteristics. Some techniques for estimating these quantities are given in Brown et al. (2013).

Figure 21. Theoretical riverine morphologic responses to the introduction of a water diversion (η_D is the bed elevation difference between upstream and downstream of the diversion site).



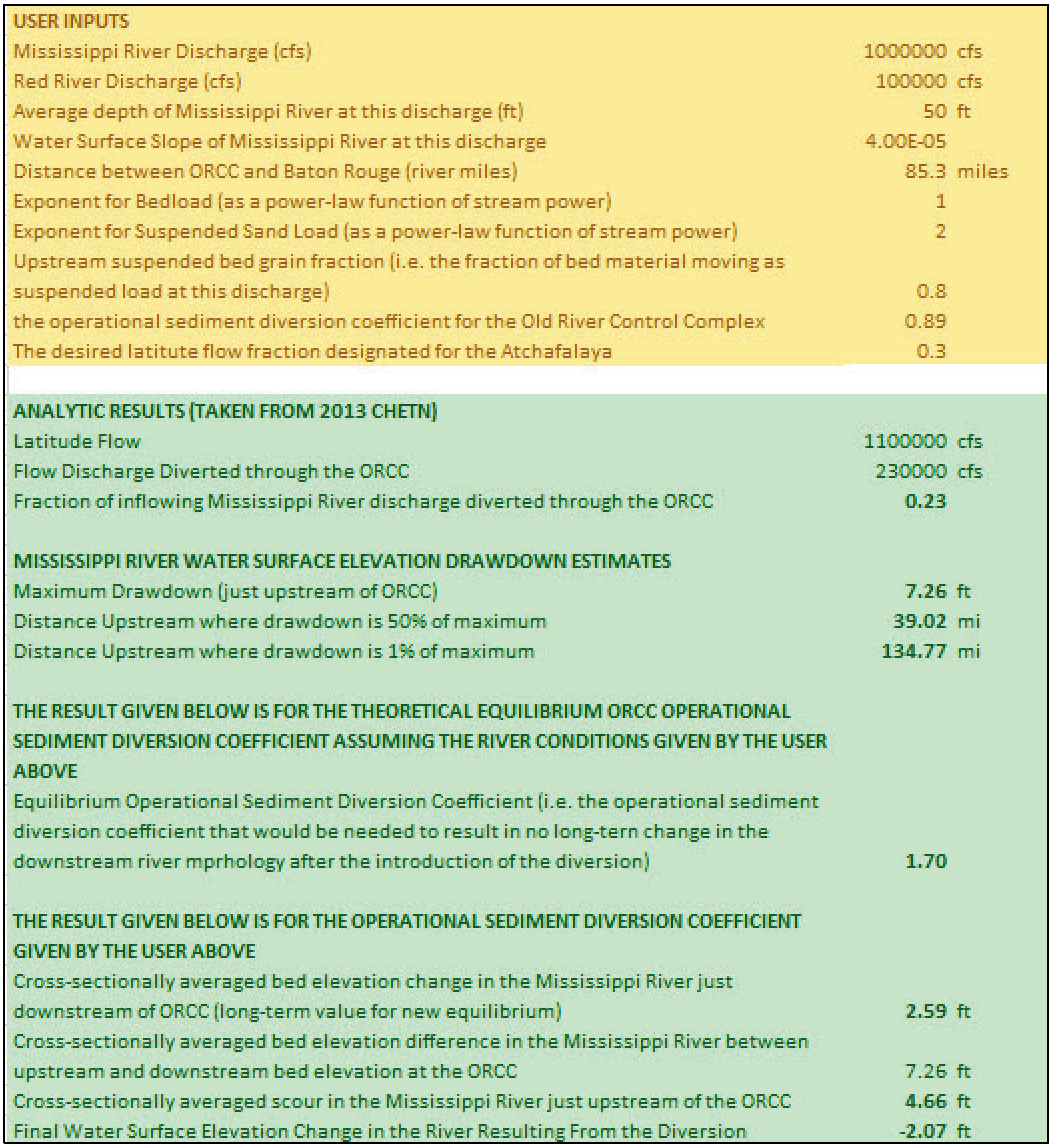
3.2 Application of sediment diversion basics to the Old River Control Complex (ORCC)

Using the principles outlined in Section 3.1, together with idealized conditions that approximate the Mississippi River and the ORCC, the methods developed in Section 3.1 can be applied to estimate the long-term response of the Mississippi River to the presence of the ORCC. The spreadsheet used to generate these results, including the inputs and results, is depicted in Figure 22. The results are discussed in the subsequent subsections.

Note that this analysis predicts the response of the Mississippi River to an introduced diversion at the ORCC. The analysis also assumes that the Mississippi River is in morphodynamic equilibrium prior to the introduction of the diversion.

Neither of these assumptions is true. The true history and complexity of the Mississippi River and the ORCC is much different than this idealization of the diversion. The influence of these differences on the utility of the analysis is discussed in Section 3.2.4.

Figure 22. Inputs and outputs for theoretical analysis of the ORCC effects on the Mississippi River.



USER INPUTS		
Mississippi River Discharge (cfs)	1000000	cfs
Red River Discharge (cfs)	100000	cfs
Average depth of Mississippi River at this discharge (ft)	50	ft
Water Surface Slope of Mississippi River at this discharge	4.00E-05	
Distance between ORCC and Baton Rouge (river miles)	85.3	miles
Exponent for Bedload (as a power-law function of stream power)	1	
Exponent for Suspended Sand Load (as a power-law function of stream power)	2	
Upstream suspended bed grain fraction (i.e. the fraction of bed material moving as suspended load at this discharge)	0.8	
the operational sediment diversion coefficient for the Old River Control Complex	0.89	
The desired latitute flow fraction designated for the Atchafalaya	0.3	
ANALYTIC RESULTS (TAKEN FROM 2013 CHETN)		
Latitude Flow	1100000	cfs
Flow Discharge Diverted through the ORCC	230000	cfs
Fraction of inflowing Mississippi River discharge diverted through the ORCC	**0.23**	
MISSISSIPPI RIVER WATER SURFACE ELEVATION DRAWDOWN ESTIMATES		
Maximum Drawdown (just upstream of ORCC)	**7.26**	ft
Distance Upstream where drawdown is 50% of maximum	**39.02**	mi
Distance Upstream where drawdown is 1% of maximum	**134.77**	mi
THE RESULT GIVEN BELOW IS FOR THE THEORETICAL EQUILIBRIUM ORCC OPERATIONAL SEDIMENT DIVERSION COEFFICIENT ASSUMING THE RIVER CONDITIONS GIVEN BY THE USER ABOVE		
Equilibrium Operational Sediment Diversion Coefficient (i.e. the operational sediment diversion coefficient that would be needed to result in no long-tern change in the downstream river mprhology after the introduction of the diversion)	**1.70**	
THE RESULT GIVEN BELOW IS FOR THE OPERATIONAL SEDIMENT DIVERSION COEFFICIENT GIVEN BY THE USER ABOVE		
Cross-sectionally averaged bed elevation change in the Mississippi River just downstream of ORCC (long-term value for new equilibrium)	**2.59**	ft
Cross-sectionally averaged bed elevation difference in the Mississippi River between upstream and downstream bed elevation at the ORCC	7.26	ft
Cross-sectionally averaged scour in the Mississippi River just upstream of the ORCC	**4.66**	ft
Final Water Surface Elevation Change in the River Resulting From the Diversion	**-2.07**	ft

3.2.1 Mississippi River drawdown and water surface elevation change associated with the introduction of an ORCC-type diversion

The analysis yields a predicted maximum initial drawdown of 7.26 ft just upstream of the ORCC in the Mississippi River for an upstream Mississippi River discharge of 1,000,000 cfs. This means that if the ORCC were suddenly introduced, the initial drawdown at the site would be 7.26 ft. This drawdown gradually reduces with distance upstream of the ORCC (following the theoretical drawdown curve), with a drawdown of 3.63 ft at a distance upstream of 39.02 mi upstream, and a drawdown of 0.0726 ft at a distance of 134.77 mi upstream.

Over time, as morphology of the Mississippi River adjusts to the presence of the diversion, deposition in the river downstream of the ORCC reduces the drawdown at the site (relative to the conditions that existed before the diversion was introduced). The analysis indicates that the final water surface elevation change just upstream of the diversion, relative to pre-project conditions, is -2.07 ft for an upstream Mississippi River discharge of 1,000,000 cfs.

3.2.2 Short-term morphological response of the river to an ORCC-type diversion

The theoretical analysis predicts an initial scouring of sediment upstream of the diversion and initial large deposition of sediment downstream of the diversion. Over time, the upstream reach will adjust to the presence of the diversion by scouring and/or armoring until it reaches a new equilibrium. The material eroded from upstream will be redistributed downstream, forming some of the material necessary to form the new downstream equilibrium bed.

The theoretical analysis does not predict the duration required for this transition from the short-term adjustment condition to a long-term new equilibrium. However, some insight into this can be gleaned from the one-dimensional (1D) modeling effort developed for this study (Copeland and Lewis 2022). Results from this effort suggest that the response time of the Mississippi River to the introduction and/or modification of a diversion at the ORCC is approximately 30 yr. Hence, it is expected that the introduction of and/or changes to the ORCC operations would require approximately 30 yr to transition from short-term to long-term adjustments at the ORCC.

3.2.3 Long-term morphological response of the river to an ORCC-type diversion

The theoretical analysis suggests that the value of the SDC necessary to maintain the same water surface slope downstream of an ORCC-type diversion that existed before the introduction of the diversion (the SDCE value) is approximately 1.7. The actual operational value of the SDC for the ORCC, according to multiple studies (Heath et al. 2015; Ayres 2018) is approximately 0.9. This means that long-term deposition and steepening of the bed slope is expected downstream of the diversion (see the graphic for SDC < SDCE in Figure 21).

The theoretical analysis of the long-term morphologic effects requires that the total change in the bed elevation between the upstream and downstream bed slopes must be equal to the initial drawdown value of 7.26 ft. This total change is computed as the maximum downstream deposition (just downstream of the diversion site) minus the maximum upstream scour (just upstream of the diversion site). The relative proportion of these quantities are a function of the SDC of the diversion. The equations used to calculate these relative proportions are given in Brown et al. (2013).

For the input values applied to this idealized ORCC-type diversion, the analysis predicts a long-term maximum downstream deposition of 2.59 ft and a maximum upstream scour of 4.66 ft.

3.2.4 Implications of the theoretical analysis for the analysis of the ORCC

The theoretical analysis is a greatly simplified model for the Mississippi River and an ORCC-type diversion. The true prototype conditions are different in many ways.

- The Mississippi River hydrographs varies greatly from year to year, as does the sediment load.
- The morphological response to these natural conditions, and to multiple anthropogenic changes to the river and the watershed, are dynamic and continuous. Hence, there is no true *equilibrium* baseline condition for the Mississippi River.
- The history of water diversion in the vicinity of the current location of the ORCC is long and varied. This is discussed in detail in the morphological analysis report associated with this study (Lauth et al. 2022). However, each of these changes in the location and distribution of water and sediment diversion has resulted in morphodynamic changes in the Mississippi River. Hence, there has been no discrete, instantaneous introduction of a diversion.

Given these differences, the results of a simplified theoretical analysis must be used with caution. However, the analysis identifies general trends that are helpful in interpreting the detailed model results of this study.

Any **increase** in the **water** diversion at the ORCC should result in the following qualitative changes in the Mississippi River (relative to baseline conditions):

- Increase in drawdown and increase in scour upstream of the ORCC
- Initial increase in deposition at and just downstream of the ORCC
- Long-term readjustment of the downstream morphology, to increase the slope of the channel.

Any **decrease** in the **water** diversion at the ORCC should result in the following qualitative changes in the Mississippi River (relative to baseline conditions):

- Decrease in drawdown and increase in deposition upstream of the ORCC
- Initial decrease in deposition and/or increase in scour at and just downstream of the ORCC
- Long-term readjustment of the downstream morphology, to reduce the slope of the channel.

Any **decrease** in the **sediment** diversion at the ORCC should result in the following qualitative changes in the Mississippi River (relative to baseline conditions):

- Initial increase in deposition at and just downstream of the ORCC
- Long-term readjustment of the downstream morphology, to increase the slope of the channel.

Any **increase** in the **sediment** diversion at the ORCC should result in the following qualitative changes in the Mississippi River (relative to baseline conditions):

- Initial decrease in deposition and/or increase in scour at and just downstream of the ORCC
- Long-term readjustment of the downstream morphology, to reduce the slope of the channel.

Note that in each case, analytic considerations indicate that changes to ORCC operations *do not* induce continuous changes to the morphologic trajectory of the Mississippi River. Rather, any change to ORCC operations will result in a finite morphologic response in the river, which occurs over a finite length of time. Results of the 1D HEC-6T modeling indicate that these *long-term* adjustments should manifest themselves over the course of approximately 30 yr.

4 Base Condition and Scenario Analyses

This chapter details the analyses of the base condition simulation and the scenario simulations. The metrics used for analysis are first described. The base condition and scenario runs are analyzed with these metrics.

The primary purpose of these analyses is to determine the impacts of various flow conditions and scenarios on sediment diversion/removal at the ORCC and the morphological response in the Mississippi River. These analyses provide insight into the dominant processes and mechanisms for sediment removal at the ORCC and the various system responses and constraints that limit the degree to which they can be adjusted.

4.1 Metrics for analysis

There are several basic metrics that are useful for analyzing the model results. Since these results focus mostly on the sediment diversion characteristics of the ORCC, and how they can potentially be modified, the metrics employed here are meant to quantify these diversion characteristics in such a way that useful insights can be ascertained from the model results and scenario comparisons.

4.1.1 Sediment trapping efficiency (STE)

The sediment trapping efficiency (STE) measures the percentage of sediment trapped within a control volume. It is used in this analysis to measure the trapping efficiency of the Auxiliary Entrance Channel. It is computed as follows:

$$STE_{\Delta t} = 100\% \left(1 - \frac{\int_{t_1}^{t_2} Q_{S.Outflow}}{\int_{t_1}^{t_2} Q_{S.Inflow}} \right) \tag{1}$$

where

$Q_{S.Inflow}$ = the sediment inflow into the control volume
$Q_{S.Outflow}$ = the sediment outflow from the control volume
Δt = the time interval over which the STE is calculated (i.e., t_1 to t_2).

4.1.2 Sediment diversion coefficient (SDC)

The sediment diversion coefficient (SDC) has been used in multiple studies (e.g., Copeland et al. 2020; Ayres 2018) to quantify the sediment diversion characteristics of a given water diversion.

In a previous study of the ORCC (Heath et al. 2015), this quantity was referred to as the sediment diversion efficiency. For this study, the traditional nomenclature of sediment diversion coefficient is used to be consistent with long-standing convention.

The SDC is a measure of the ratio of the cross-sectionally averaged concentration in the diversion to the cross-sectionally averaged concentration in the river upstream of the diversion (i.e., the river being diverted *from*). The formal mathematical definition is given as follows:

$$SDC_{\Delta t} = \frac{\int_{t_1}^{t_2} Q_{S.Diversion} \int_{t_1}^{t_2} Q_{River}}{\int_{t_1}^{t_2} Q_{Diversion} \int_{t_1}^{t_2} Q_{S.River}} \qquad (2)$$

where

Q_{River} = the water discharge at a reference cross section in the river

$Q_{Diversion}$ = the water discharge at a reference cross section in the diversion

$Q_{S.River}$ = the sediment discharge at a reference cross section in the river

$Q_{S.Diversion}$ = the sediment discharge at a reference cross section in the diversion.

Integrating over the time interval t_1 to t_2 (Δt) generalizes the mathematical definition of the sediment diversion coefficient such that both the *structural sediment diversion coefficient* (i.e., the inherent sediment diversion characteristics of the diversion) and the *operational sediment diversion coefficient* (i.e., the net sediment diversion characteristics of the diversion, including the frequency and duration of operations) are described by this equation.

To estimate the *structural sediment diversion coefficient,* Δt should be small relative to the time scale of relevance for the prototype. For the ORCC, this is on the order of 1 day.

To estimate the *operational sediment diversion coefficient,* Δt should be large relative to the time scale of relevance for the prototype. For the ORCC, this is on the order of 1 year.

4.1.3 Sediment removal ratio (SRR)

The sediment removal ratio (SRR) is a measure of the amount of sediment removed for a given scenario, relative to the amount of sediment supplied. It permits relative comparisons between various alternatives and/or simulation years. Since it does not include the water diversion characteristics, it allows for comparison among alternatives and years with different diversion protocols. That is, it permits the comparison of alternatives to determine which year and/or scenario diverts the most or least sediment.

The sediment removal ratio is computed as follows:

$$SRR_{\Delta t} = \frac{\int_{t_1}^{t_2} Q_{S.Diversion} + \sum_{i=1}^{i=NDE} M_{D.i}}{\int_{t_1}^{t_2} Q_{S.River}} \tag{3}$$

where

$Q_{S.River}$ = the sediment discharge at a reference cross section in the river
$Q_{S.Diversion}$ = the sediment discharge at a reference cross section in the diversion
$M_{D.i}$ = the sediment mass dredged for dredge event i
NDE = the number of dredge events occurring between t_1 and t_2.

4.1.4 Sediment removal index (SRI)

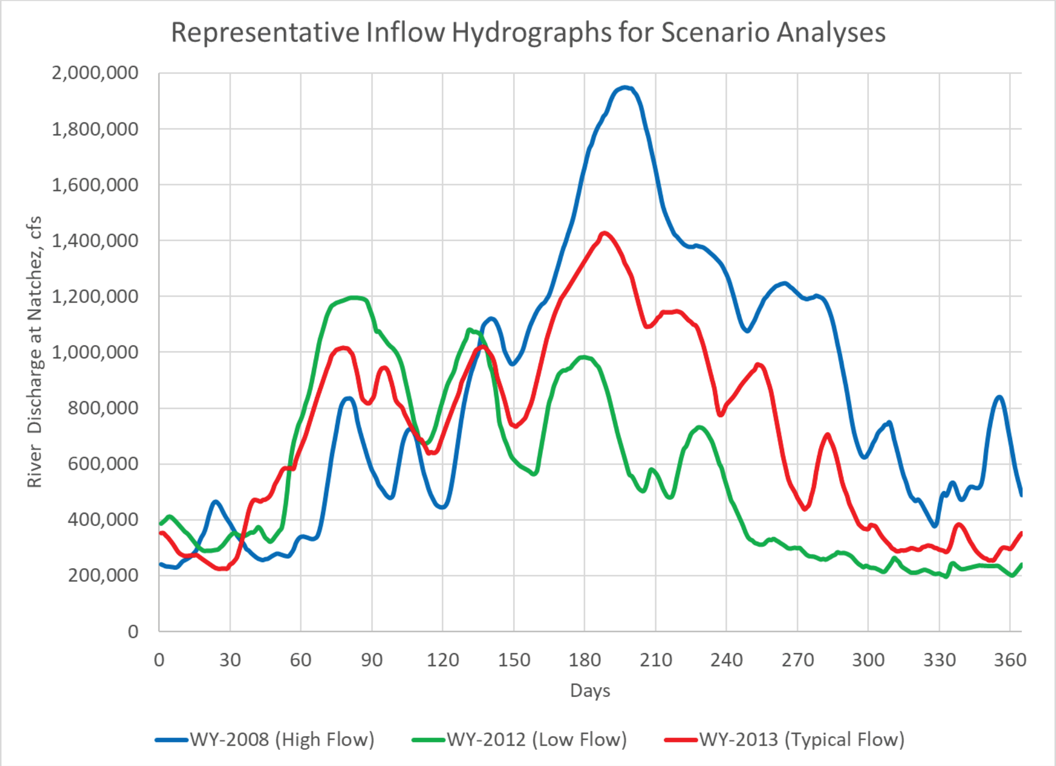
The sediment removal index (SRI) is the ratio of the sediment removal ratio for a given scenario to the sediment removal ratio for the base condition. It is a way to rapidly assess the relative impacts of each scenario on the sediment diversion characteristics of the ORCC. An index value greater than 1 indicates increased sediment diversion relative to the base condition, an index value less than 1 indicates decreased sediment diversion relative to the base condition. The sediment removal index is computed as follows:

$$SRI_{Scenario-i} = \frac{SRR_{Scenario-i}}{SRR_{BaseCondition}} \tag{4}$$

4.2 Base Condition simulations

The base conditions were simulated with three separate flow years, intended to represent low, typical, and high flow years. The historic inflow hydrographs and ORCC operational protocols from WY 2008, 2013, and 2012 were chosen to represent high, typical, and low flow conditions, respectively. The inflow hydrographs for these years are shown in Figure 23.

Figure 23. Representative inflow hydrographs for scenario analyses.



4.2.1 Base Condition simulations: morphologic response

Each of the flow years was simulated independently. The bed displacement (i.e., the change in bed elevation) associated with each flow year is shown in Figure 24, Figure 25, and Figure 26.

Figure 24. Base Condition bed displacement at the end of the high flow year (WY 2008).

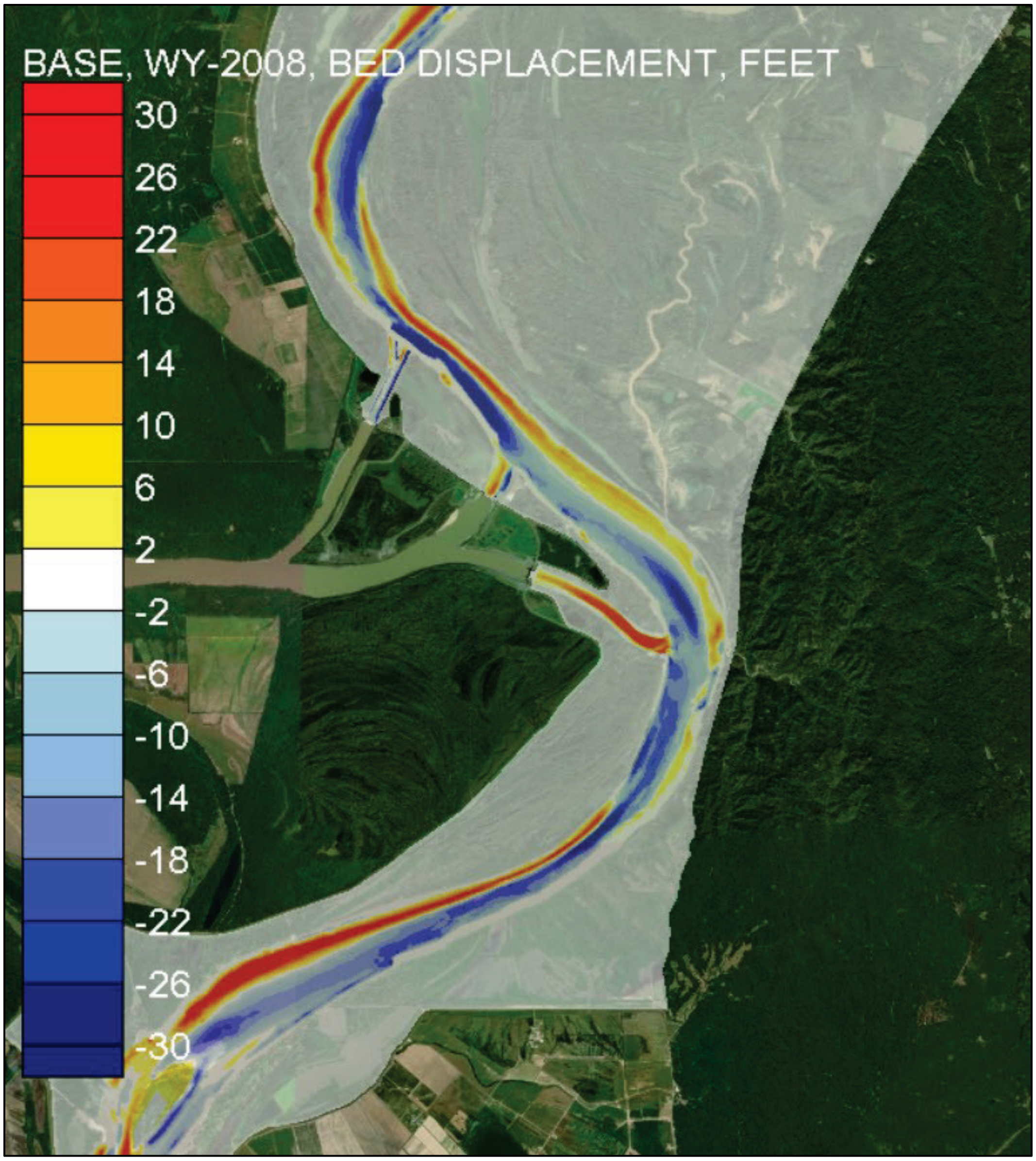


Figure 25. Base Condition bed displacement at the end of the typical flow year (WY 2013).

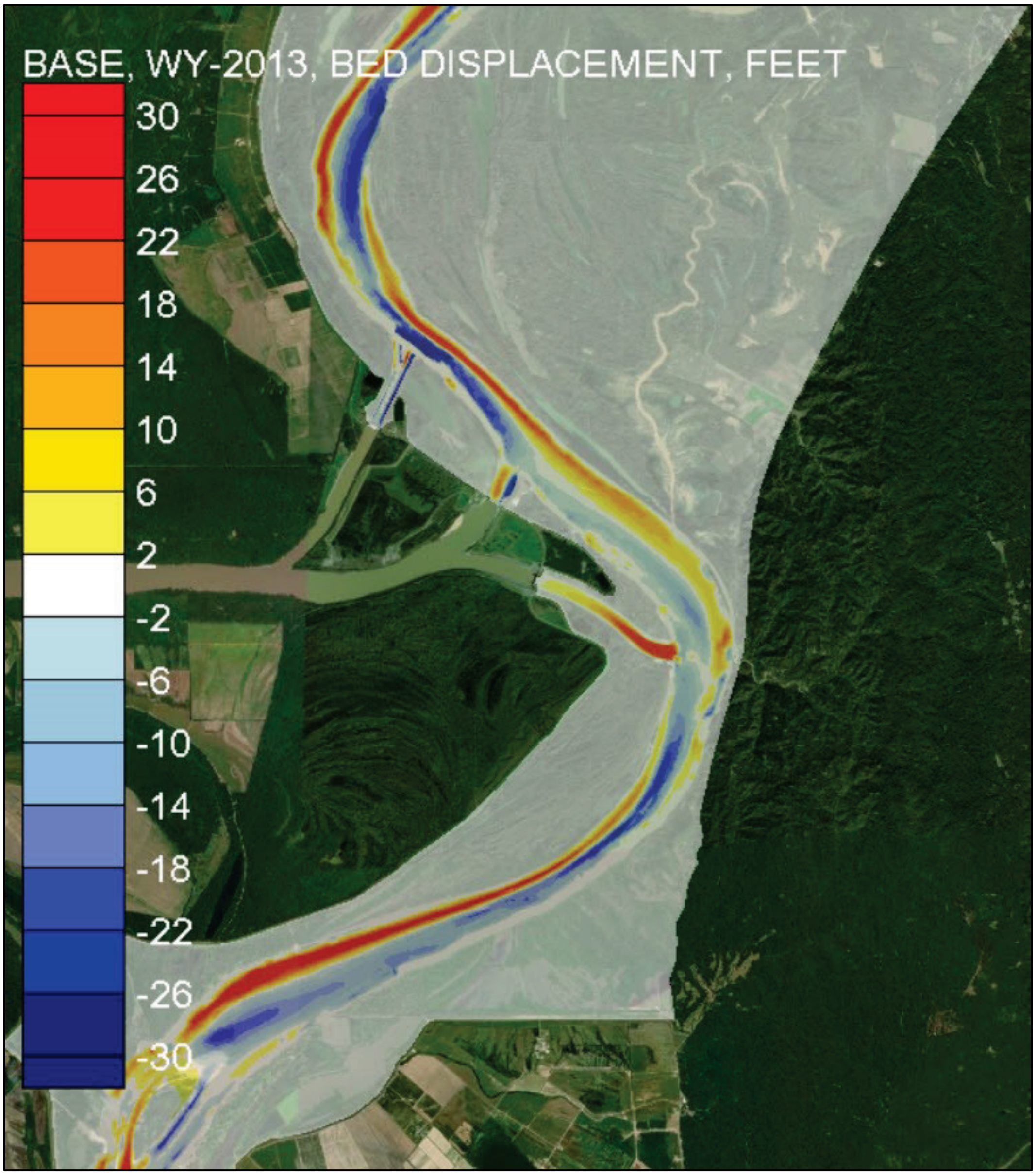
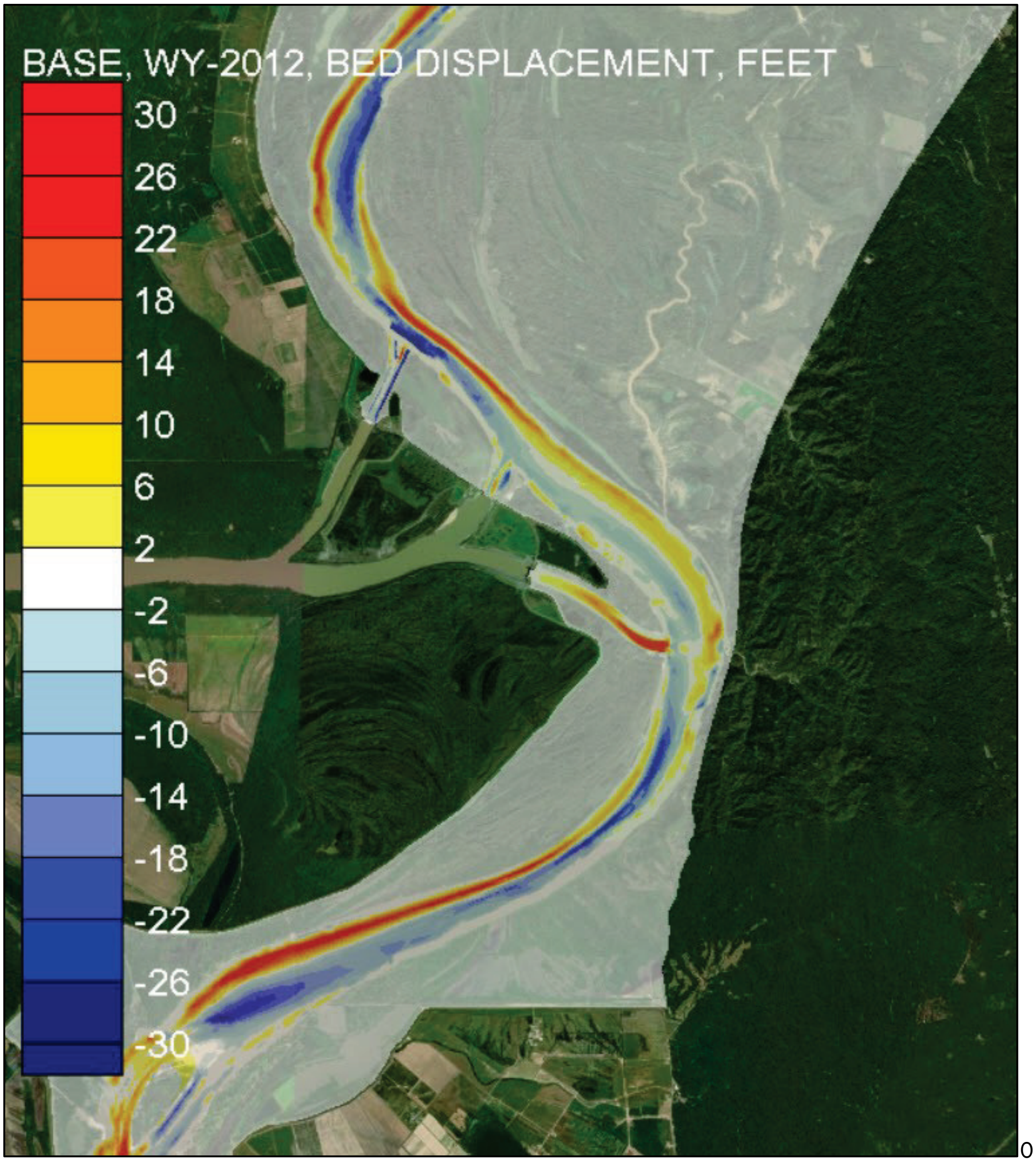


Figure 26. Base Condition bed displacement at the end of the low flow year (WY 2012).



For each scenario simulation, there is a pattern of deposition along the left descending bank of the Mississippi River opposite the ORCC, and scour along the center of the Mississippi River. However, the degree of deposition and scour is different for each simulation. Notably, there is much greater net scour in the Mississippi River for the high flow year than for the other flow years.

The model also yields consistent accumulation of sediment in the Auxiliary Entrance Channel. This accumulation is consistent with both the Auxiliary Entrance Channel design and the observed morphologic patterns (USACE 1980a). The Auxiliary Entrance Channel was designed to trap sediment that would then be transported through to the downstream side via flushing operations.

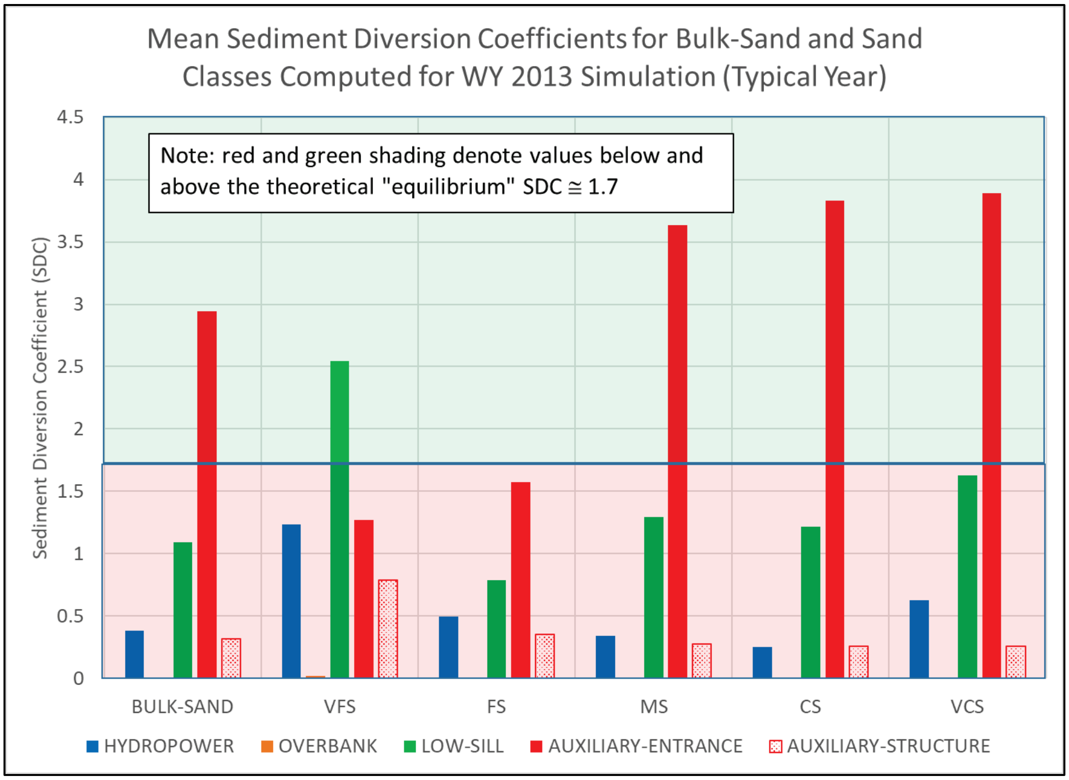
4.2.2 Base Condition simulations: sediment diversion coefficient analysis

The SDC for each of the ORCC complex control structures was estimated from the model results. For this analysis, the statistics for the structural (as opposed to operational) sediment diversion coefficient were calculated. This was done by time-integrating the SDC calculations over a Δt of 1 day and calculating statistics for the SDC for each day that the structure was operated, for the typical flow year simulation (WY 2013).

The mean values of the SDC for each of the ORCC structures are given in Figure 27. For each calculation except for the Auxiliary Structure, the riverside range (i.e., cross section) is located upstream of the hydropower structure at Union Point (Figure 1). The diversion range is located at each diversion structure.

The Auxiliary Structure is analyzed for two different diversion ranges. One range is at the intersection of the Auxiliary Entrance Channel and the Mississippi River (Auxiliary-riverside) and the other is at the Auxiliary Structure. This is done because the Auxiliary Entrance Channel stores most of the sediment that is diverted, only passing it through the structure during designated flushing events. Therefore, the auxiliary-riverside range is the appropriate measure of what is diverted from the Mississippi River (and eventually to the Atchafalaya). The diversion structure range illustrates the volume of sediment passing under normal operations, but it does not include flushing flows unless they are included in the boundary conditions for a given simulation.

Figure 27. Time-mean values of the sediment diversion coefficient for the ORCC diversion structures: computed for WY 2013 simulation (typical year).



These SDC values reflect similar sediment diversion characteristics to those that have been obtained from multiple studies (Heath et al. 2015; Ayres 2018). The ORCC is essentially a manifold system. It takes advantage of the natural hydraulic sorting associated with the river bends to preferentially exclude and/or extract sediment, depending on the proportion of water diverted at each of the structures.

- The Hydropower Channel entrance is located on the outside of the bend, perched over the deep thalweg of the river channel. It diverts a relatively low concentration of sand.
- The Overbank Structure is a perched structure located well away from the river, in the batture. It is essentially a clear-water diversion (Figure 3).
- The Low Sill Channel entrance is located in the crossing. It is located next to a shoal in the channel that forms downstream of the hydropower channel diversion, due to the loss of stream power to that diversion. It tends to divert a larger proportion of sand than the Hydropower Channel.

- The Auxiliary Entrance Channel is located on the inside of a river bend, at a shoal formed as a result of channel expansion, the point bar associated with the bend, and shoaling downstream of the low sill diversion. It diverts a relatively high concentration of sand.
- The Auxiliary Structure SDC values are much lower than the Auxiliary Entrance SDC values. This indicates sediment trapping in the Auxiliary Entrance Channel. This aspect of Auxiliary Entrance Channel behavior is discussed in more detail in Section 4.4.2.

The influence of the natural bend sorting effects is generally proportional to the characteristic grain diameter of each grain class. That is, coarser grains experience more sorting than finer grains. This is reflected in the SDC values by grain class: the coarser grains have a broader range of values than the finer grains.

The notable exception to this is the very fine sand (VFS) class. VFS in this part of the Mississippi River transports as a hybrid class: neither fully bed material load nor full wash load. It is only found in appreciable quantities in the bed material sampled from more quiescent areas, such as the channel margins, in the lee of structures, or in the batture. Hence, it tends to transport along the channel margins in higher concentrations than in the main channel. This is why there are values of the SDC that are greater than 1 for VFS: the diversions are drawing water at the channel margin, where VFS concentrations are greater than in the main flow of the river.

From Chapter 3, the analytic value of the *equilibrium* SDC is approximately 1.7. This is shown in the plot as red and green shading regions. Note, however, that this equilibrium value is, by definition, the value of the SDC necessary to maintain equal river channel dimensions both upstream and downstream of the diversion. This means, for example, that if the downstream channel has already adjusted to the presence of a diversion with a SDC lower than the equilibrium value, then changing the diversion to the equilibrium SDC will necessarily scour the downstream channel.

The values reported in Figure 27 are time-mean values. The actual values of the SDC are subject to significant variation. Figure 28 through Figure 32 are box-and whisker plots of the median, mean (small x), statistical quartiles, minimum, and maximum of the SDC values. Note that the vertical axis of each of the plots is uniquely scaled such that the characteristic values for each structure can be easily examined.

Figure 28. Sediment diversion coefficient quartiles (box and whisker plot): Hydropower Structure.

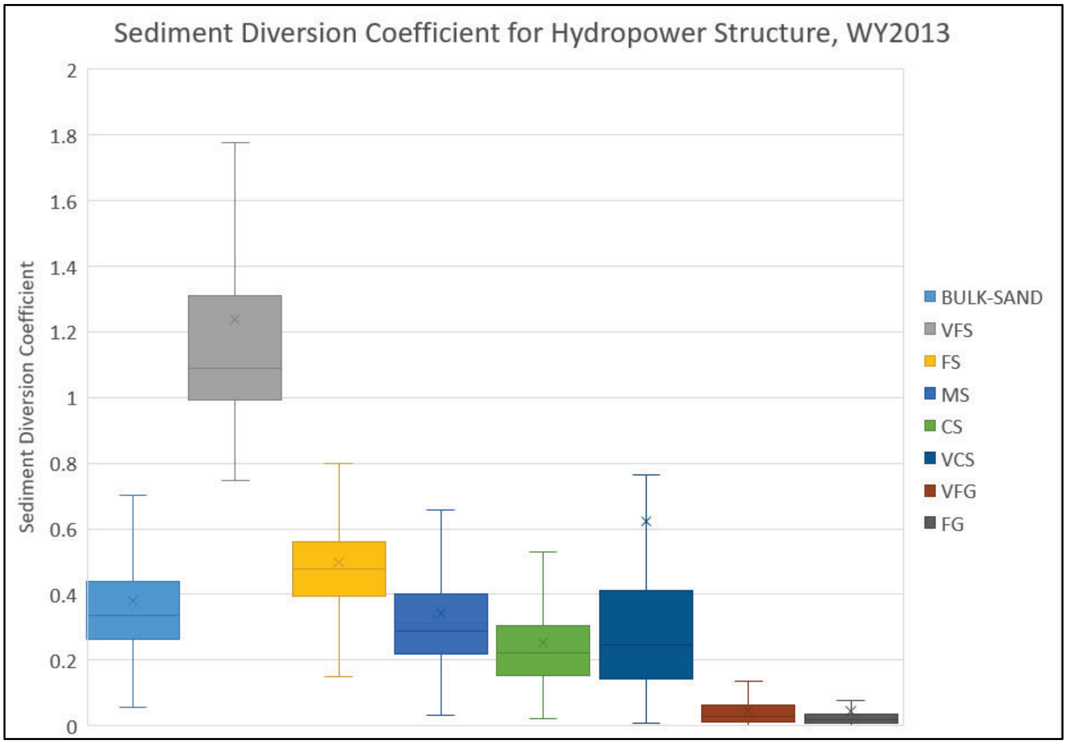


Figure 29. Sediment diversion coefficient quartiles (box and whisker plot): Overbank Structure.

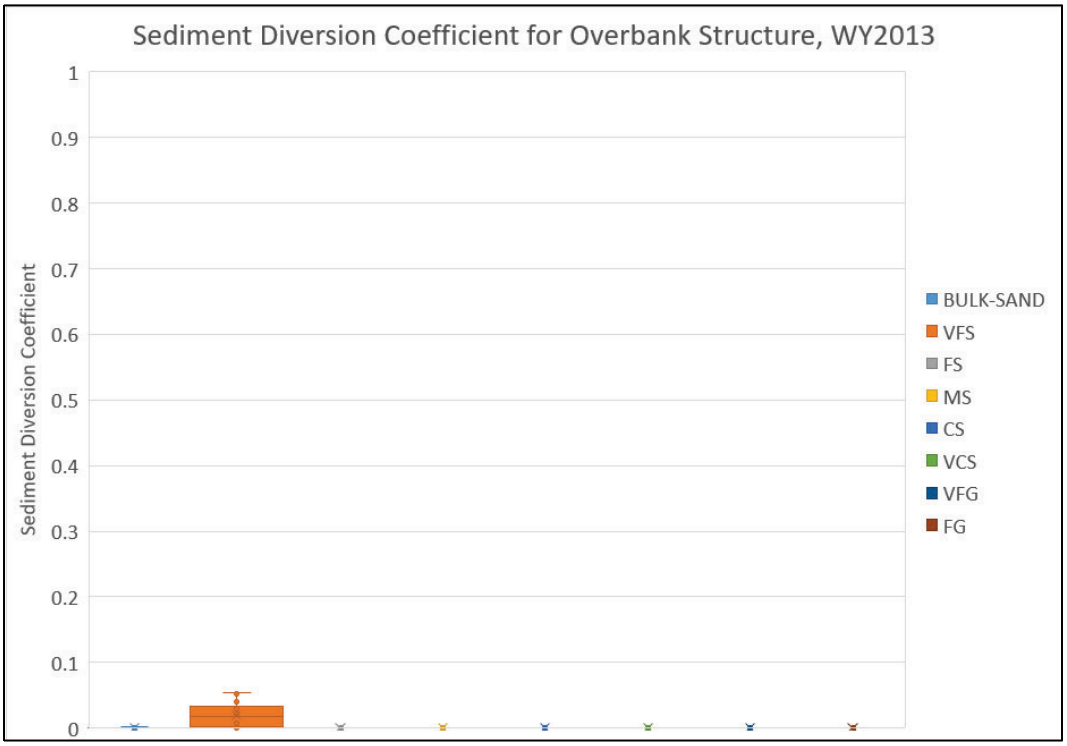


Figure 30. Sediment diversion coefficient quartiles (box and whisker plot): Low Sill Structure.

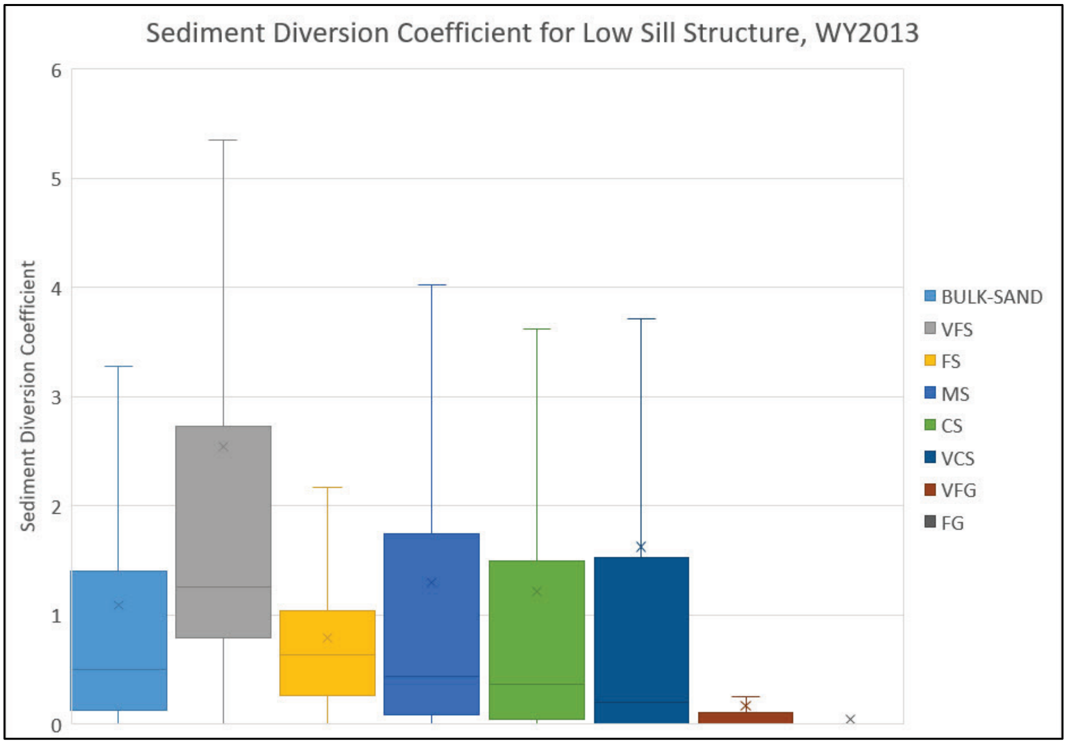


Figure 31. Sediment diversion coefficient quartiles (box and whisker plot): Auxiliary Entrance Channel (riverside).

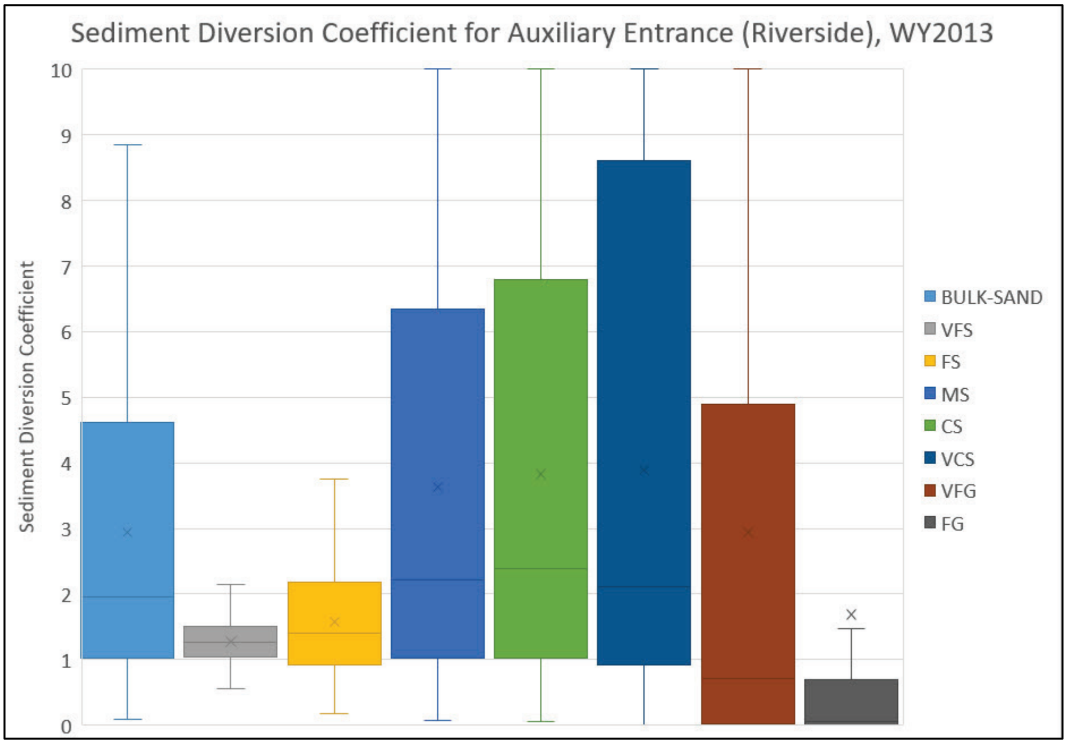
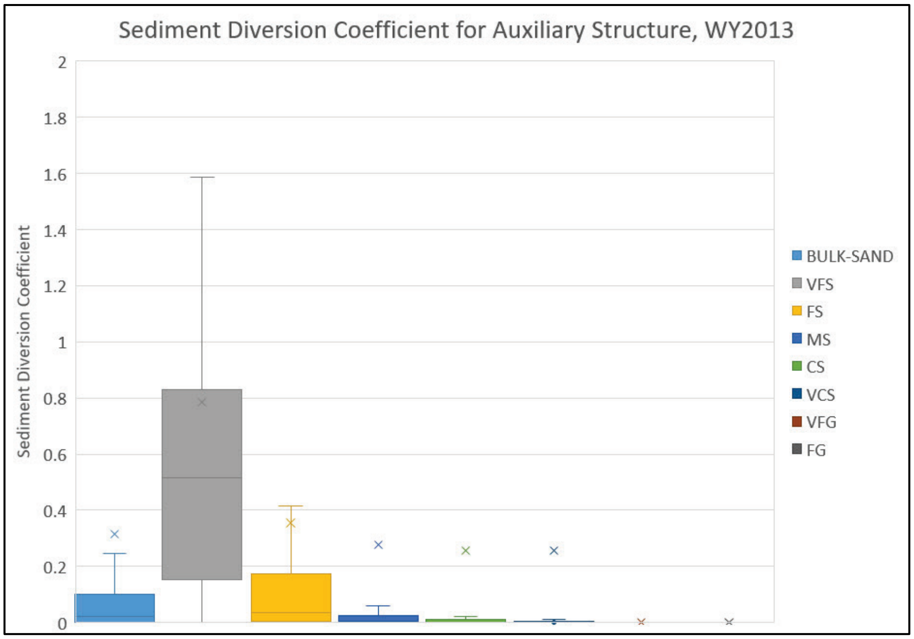


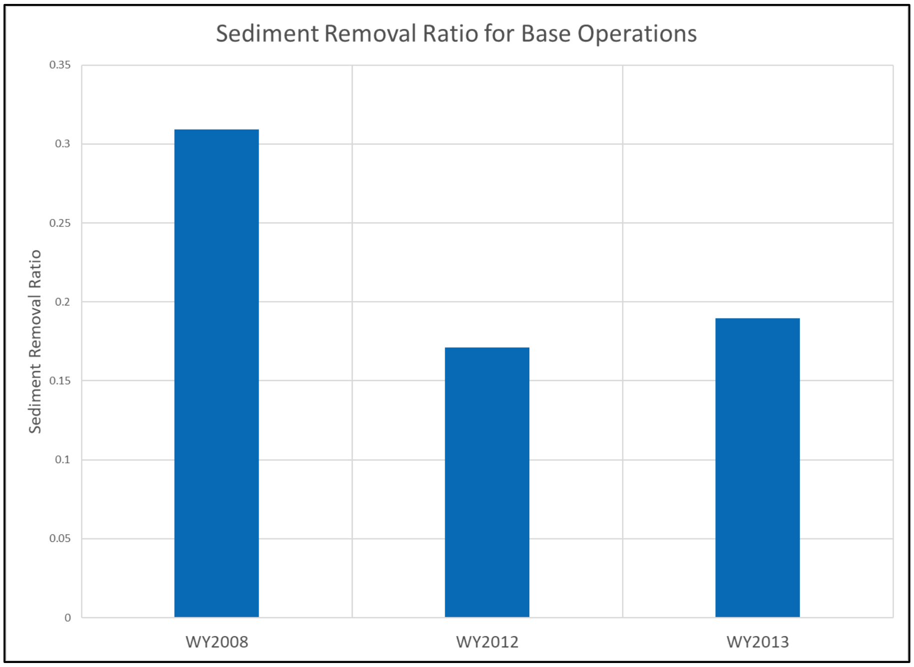
Figure 32. Sediment diversion coefficient quartiles (box and whisker plot): Auxiliary Structure.



4.2.3 Base Condition simulations: sediment removal ratio analysis

It is useful to compare between WYs to investigate the sediment diversion characteristics of the ORCC between years. Figure 33 depicts the SRR of the ORCC for each of the simulated years.

Figure 33. Sediment removal ratio for Base operations, for each simulated WY.



These ratios represent the total mass of sediment diverted to the ORCC as a fraction of the total mass of sediment in the Mississippi River (at Union Point) for each year. The mass entering the Auxiliary Entrance Channel (as opposed to the mass passing the Auxiliary Structure) is used in this calculation, so this is a measure of what is diverted, rather than what is passed through the structure.

Note that the WY 2012 and 2013 are not significantly different from each other, but WY 2008 shows a significant increase in the fraction of sediment passed. This means that the complex, as operated, is more efficient at passing sediment for very high flow years. This is largely due to the fact that a much greater fraction of the flow is diverted at the Low Sill and Auxiliary in high flow years when more sand is moving. The sediment diversion coefficient analysis demonstrates that those structures divert more sediment than does the hydropower structure.

4.3 Description of scenarios

A series of scenarios were developed to determine their effects on both the sediment diversion characteristics of the ORCC and the morphologic response of the Mississippi River to the changes. The scenarios were chosen by the OMAR Assessment steering committee. These were chosen to represent a range of options, some more feasible than others, that could potentially be implemented as a means of altering the sediment and/or water balance at the ORCC site. The goal of the analysis is to provide insight that can be used to help address the charge questions developed by the steering committee for the OMAR Assessment.

The scenarios are grouped into three subgroups: operational scenarios, dredging scenarios, and structural scenarios. A description of each scenario is given in Table 8.

A few descriptions of terminology used Table 8 in will assist in interpreting it:

- *Latitude flow* is the combined discharge of the Mississippi and Red Rivers, just upstream of the ORCC.
- *Ratio 1* is an operational plan for the ORCC that utilizes the Low Sill and Auxiliary structures only and is intended to maximize the diversion

of sediment from the Mississippi River. It was developed as part of the physical model study cited here (USACE 1980a).

Table 8. OMAR Assessment multi-dimensional modeling scenarios.

Scenario ID	Brief Description	Full Description
Operational Scenarios		
Scenario 3	Ratio 1	RATIO 1, as defined in Design Memorandum 17 (USACE 1980b): This is a scenario where there is no hydropower, and a large amount of flow goes through the Auxiliary Structure.
Scenario 4	Ratio 1 with Hydropower	RATIO 1 WITH HYDROPOWER, (as defined in USACE [1988]). Hydropower shares with Auxiliary. Low Sill is not used in this scenario. Anything that would go to Low Sill in the table of the O&M Manual will be added to Auxiliary instead.
Scenario 5	60/40 during high flow	60/40 latitude flow distribution during high flow but 70/30 on a long-term basis through the use of a payback/tracking algorithm.
Scenario 6	80/20 during high flow	80/20 latitude flow distribution during high flow, but 70/30 on a long-term basis through the use of a payback/tracking algorithm.
Scenario 7	Cap Tarbert Flow at 1.25 Mcfs	All flow over 1.25 Mcfs at Tarbert is diverted through ORCC (up to the capacity of the Atchafalaya). 70/30 latitude flow distribution on long-term basis is maintained through the use of a payback/tracking algorithm.
Scenario 8a	Daily 80/20 no Low Sill constraint	Daily 80/20 latitude flow distribution; no safety constraints on Low Sill head differential.
Scenario 8b	Daily 80/20 with Low Sill constraint	Daily 80/20 latitude flow distribution; apply safety constraints on Low Sill head differential.
Scenario 9	Daily 60/40	Daily 60/40 latitude flow distribution.
Scenario 10	Maximize Auxiliary	Maintain 70/30 latitude flow distribution. Increase contribution to Auxiliary and decrease contribution to Hydropower (up to ~ 1/3 ORCC flow), based on conditions.

Table 8. (cont.) OMAR Assessment multi-dimensional modeling scenarios.

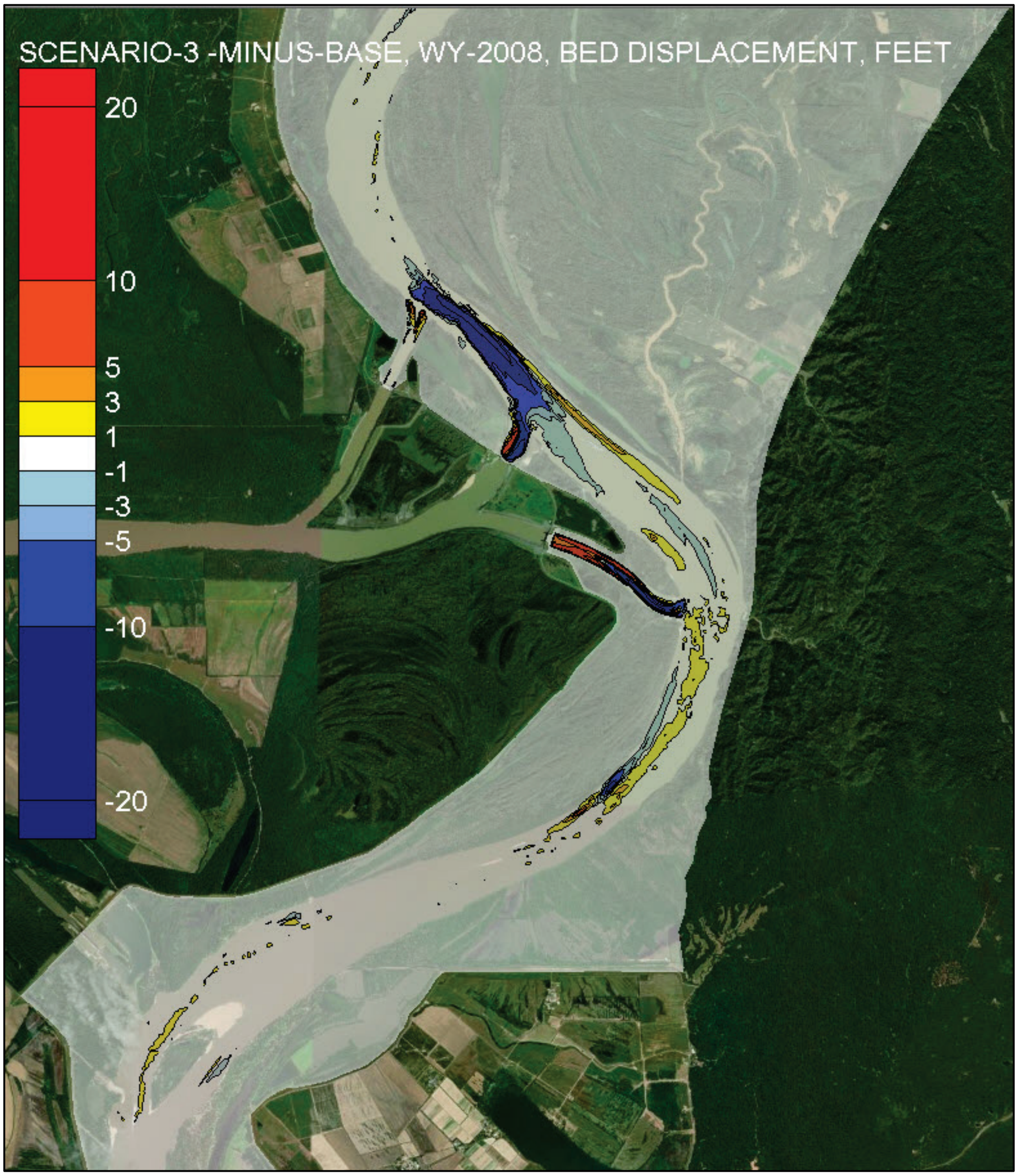
Scenario ID	Brief Description	Full Description
Dredging Scenarios		
Scenario 11	Continuous Dredging at Low Sill	Continuous dredging of the main channel in front of the Low Sill entrance channel with material removed completely from the Mississippi River. 4.75 million tons/yr.
Scenario 12	Annual Dredging at Low Sill with in-river placement	Annual dredging of the main channel in front of the Low Sill entrance channel with material placed back into the Mississippi River water column just east of the dredge site. 4.75 million tons/yr
Scenario 13	Annual Dredging at Low Sill	Annual dredging of the main channel in front of the Low Sill entrance channel with material removed completely from the Mississippi River. 4.75 million tons/yr.
Scenario 14	Continuous Dredging across from Hydropower	Continuous dredging of the bar on the left-descending bank across from the hydropower entrance channel with material removed completely from the Mississippi River. 4.75 million tons/yr.
Structural Scenarios		
Scenario 15	Bendway Weirs at Hydropower	Bendway weirs installed on the right descending bank of the river: three weirs upstream of the hydropower entrance and one weir downstream of the hydropower entrance
Scenario 16	Batture Dike at Hydropower Channel	Dike installed in the right-descending bank batture upstream of hydropower: used to prevent short-circuiting of flow though the batture into the hydropower channel.
Scenario 17	Batture Dikes at all Diversion Channels	Dikes installed in the right-descending bank batture upstream of the hydropower and low sill channels, and both upstream and downstream of the auxiliary entrance channel: used to prevent short-circuiting of flow though the batture into the diversion channels.
Scenario 18	Dikes across from Low Sill	Implementation of left-descending bank dike field as proposed in Plan D-6 in the WES physical model study (Catalyst, Old River Hydroelectric 1999)

4.4 Operational scenarios analysis

4.4.1 Qualitative analysis of Mississippi River morphologic response

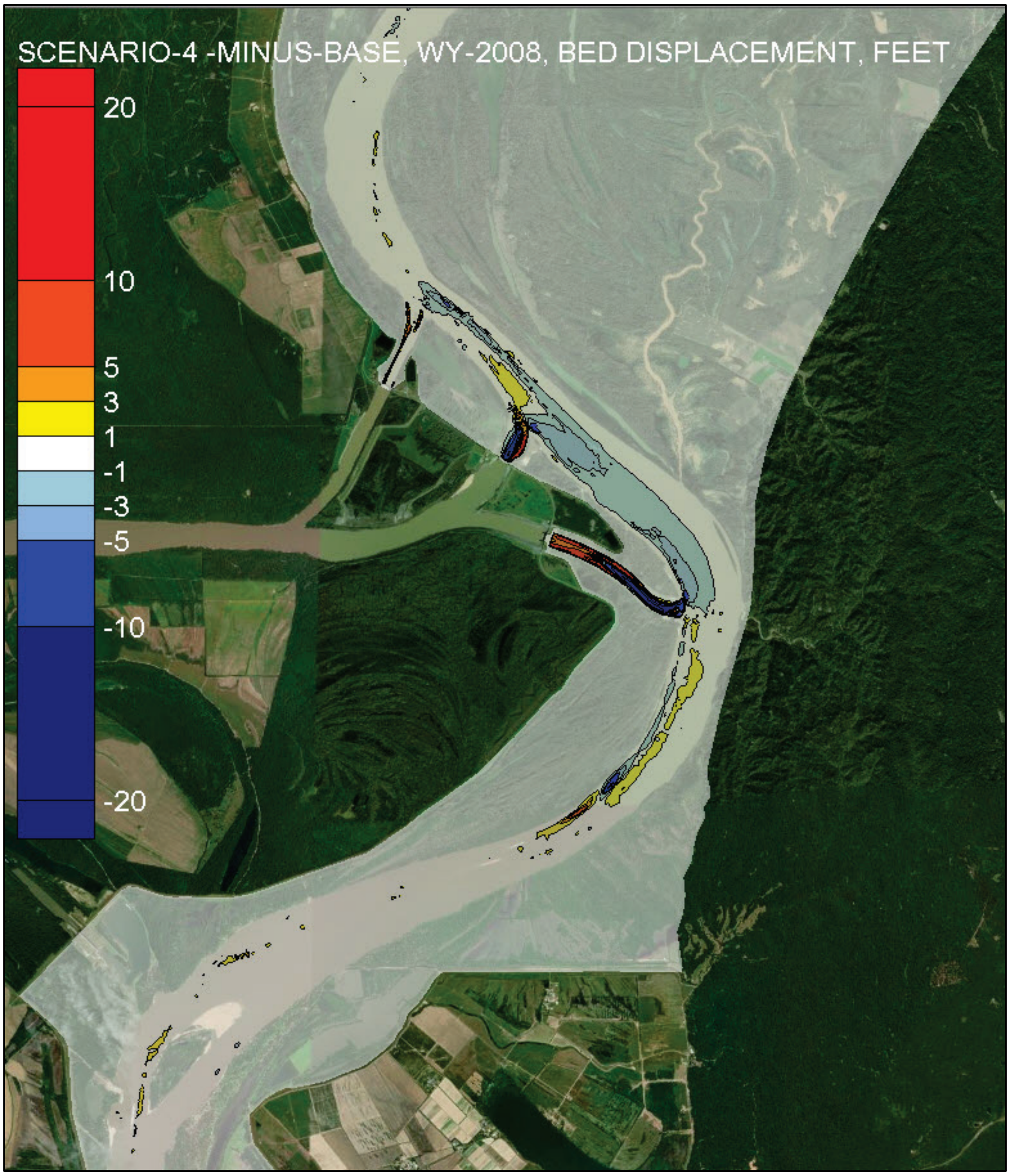
Figure 34 through Figure 42 depict the difference in the bed displacement between each of the scenarios and the base simulation, for the WY 2008 (high flow) simulations. This provides a convenient means to discuss some of the qualitative aspects of the scenario results. Each figure is accompanied by a brief description of the results.

Figure 34. Bed displacement difference WY 2008: Scenario 3 minus Base.



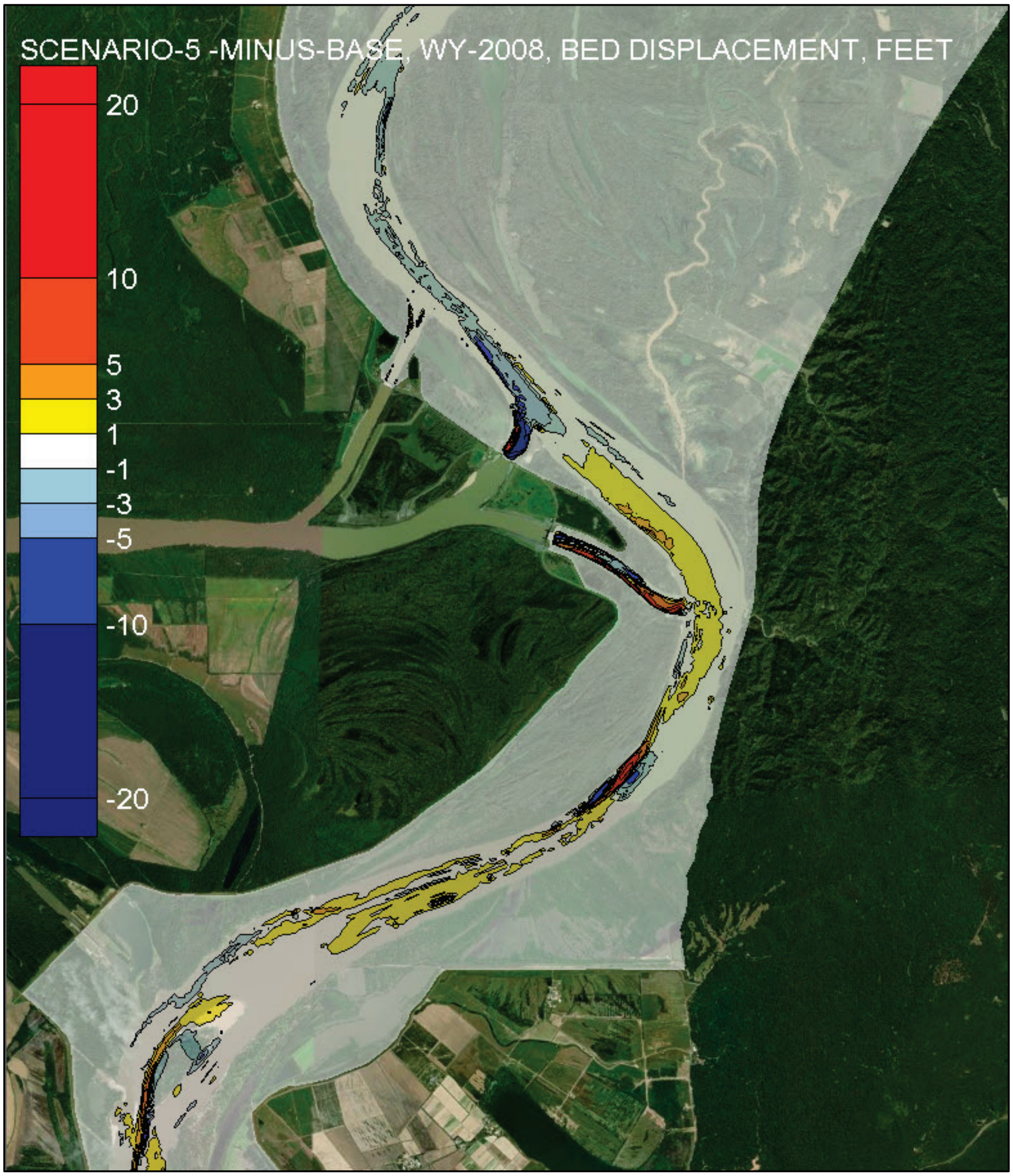
Scenario 3 is Ratio 1 operations, which zeroes all flow diversion at Hydropower and redirects to the other structures. Scour is induced upstream of the Low Sill Structure due to the transfer of flow from the Hydropower structure to the Low Sill Structure and the consequent transfer of the Mississippi River drawdown acceleration to just upstream of Low Sill. There is also evidence of the remobilization of sediment in the Auxiliary Entrance Channel and transfer of shoaling to the section of the channel proximate to the structure.

Figure 35. Bed displacement difference WY 2008: Scenario 4 minus Base.



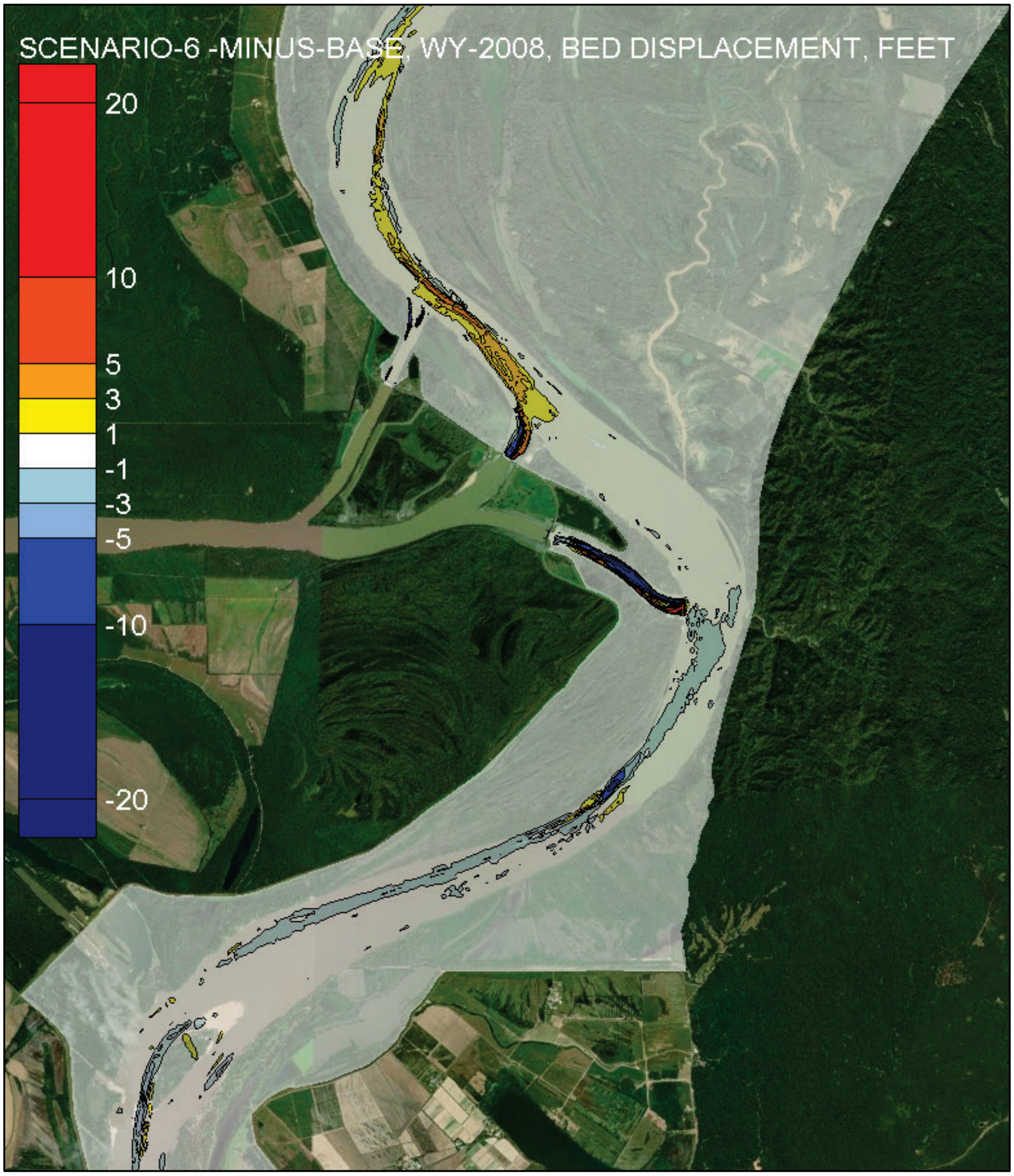
Scenario 4 is Ratio 1 operations, except that the flow at Low Sill in Ratio 1 is transferred to Hydropower. There is an increase in scour in the Mississippi River in between the Low Sill and Auxiliary Entrance Channels. This is associated with increased Auxiliary Structure discharge (relative to base operations).

Figure 36. Bed displacement difference WY 2008: Scenario 5 minus Base.



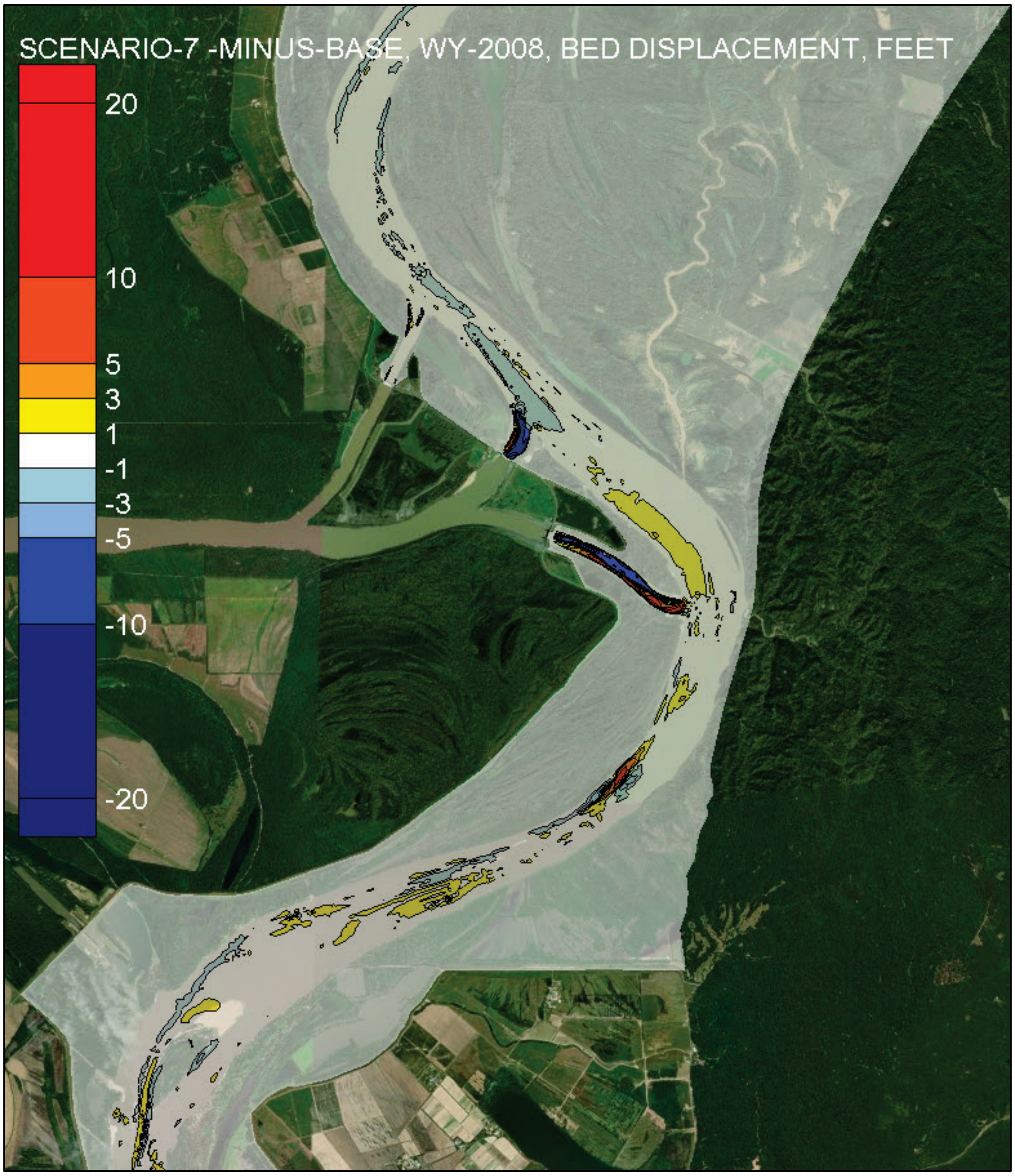
There is an increase in scour in the Mississippi River upstream of Low Sill and an increase in deposition downstream of Low Sill in the Mississippi River. These are due to the increase of flow through the ORCC at high flow (60/40 latitude flow distribution at high flow). Both the increased upstream scour and increased downstream deposition are consistent with analytic diversion theory (see Chapter 3).

Figure 37. Bed displacement difference WY 2008: Scenario 6 minus Base.



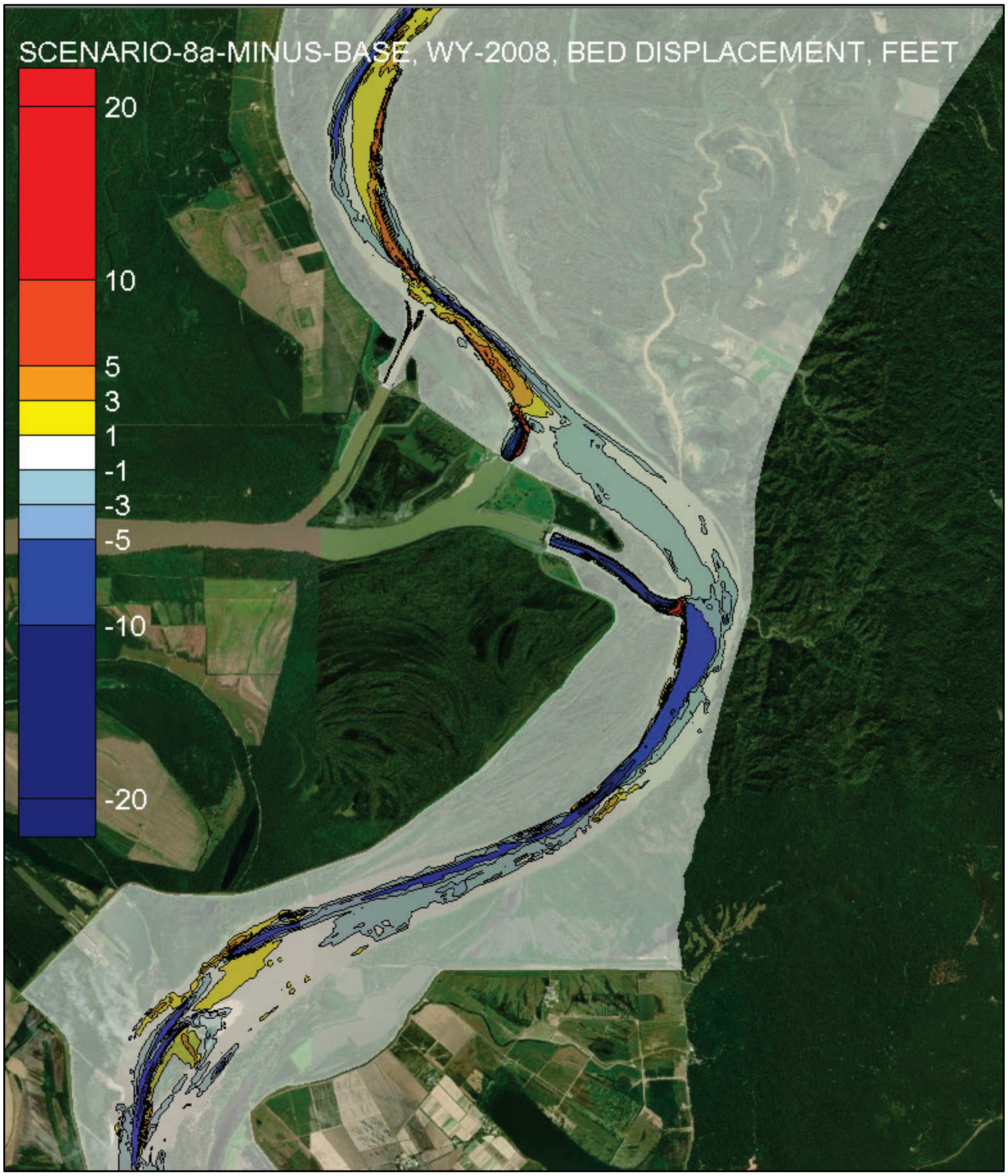
The effects observed for Scenario 6 (80/20 latitude flow distribution at high flow) are essentially a mirror image of the effects observed for Scenario 5 (60/40 latitude flow distribution at high flow). There is a decrease in scour in the Mississippi River upstream of Low Sill and a decrease in deposition downstream of Low Sill in the Mississippi River. These are both due to the reduction of flow through the ORCC at high flow. Both the decreased upstream scour and decreased downstream deposition are consistent with analytic diversion theory (see Chapter 3).

Figure 38. Bed displacement difference WY 2008: Scenario 7 minus Base.



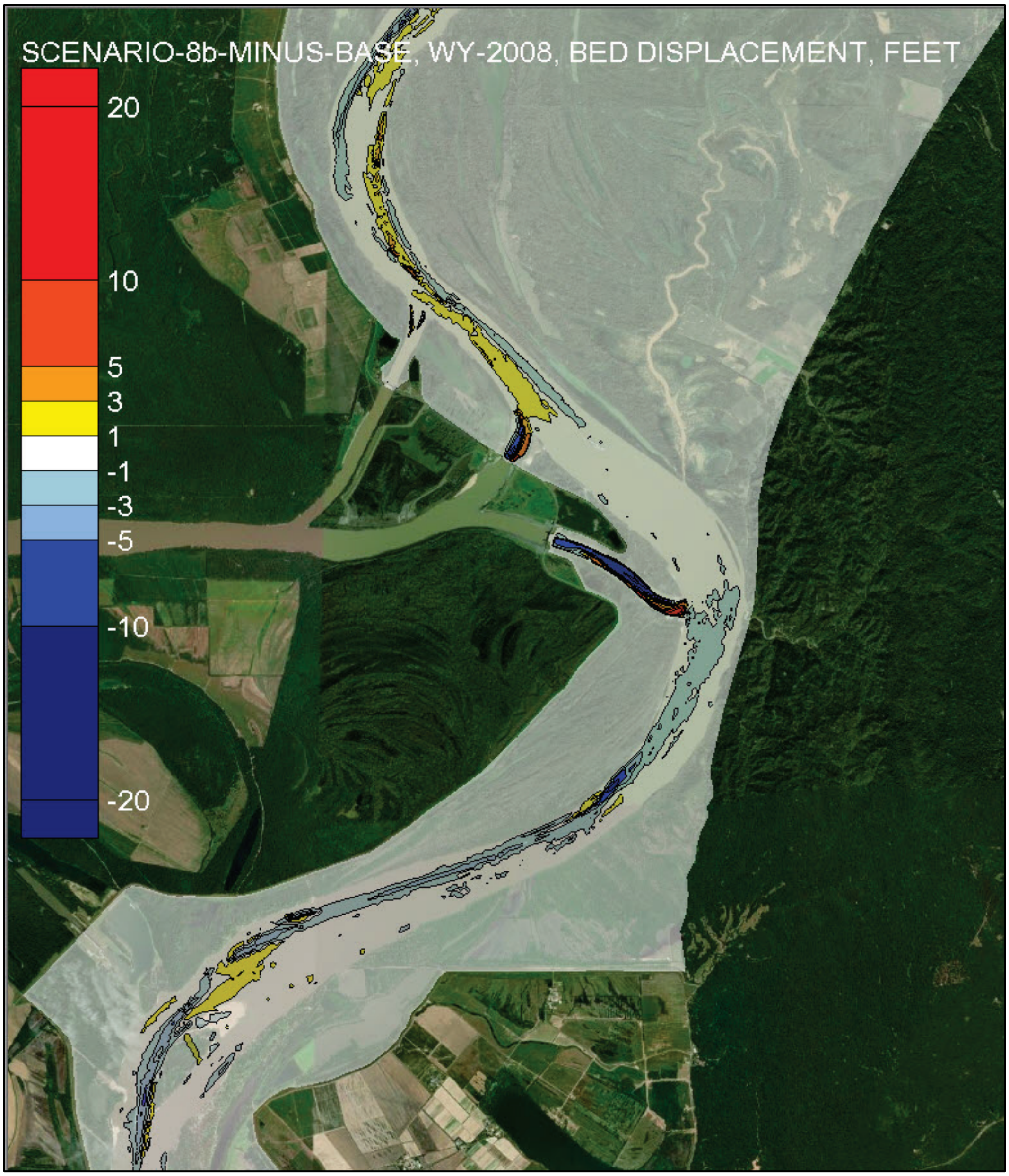
For Scenario 7, any excess Mississippi River discharge above 1.25 Mcfs at Tarbert Landing is redirected though the ORCC. The results are qualitatively similar to those observed for Scenario 5. There is an increase in scour in the Mississippi River upstream of Low Sill, and an increase in deposition downstream of Low Sill in the Mississippi River. These are both due to the increase of flow through the ORCC at high flow. Both the increased upstream scour and increased downstream deposition are consistent with analytic diversion theory (see Chapter 3).

Figure 39. Bed displacement difference WY 2008: Scenario 8a minus Base.



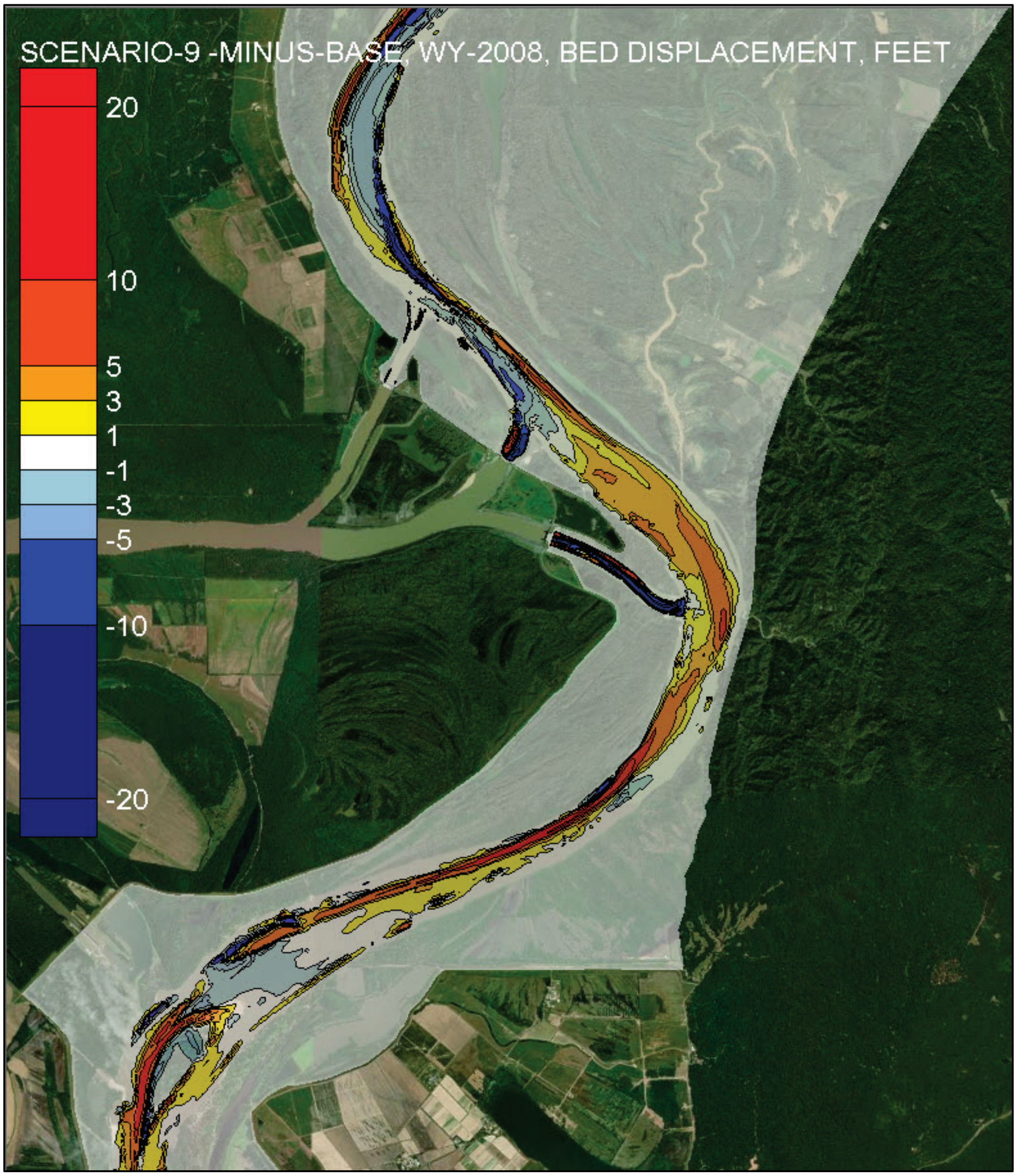
Scenario 8a is daily 80/20 latitude flow distribution. This reduction in ORCC discharge results in both a reduction in upstream scour (or induced upstream deposition) and a reduction in downstream deposition. Both the reduced upstream scour and reduced downstream deposition are consistent with analytic diversion theory (see Chapter 3).

Figure 40. Bed displacement difference WY 2008: Scenario 8b minus Base.



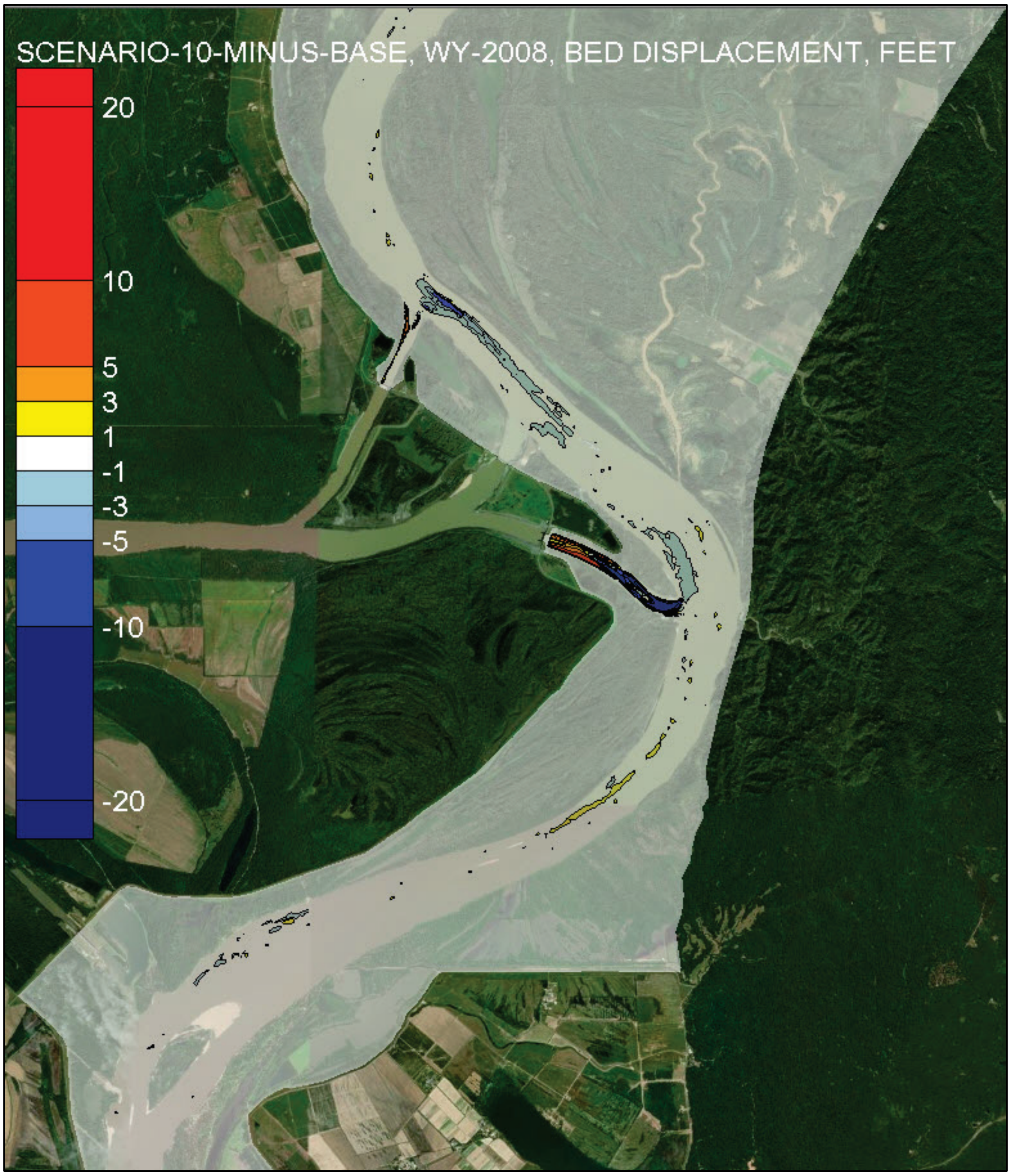
Scenario 8b is daily 80/20 latitude flow distribution, with a head differential constraint applied to the Low Sill that limits the permissible reduction in discharge through the ORCC. The result is qualitatively similar to Scenario 8a, but the magnitude of the effects is smaller. The reduction in ORCC discharge results in both a reduction in upstream scour (or induced upstream deposition) and a reduction in downstream deposition. Both the reduced upstream scour and reduced downstream deposition are consistent with analytic diversion theory (see Chapter 3).

Figure 41. Bed displacement difference WY 2008: Scenario 9 minus Base.



Scenario 9 is daily 60/40 latitude flow distribution. This increase in ORCC discharge results in both an increase in upstream scour and an increase in downstream deposition. Both the increased upstream scour and increased downstream deposition are consistent with analytic diversion theory (see Chapter 3).

Figure 42. Bed displacement difference WY 2008: Scenario 10 minus Base.



Scenario 10 maximizes the use of the Auxiliary structure. This has the effect of remobilizing stored sediment in the Auxiliary Entrance Channel, effectively reducing the trapping efficiency of the channel and increasing the transport of sediment through the structure. The impacts to the hydropower channel are limited, due to the armored condition of the bed (i.e., the flow is still sufficient to transport the lean sediment load that is diverted at hydropower).

4.4.2 Quantitative analysis of sediment removal and Mississippi River morphologic response

Figure 43 though Figure 45 depict the coarse sediment load diverted through the ORCC for each operational scenario. The loads for each control structure are identified. There is a separate figure for each WY.

Figure 43. Simulated coarse sediment load diverted through the ORCC for the operational scenarios: WY 2008.

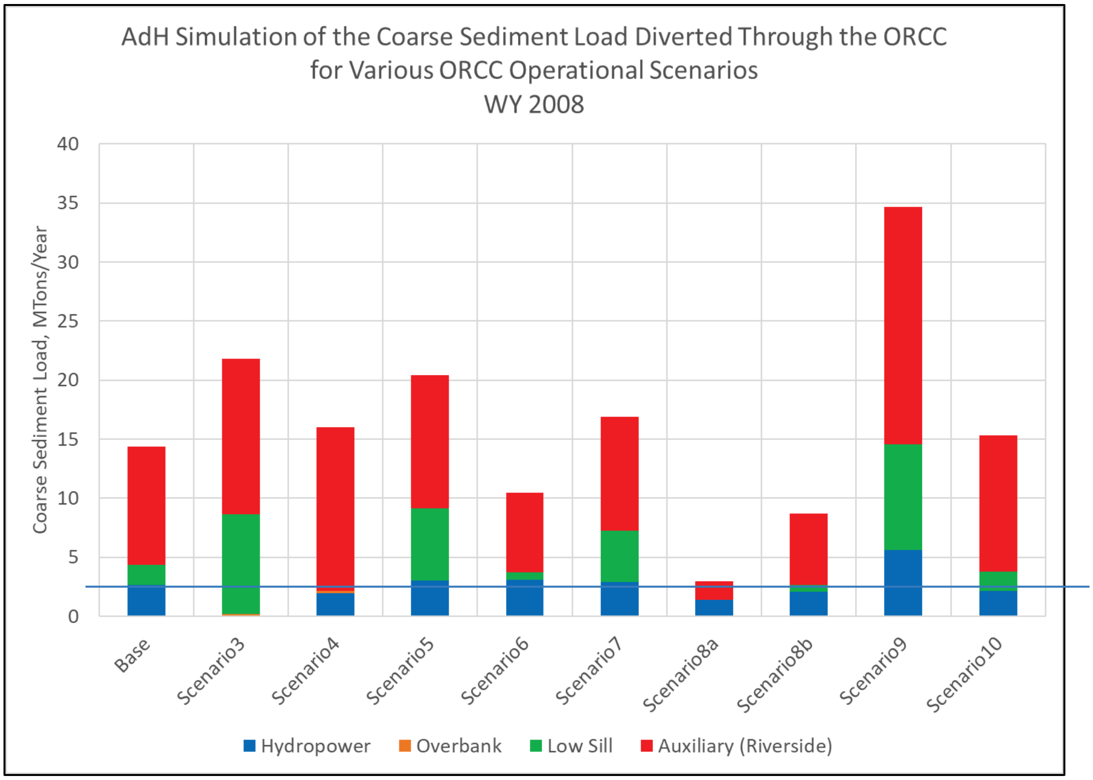


Figure 44. Simulated coarse sediment load diverted through the ORCC for the operational scenarios: WY 2012.

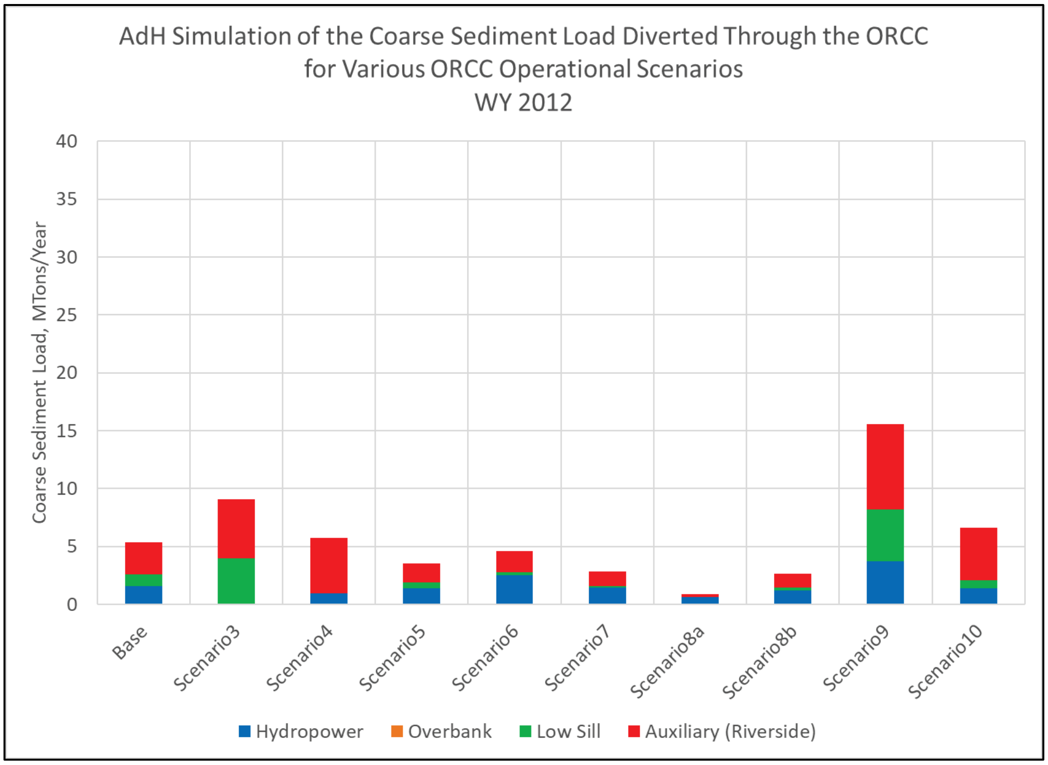
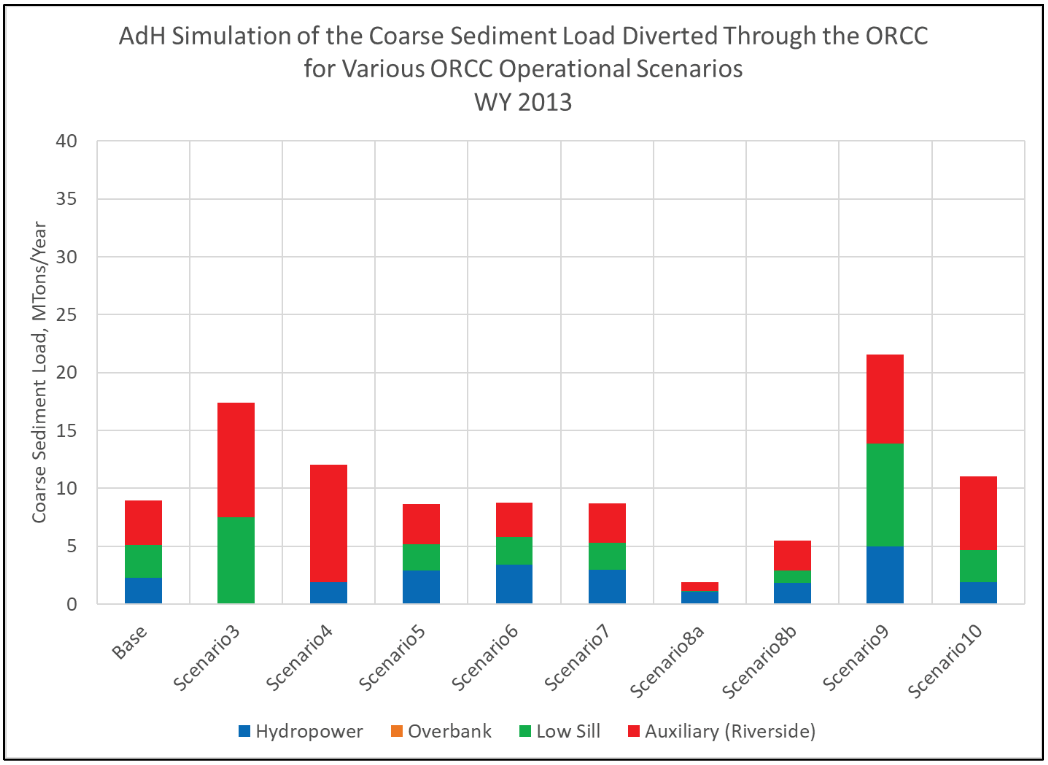


Figure 45. Simulated coarse sediment load diverted through the ORCC for the operational scenarios: WY 2013.

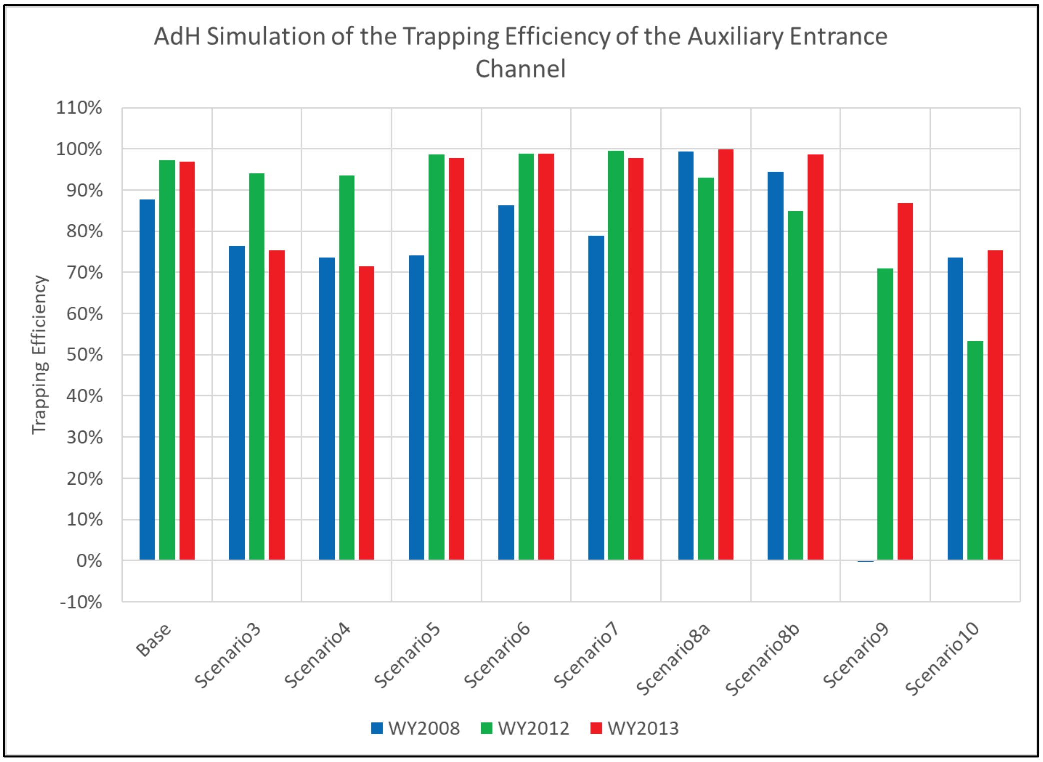


There are two general conclusions that can be drawn from these analyses:

- The preferential utilization of the Low Sill and Auxiliary Structures results in more diverted sediment at the ORCC. This is most clearly observed with the comparison of Scenario 3 (which does not utilize hydropower) and Scenario 4 (which does not utilize low sill) with the Base Condition. These two scenarios divert the same total complex discharge, so the differences are due entirely to the flow distribution among the structures.
- Changes to the latitude flow distribution have a significant effect on the sediment diversion. This is seen most clearly in the results for Scenario 8a (80/20 latitude flow distribution) and Scenario 9 (60/40 latitude flow distribution). Note that Scenario 5 and Scenario 7 result in increased sediment diversion for the high flow WY (2008), but they result in decreased sediment diversion for the other flow years. This is because these scenarios are designed to maintain a long-term flow distribution of 70/30, which means they must reduce the flow diversion in lower flow years to compensate for the increased flow diversion in higher flow years. This further illustrates the influence of the latitude flow distribution on sediment diversion.

Note that these results are evaluating the sediment diverted from the Mississippi River and hence are evaluated using the riverside range of the Auxiliary Entrance Channel. However, a large percentage of the sediment diverted to the Auxiliary Entrance Channel is trapped within the channel and must be either be flushed or dredged on a regular basis. Figure 46 shows the simulated trapping efficiency of the Auxiliary Entrance Channel for each scenario and WY.

Figure 46. Simulated trapping efficiency of the Auxiliary Entrance Channel: operational scenarios.



Note that the trapping efficiency is very high for all of the scenarios. The exception to this is WY 2008, for Scenario 9 (60/40 latitude flow distribution). For this simulation, there is a flushing event that occurs in August of 2008. The event is present in the base condition but results in only minor flushing. The same event, with the Auxiliary inflow increased by 33%, results in a massive flushing of sediment. This shows that flushing is a threshold event in the Auxiliary Entrance Channel.

To understand the influence of the operational scenarios on the local Mississippi River bed morphology, and on the Mississippi River sediment flux downstream of the ORCC, it is useful to perform a mass balance computation. For this mass balance, the control volume is the Mississippi River between Union Point and Tarbert Landing. It is bounded on the west by the ORCC (see Figure 1 for these locations). The western boundary for the Auxiliary Entrance Channel is the riverside location (i.e., the junction of the Auxiliary Entrance Channel and the Mississippi River). Hence, the mass balance reveals the influence of the operations on the Mississippi River between Union Point and Tarbert Landing, excluding the Auxiliary Entrance Channel. The mass balance plots are shown in Figure 47 through Figure 49.

Figure 47. Coarse sediment mass balance for Mississippi River between Union Point and Tarbert Landing: WY 2008.

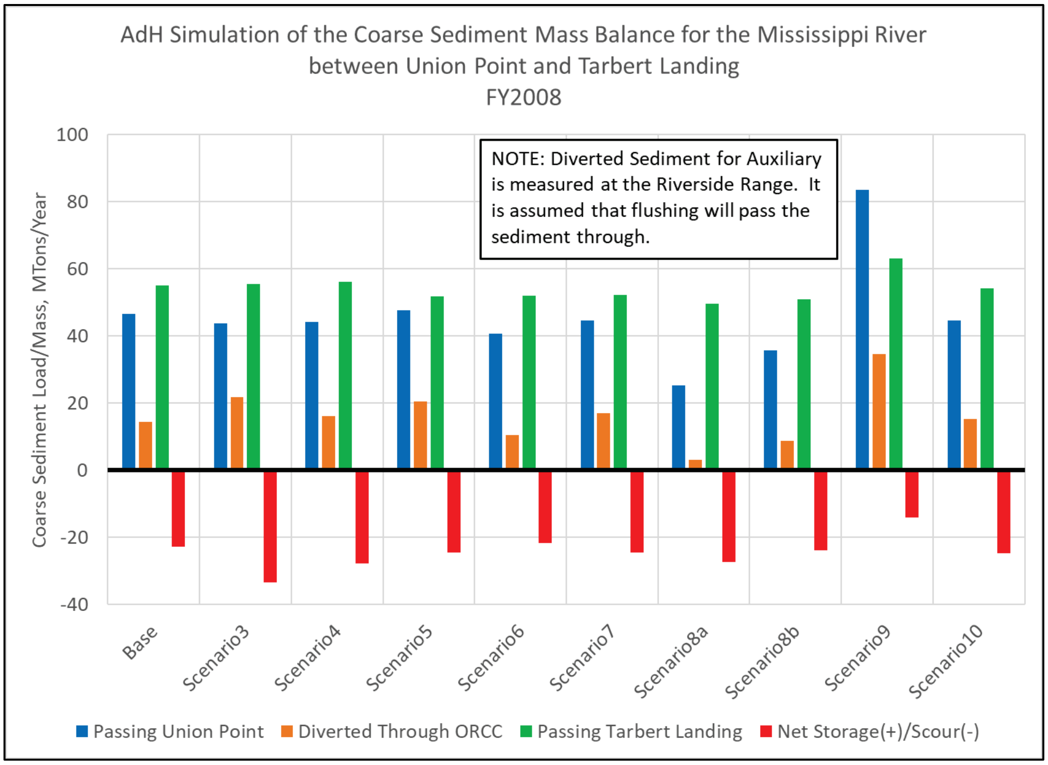


Figure 48. Coarse sediment mass balance for Mississippi River between Union Point and Tarbert Landing: WY 2012.

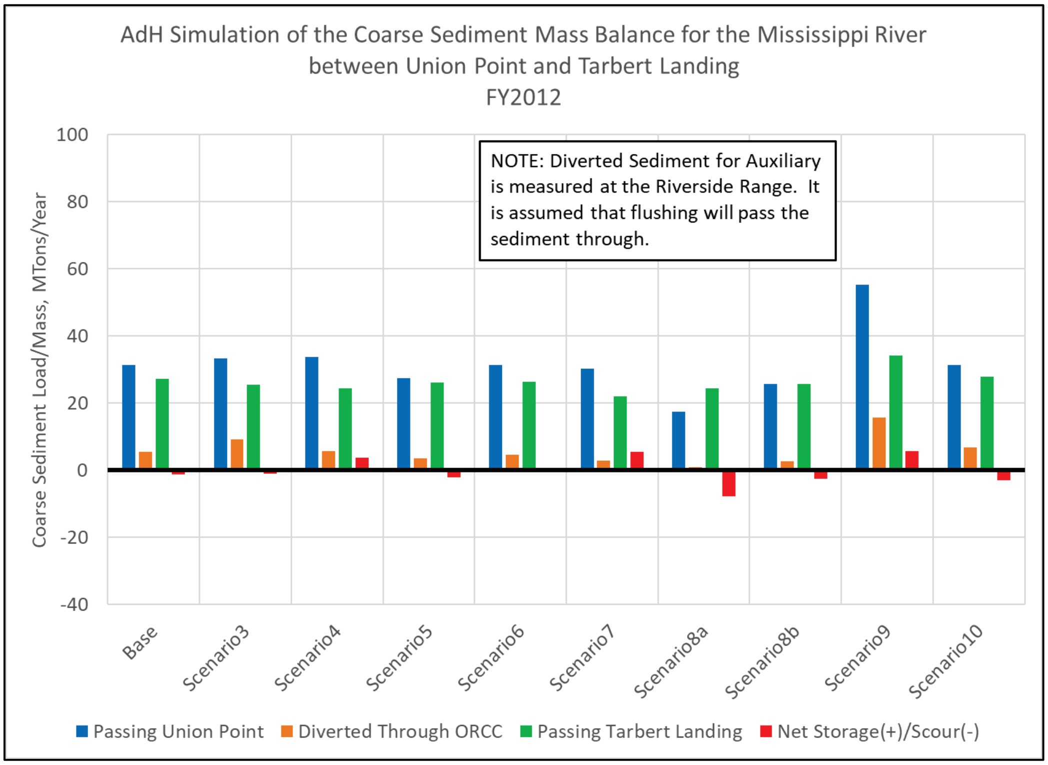
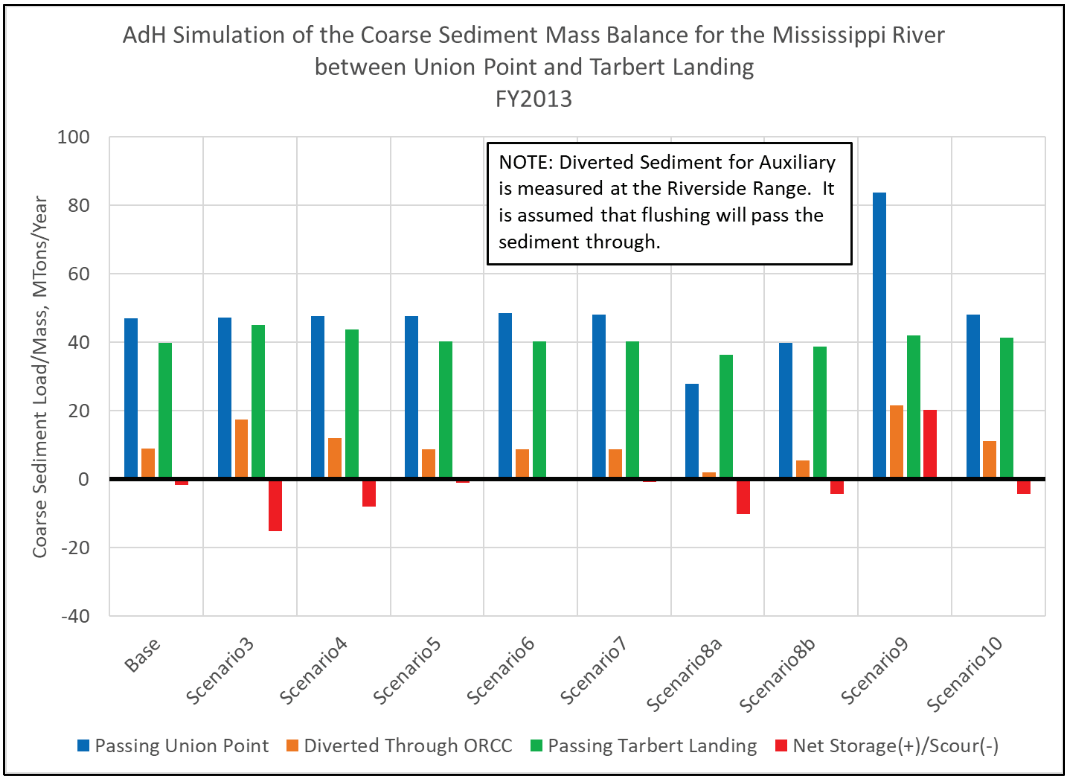


Figure 49. Coarse sediment mass balance for Mississippi River between Union Point and Tarbert Landing: WY 2013.



There are several things to note in these results.

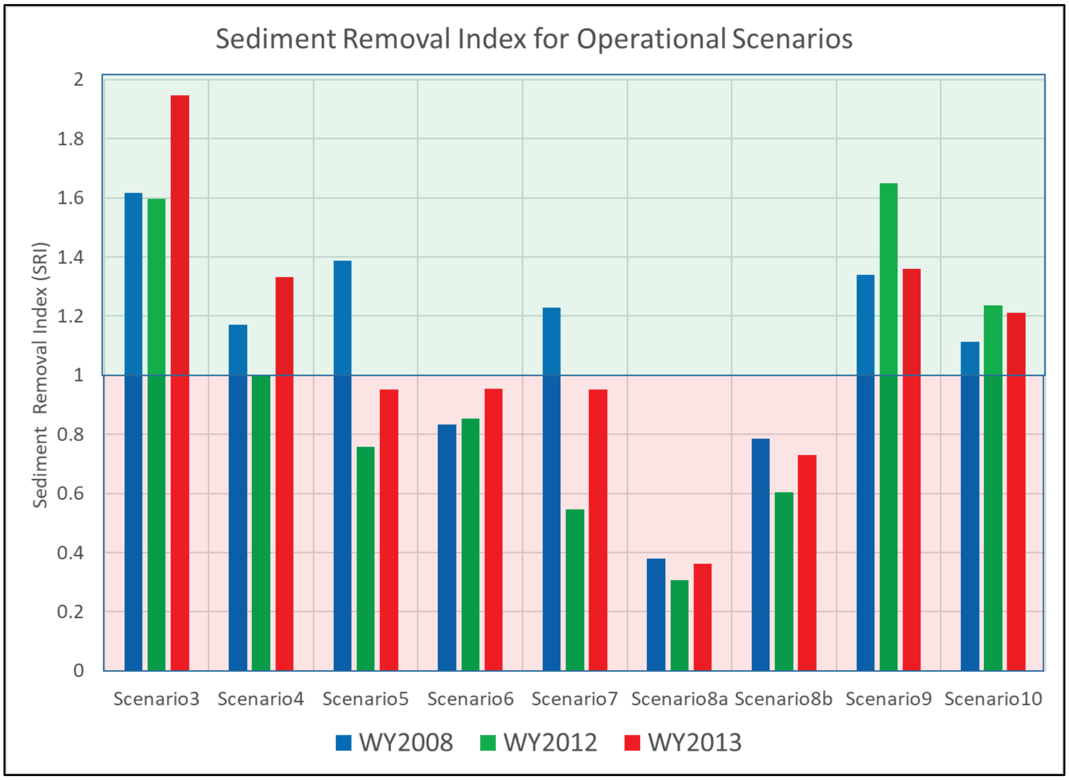
- Scenario 3 appears to erode sediment locally to increase the supply to the ORCC, resulting in little net change in the flux at Tarbert Landing. This is a local effect that is expected to occur until the local morphology adjusts to the diversion (see Chapter 3). Once this adjustment occurs, a larger reduction in the flux at Tarbert Landing is expected.
- The decreased drawdown in the river for Scenario 8a (80/20 latitude flow distribution) results in a decrease in the sediment load at Union Point. This, in turn, decrements the sediment load into the ORCC and the sediment load at Tarbert Landing. This is expected to occur until the local morphology adjusts to the diversion (see Chapter 3). Once this adjustment occurs, the sediment inflow at Union Point is expected to adjust to near Base conditions.
- The increased drawdown in the river for Scenario 9 (60/40 latitude flow distribution) results in an increase in the sediment load at Union Point. This, in turn, augments the sediment load into the ORCC and the sediment load at Tarbert Landing. This is expected to occur until the local morphology adjusts to the diversion (see Chapter 3). Once this

adjustment occurs, the sediment inflow at Union Point is expected to adjust to near Base conditions.

To summarize all of the operational model results, it is useful to perform an SRI. This analysis indicates how much sediment is removed from the river for each scenario, relative to Base conditions. Since the index is computed as a function of the sediment inflow for each scenario, it minimizes the local adjustment effects that are seen in the mass balance analyses. Hence, it is a measure of the long-term performance of the scenarios.

Figure 50 is a plot of the SRI analysis for the operational scenarios. The plot is shaded red for values below 1 (i.e., scenarios that divert less sediment as a proportion of the incoming load than the base) and shaded green for values above 1 (i.e., scenarios that divert more sediment as a proportion of the incoming load than the Base).

Figure 50. The SRI for the operational scenarios.



This analysis indicates that the Scenario 3 (Ratio 1) is more efficient than Scenario 9 (60/40 latitude flow distribution) in the long-term diversion of sediment. This means that a significant portion of the additional sediment diverted in Scenario 9 is due to sediment eroded from the riverbed upstream of the ORCC because of the increased drawdown of the river. Over time, as the river adjusts and this riverbed source is lost, the amount of sediment diverted is expected to be less than would be diverted with 70/30 operations and Ratio 1.

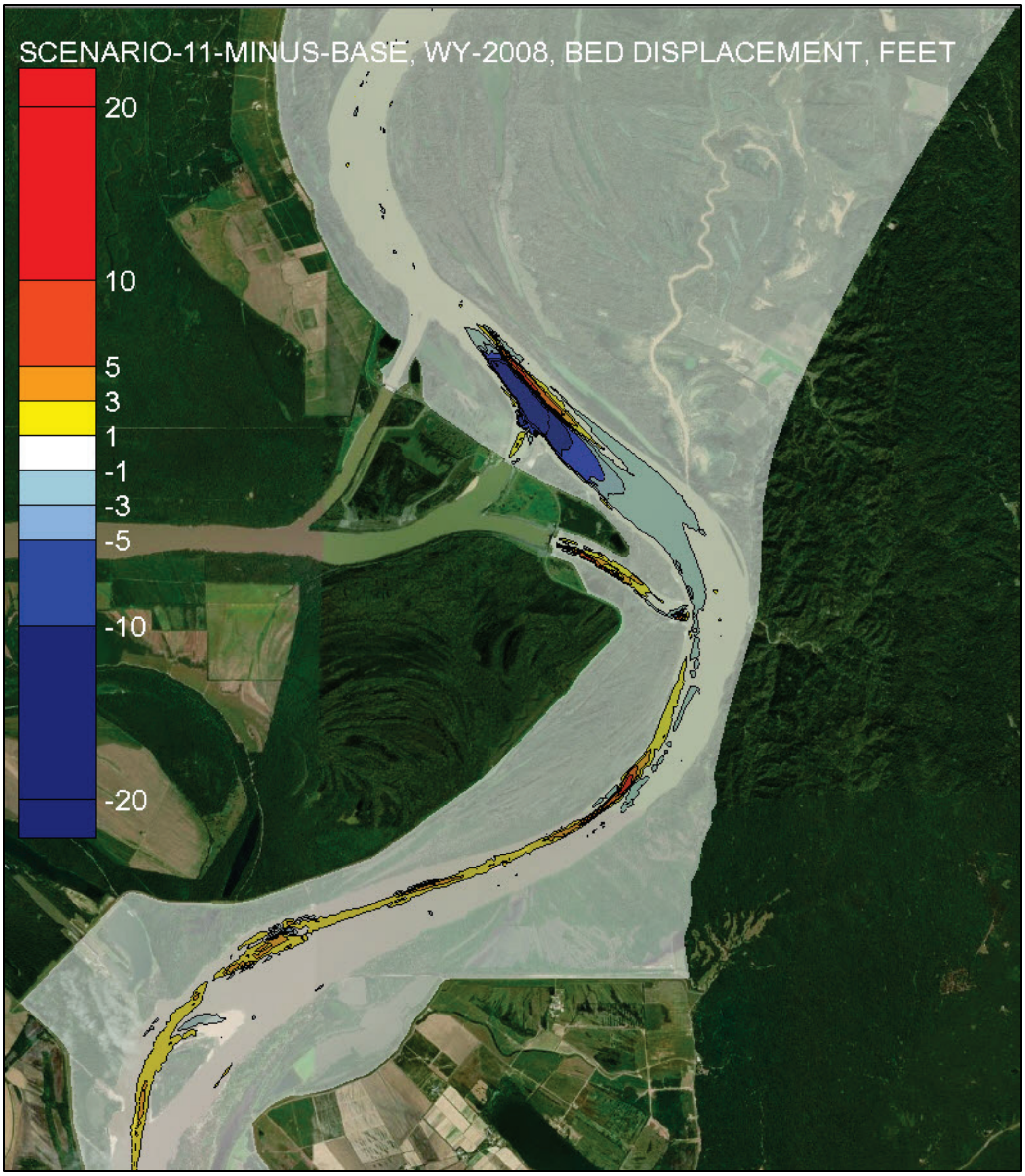
Note that this analysis does not account for the source associated with local erosion in the Mississippi River between Union Point and Tarbert. This source is greater for the ratio 1 operations, and this source would also dissipate over time. Therefore, the SRI values of Scenario 3 and Scenario 4 are slightly higher than they would be if this local erosion was accounted for in the calculation. However, note that the short-term effects (as the river adjusts) can be significantly different than the long-term effects.

4.5 Dredging scenarios analysis

4.5.1 Qualitative analysis of Mississippi River morphologic response

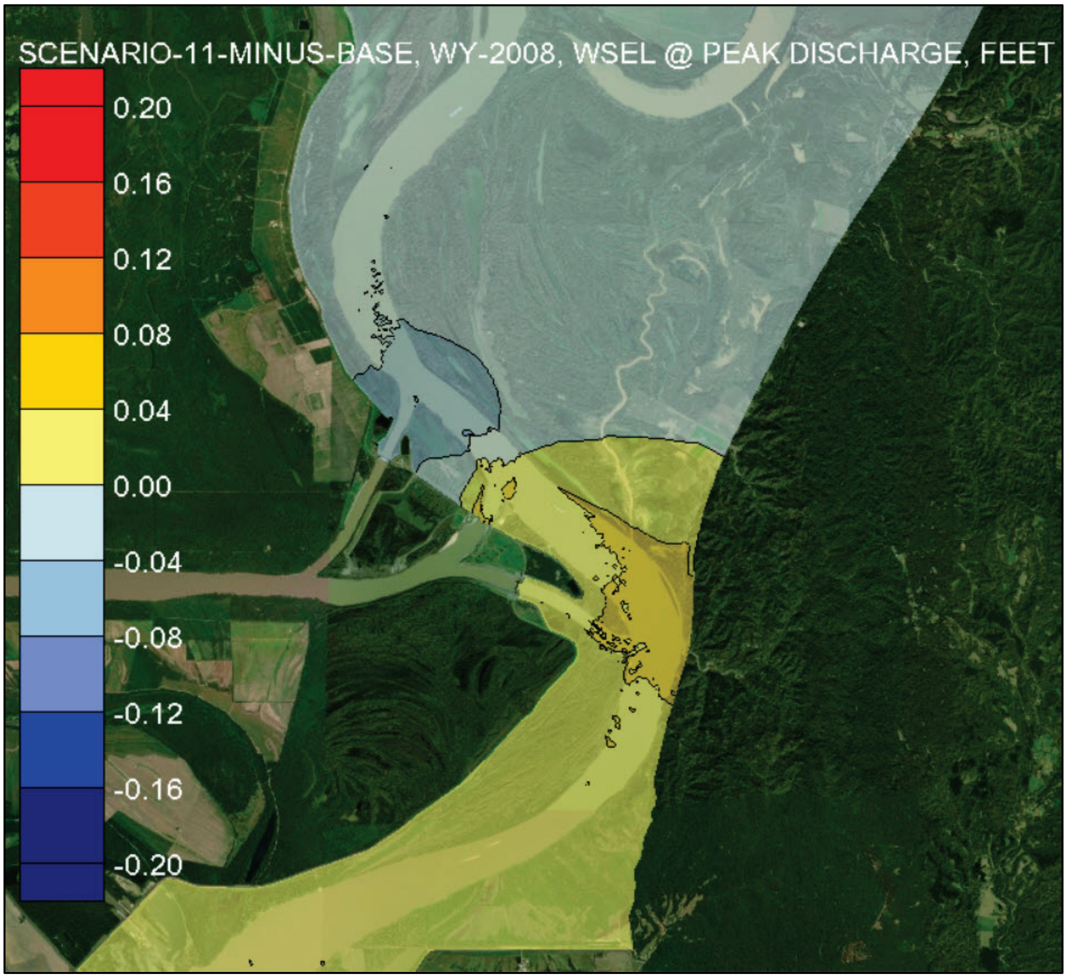
Figure 51 and Figure 53 through Figure 64 depict the difference in the bed displacement between each of the dredging scenarios and the Base simulation, for the WY 2008 (high flow) simulations. Figure 52 depicts the difference in water surface elevation between Scenario 11 and the Base condition. These figures provide a convenient means to discuss some of the qualitative aspects of the scenario results. Each figure is accompanied by a brief description of the results.

Figure 51. Bed displacement difference WY 2008: Scenario 11 minus Base.



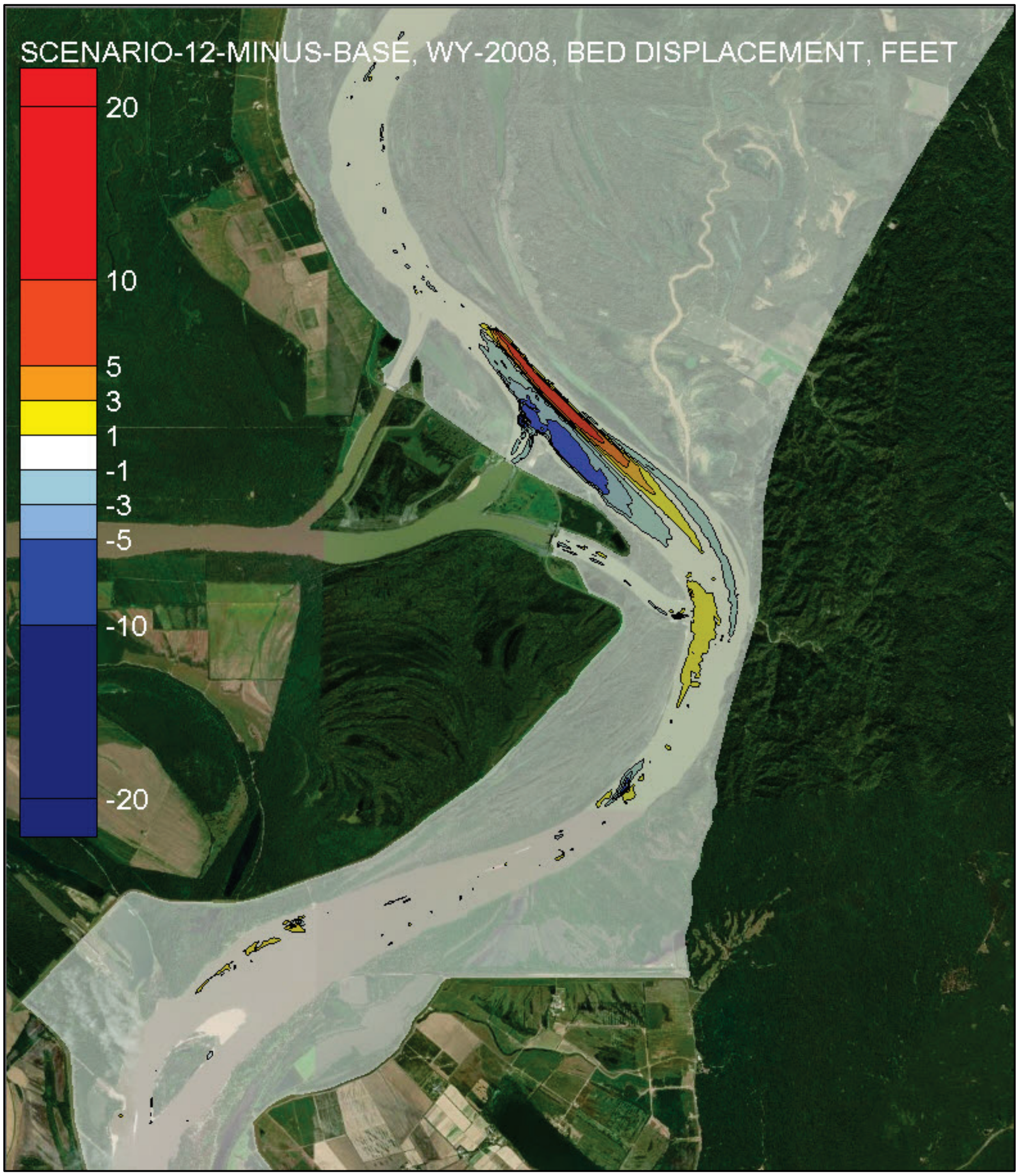
The results for Scenario 11 (continuous dredging in the Mississippi River adjacent to the Low Sill Structure entrance channel with removal of sediment) shows the dredging of the sediment in front of Low Sill as well as the progression of scour downstream. This progression indicates that the river is scouring sediment from the bed. This occurs because the sediment concentration has dropped (sediment is settling in the dredged template) and the river has capacity to scour more sediment when the flow accelerates downstream of the hole. Figure 52 shows the difference in water surface elevation between the Base and Scenario 11 simulations.

Figure 52. Water surface elevation difference WY 2008: Scenario 11 minus Base.



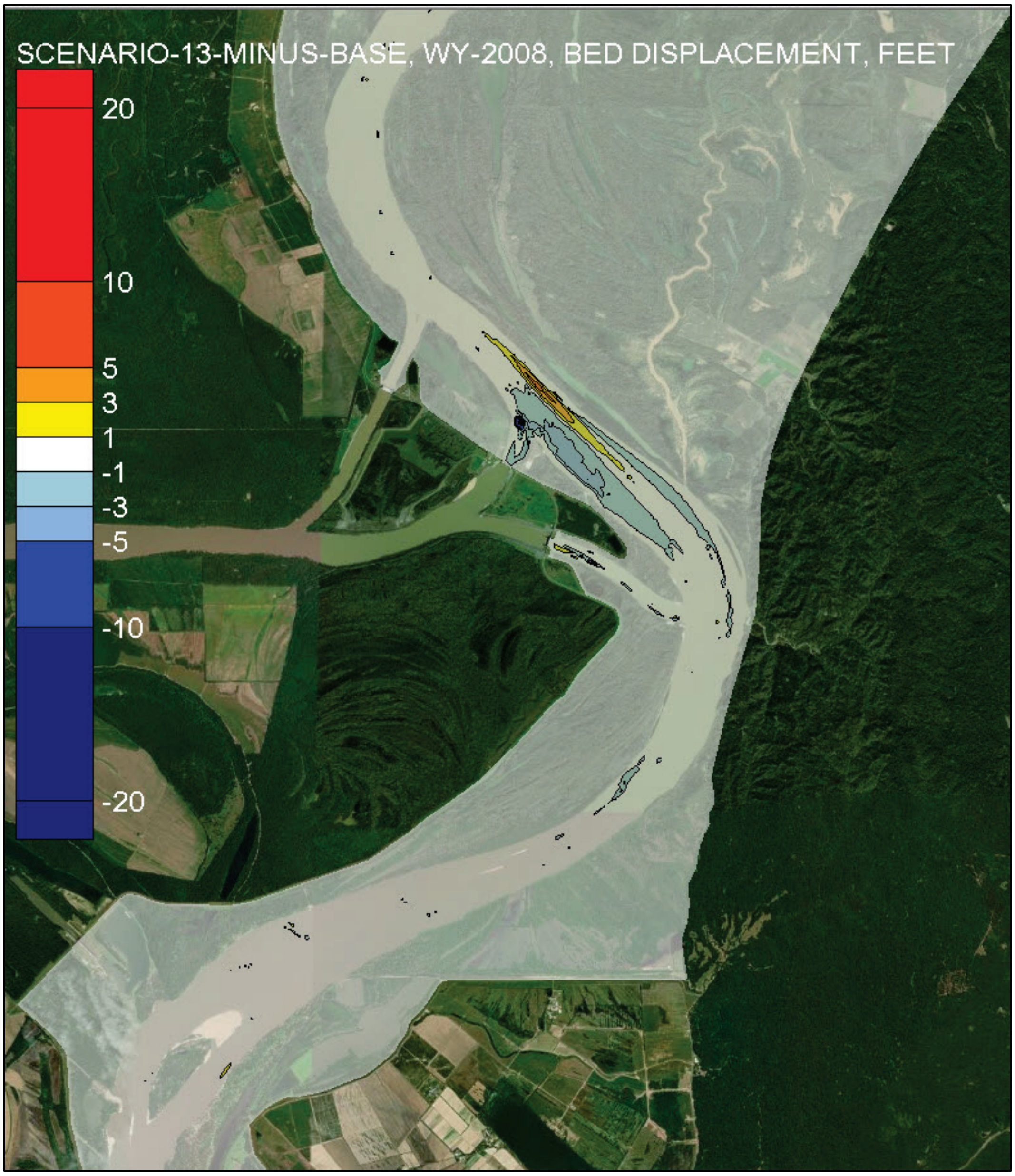
Note that the water surface slope steepens upstream of the dredging location, as the increase in conveyance capacity at the site permits a steeper drawdown toward the diversion. The sudden loss of conveyance downstream of the dredge location results in an increase in stage. These changes together result in a local loss of stream power downstream of the dredge location, which induces local downstream deposition in the Mississippi River.

Figure 53. Bed displacement difference WY 2008: Scenario 12 minus Base.



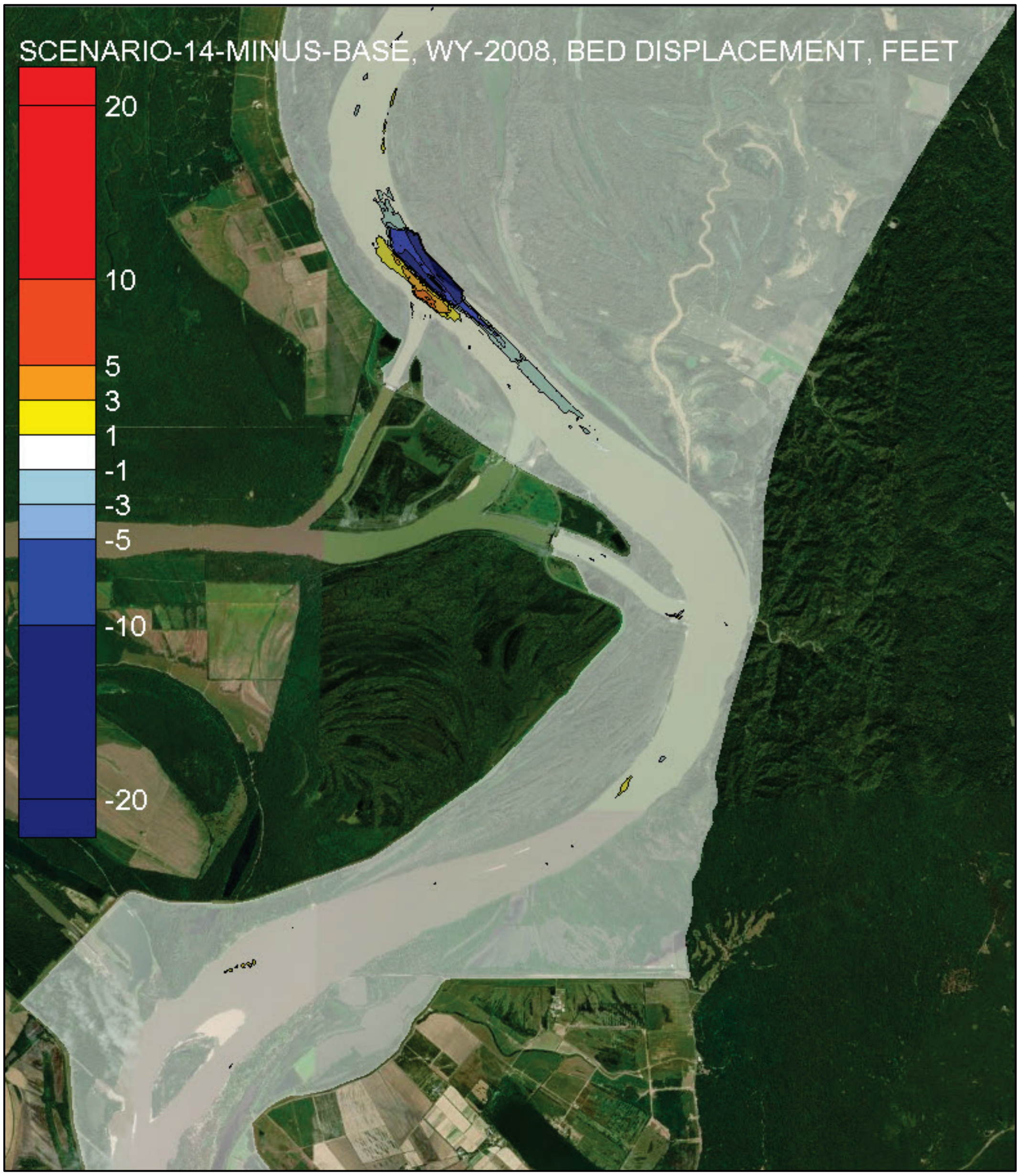
Scenario 12 is similar to Scenario 11, except that the dredged sediment is deposited in the Mississippi River just to the east of the dredging location. This means there is no net change in the sediment load in the Mississippi River. There is also no significant net change in the conveyance of the cross section, so there is very little morphological impact of the dredging upstream or downstream of the site.

Figure 54. Bed displacement difference WY 2008: Scenario 13 minus Base.



Scenario 13 simulates instantaneous dredging at the Low Sill site, which occurs at the beginning of the simulation. The simulation shows that the resulting scout hole is almost entirely filled by river sediment by the end of the 1 yr simulation.

Figure 55. Bed displacement difference WY 2008: Scenario 14 minus Base.



Scenario 14 simulates continuous dredging and removal of sediment from the bar opposite the Hydropower Channel. Since this is on the inside of a bend where the adjacent thalweg is very deep, it has less relative impact on the conveyance of the cross section than does the dredging at Low Sill (seen in Scenario 11). Hence, the upstream and downstream effects are not significant. Also, the riverbed upstream of Hydropower is in an armored condition due to the drawdown of the Hydropower Channel, so it does not erode as easily as the material downstream.

4.5.2 Quantitative analysis of sediment removal and Mississippi River morphologic response

Figure 56 through Figure 58 depict the coarse sediment load diverted through the ORCC for each dredging scenario. The loads for each control structure are identified. There is a separate figure for each WY.

Figure 56. Simulated coarse sediment load diverted through the ORCC for the dredging scenarios: WY 2008.

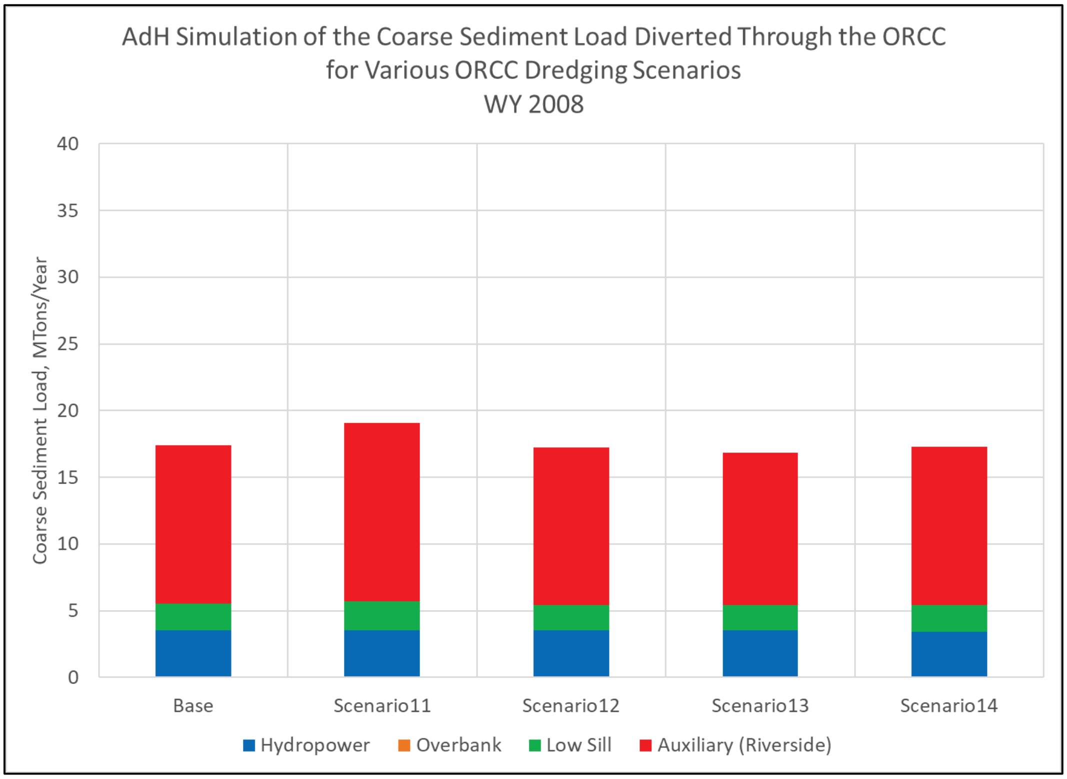


Figure 57. Simulated coarse sediment load diverted through the ORCC for the dredging scenarios: WY 2012.

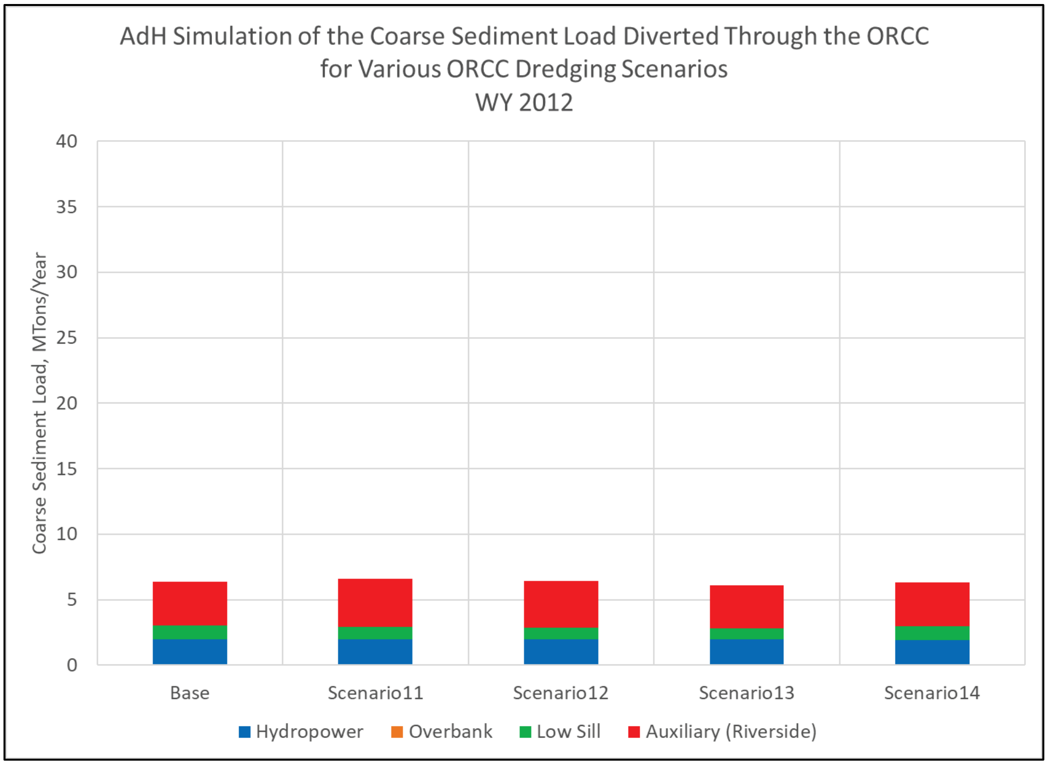
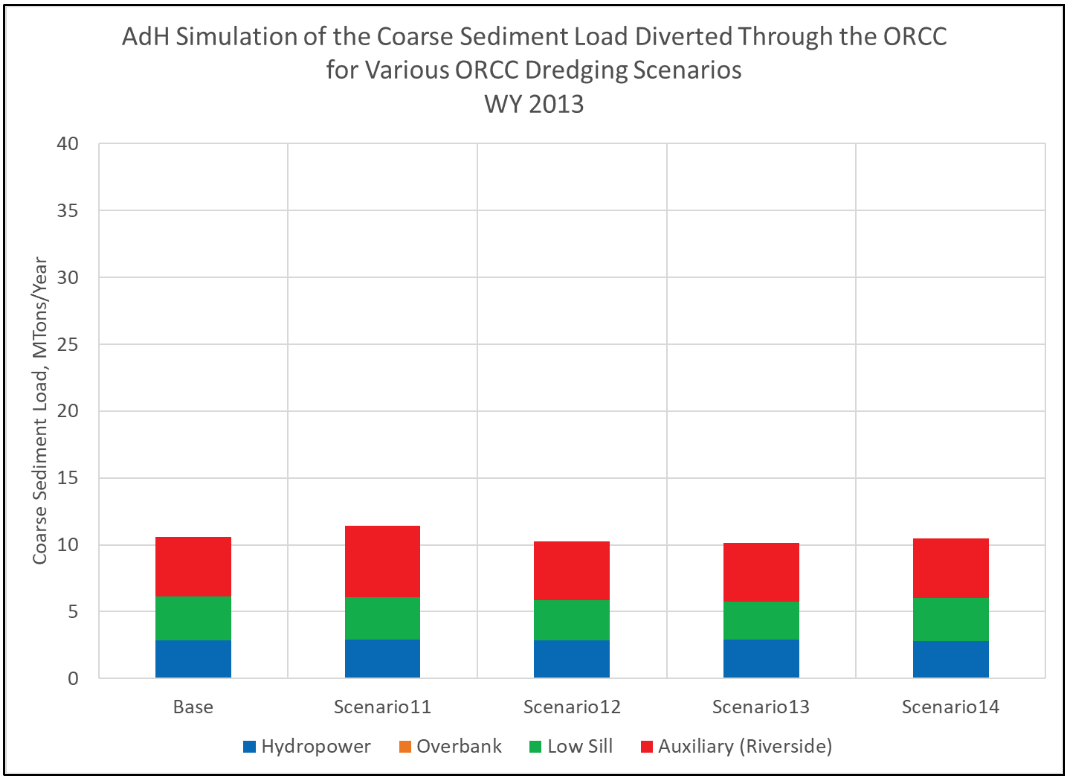


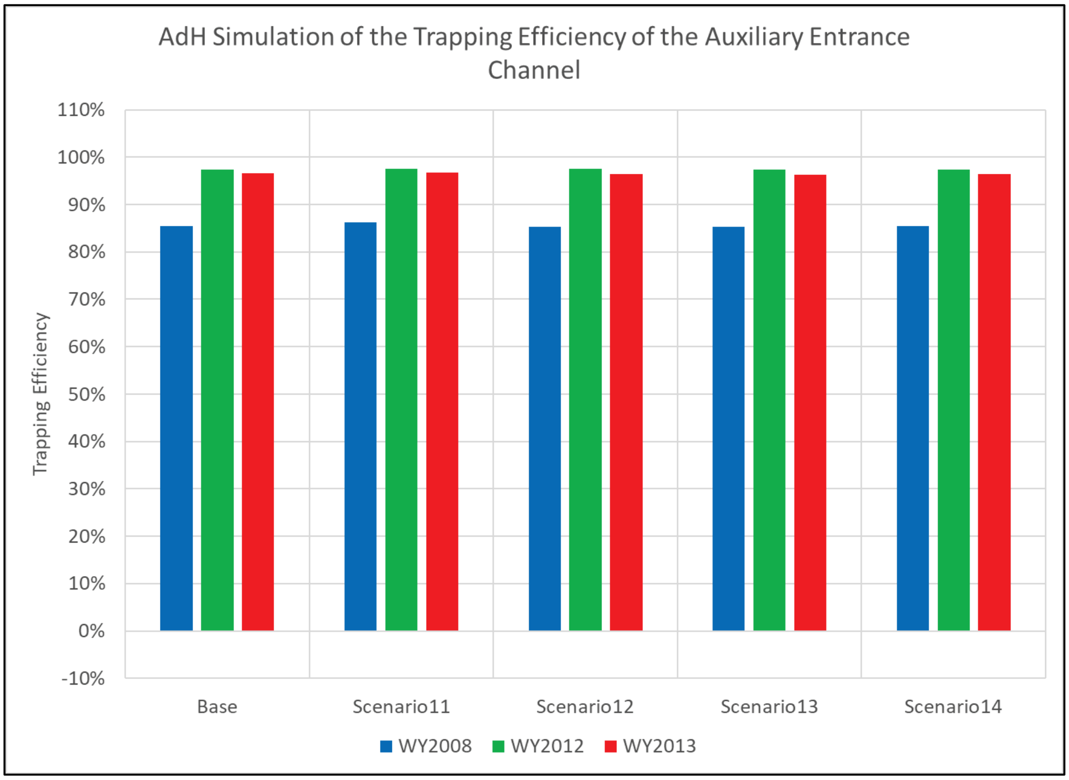
Figure 58. Simulated coarse sediment load diverted through the ORCC for the dredging scenarios: WY 2013.



There is a small increase in the volume of sediment diverted to the Auxiliary Structure in Scenario 11. This is due to the sediment load eroded from the sediment bed just downstream of the dredge template.

Figure 59 depicts the trapping efficiency of the Auxiliary Entrance Channel for each dredging scenario. It is essentially unchanged.

Figure 59. Simulated trapping efficiency of the Auxiliary Entrance Channel: dredging scenarios.



To understand the influence of the dredging scenarios on the local Mississippi River bed morphology, and on the Mississippi River sediment flux downstream of the ORCC, it is useful to perform a mass balance computation. For this mass balance, the control volume is the Mississippi River between Union Point and Tarbert Landing. It is bounded on the west by the ORCC. The western boundary for the Auxiliary Entrance Channel is the riverside location (i.e., the junction of the Auxiliary Entrance Channel and the Mississippi River). Hence, the mass balance reveals the influence of the operations on the Mississippi River between Union Point and Tarbert Landing, excluding the Auxiliary Entrance Channel. The mass balance plots are shown in Figure 60 through Figure 62.

Figure 60. Coarse sediment mass balance for Mississippi River between Union Point and Tarbert Landing: WY 2008.

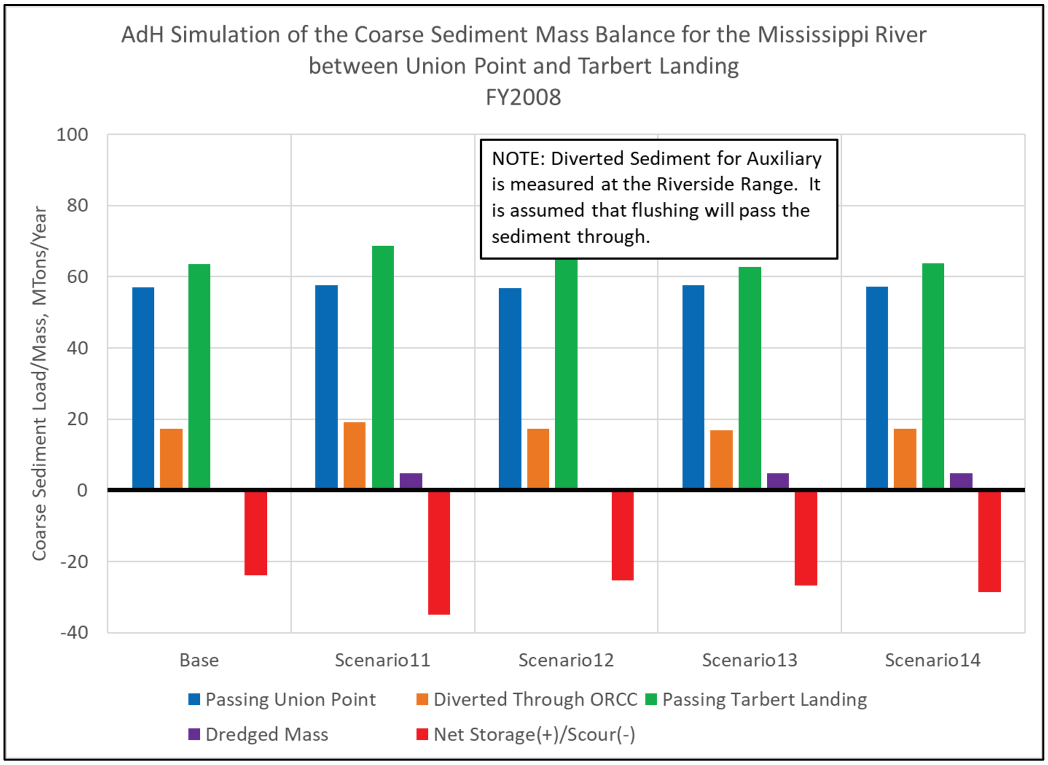


Figure 61. Coarse sediment mass balance for Mississippi River between Union Point and Tarbert Landing: WY 2012.

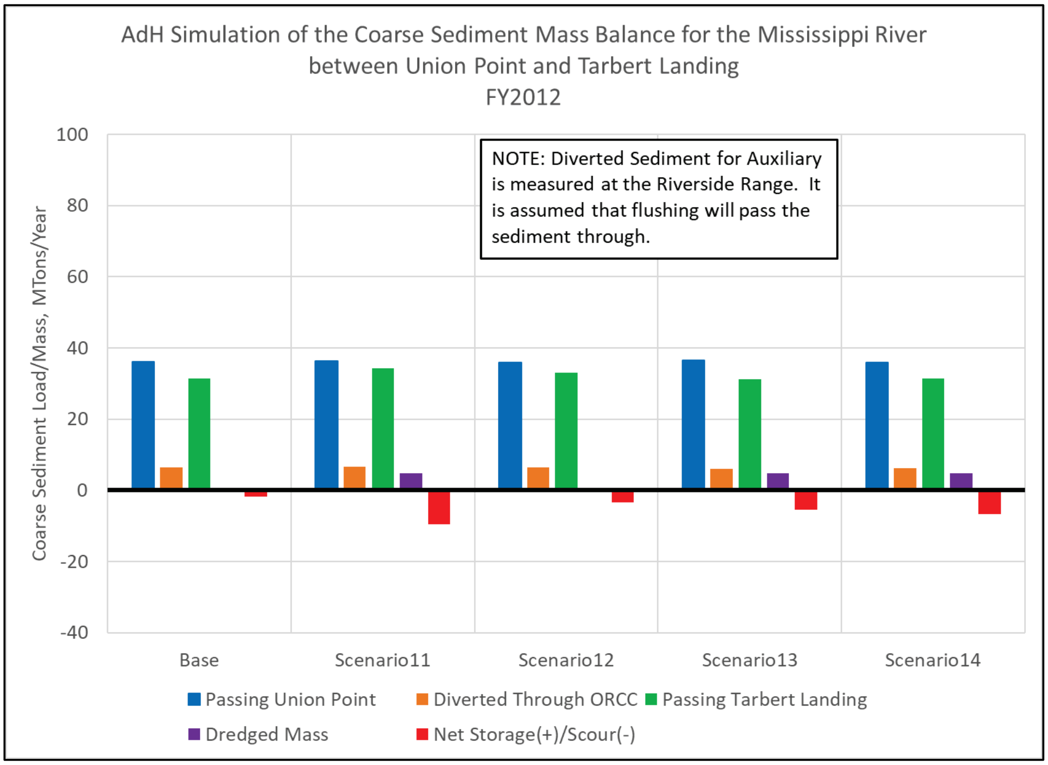
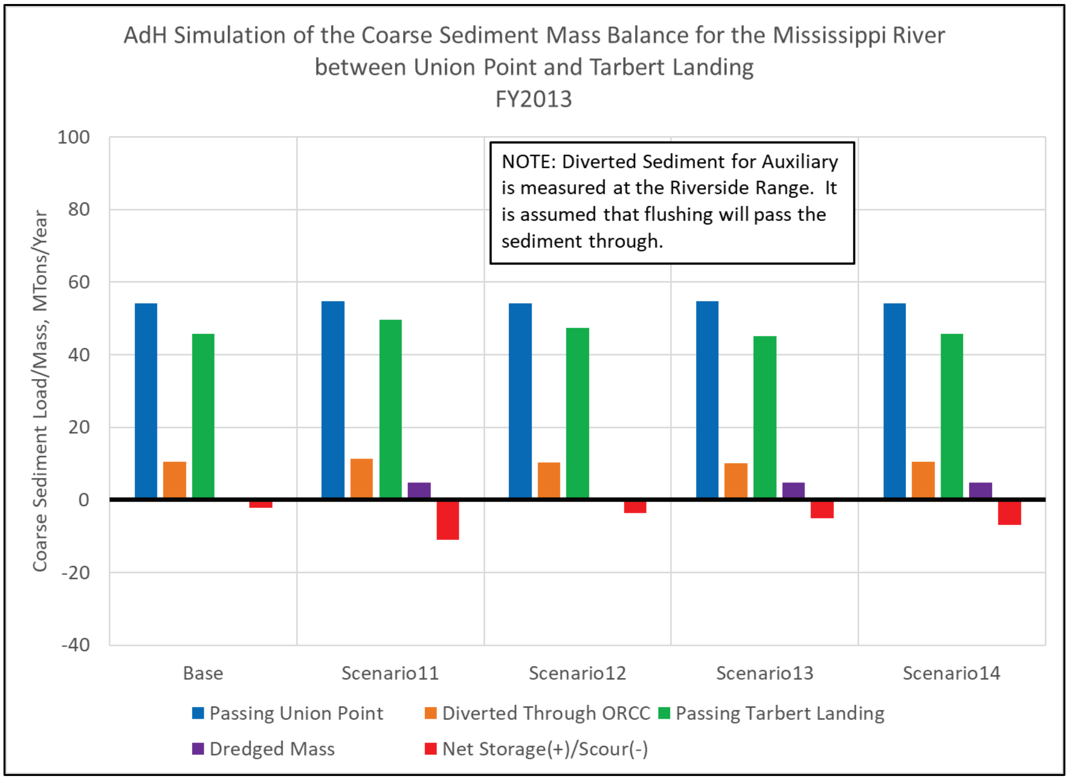


Figure 62. Coarse sediment mass balance for Mississippi River between Union Point and Tarbert Landing: WY 2013.



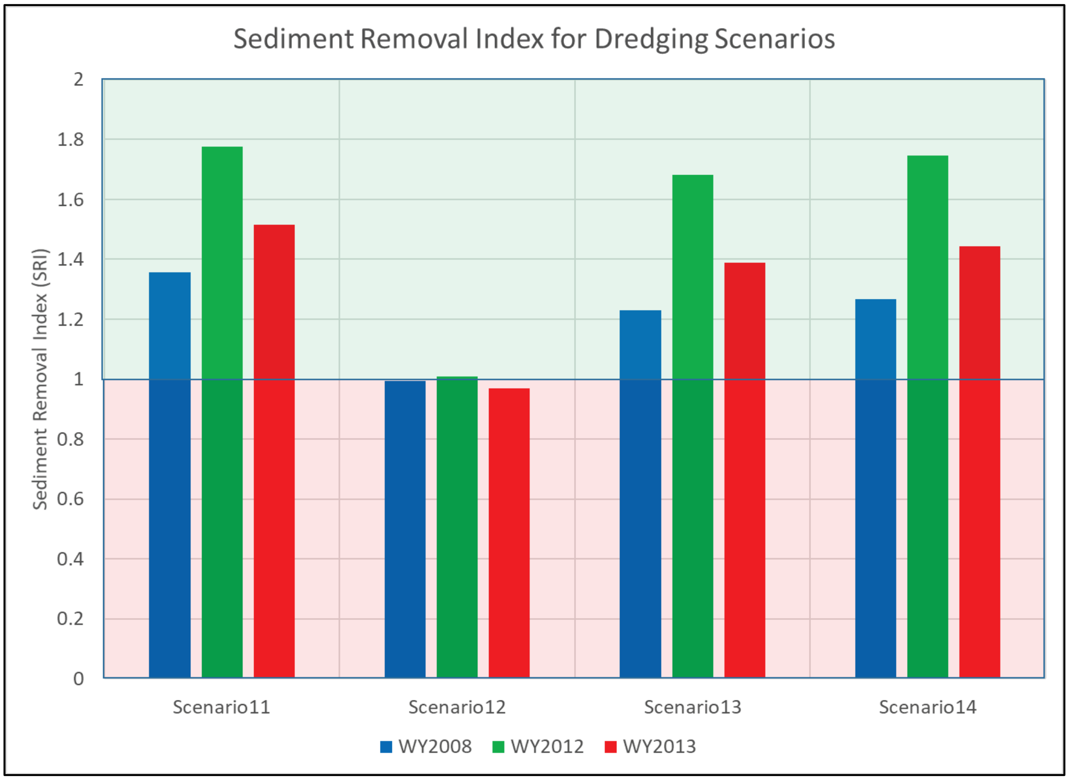
The largest differences from the base conditions are shown in Scenario 11, where the presence of the dredged hole induces scouring of the sediment downstream of the hole, which in turn increases the sediment concentration passing into the Auxiliary Entrance Channel and downstream to Tarbert Landing. For all the other dredging scenarios, the dredged material is replaced by local scour, resulting in little change to the Tarbert Landing fluxes.

For all the dredging scenarios, the observed changes are essentially local adjustments of the morphology. Therefore, it is expected that if the dredging were maintained for several years, these adjustments would cease, and the sediment mass balance would resemble the base condition, minus the 4.75 Mtons that is annually dredged. This reduction would be seen at Tarbert Landing.

To summarize all the dredging model results, it is useful to perform an SRI analysis. This indicates how much sediment is removed from the river for each scenario, relative to base conditions. Since the index is computed as a function of the sediment inflow for each scenario, it minimizes the local adjustment effects that are seen in the mass balance analyses. Hence, it is a measure of the long-term performance of the scenarios.

Figure 63 is a plot of the SRI analysis for the dredging scenarios. The plot is shaded red for values below 1 (i.e., scenarios that divert less sediment as a proportion of the incoming load than the base) and shaded green for values above 1 (i.e., scenarios that divert more sediment as a proportion of the incoming load than the Base). The removal quantity includes the dredged quantities in each case where the dredging removes sediment from the river.

Figure 63. The SRI for the dredging scenarios.



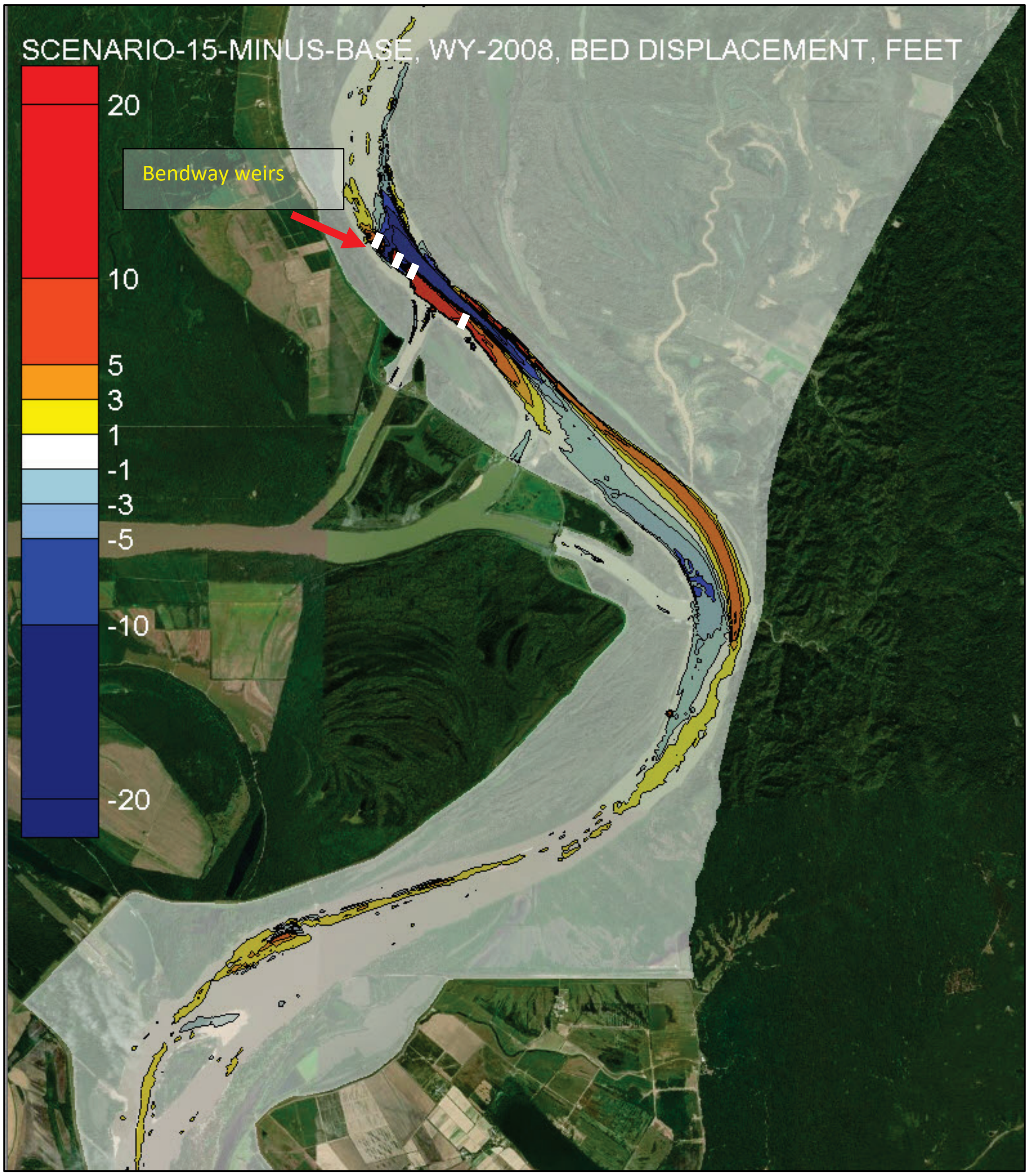
This analysis essentially reflects the expected long-term trends. That is, in each case, the sediment removal index is proportional to the amount dredged. Since the amount diverted is essentially unchanged in each scenario, then once the river adjustments for the local morphologic changes are complete, the downstream adjustment is essentially just equal to the Base load minus the dredged amount.

4.6 Structural scenarios analysis

4.6.1 Qualitative analysis of Mississippi River morphologic response

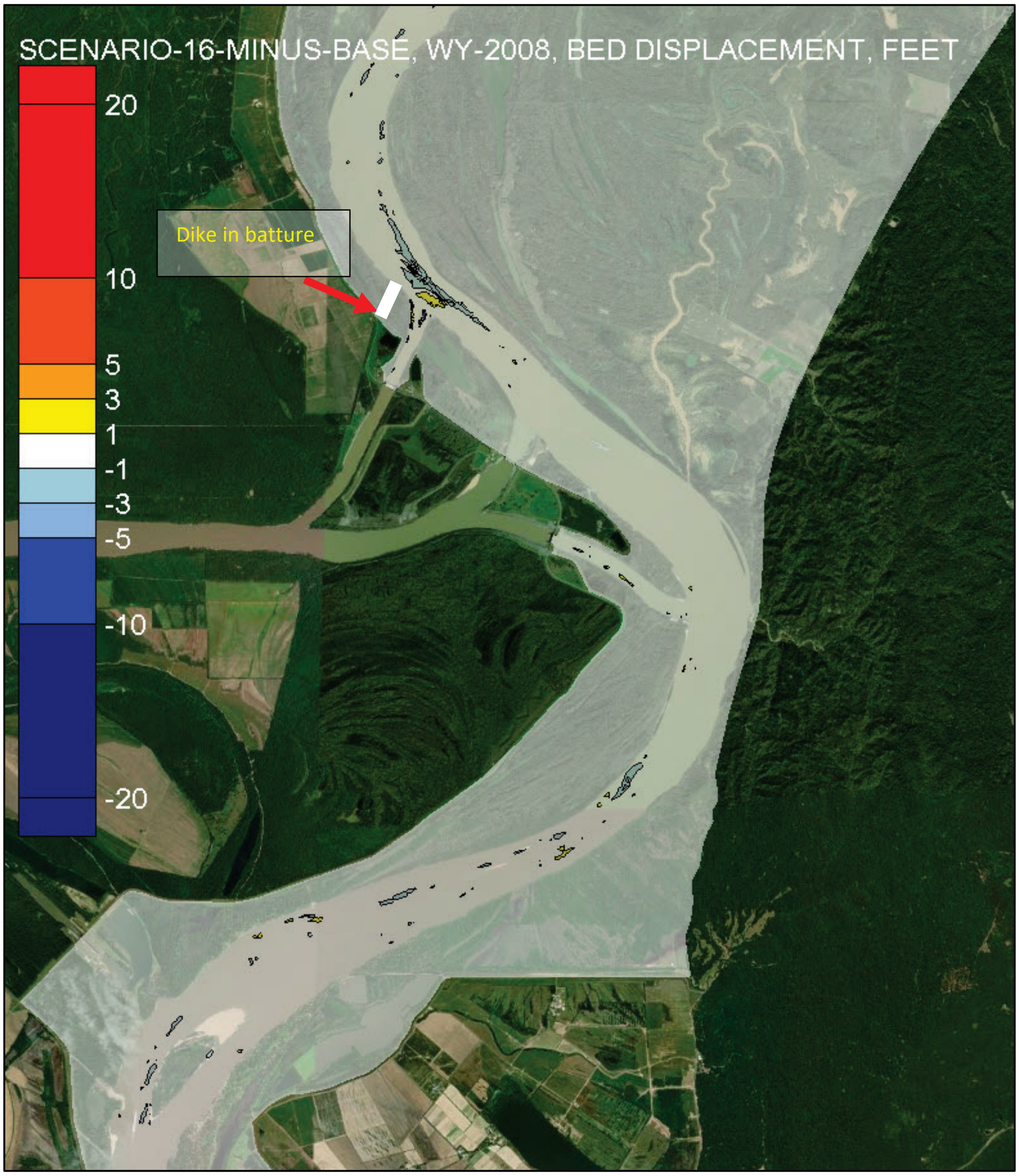
Figure 64 through Figure 68 depict the difference in the bed displacement between each of the scenarios and the Base simulation, for the WY 2008 (high flow) simulations. This provides a convenient means to discuss some of the qualitative aspects of the scenario results. Each figure is accompanied by a brief description of the results.

Figure 64. Bed displacement difference WY 2008: Scenario 15 minus Base.



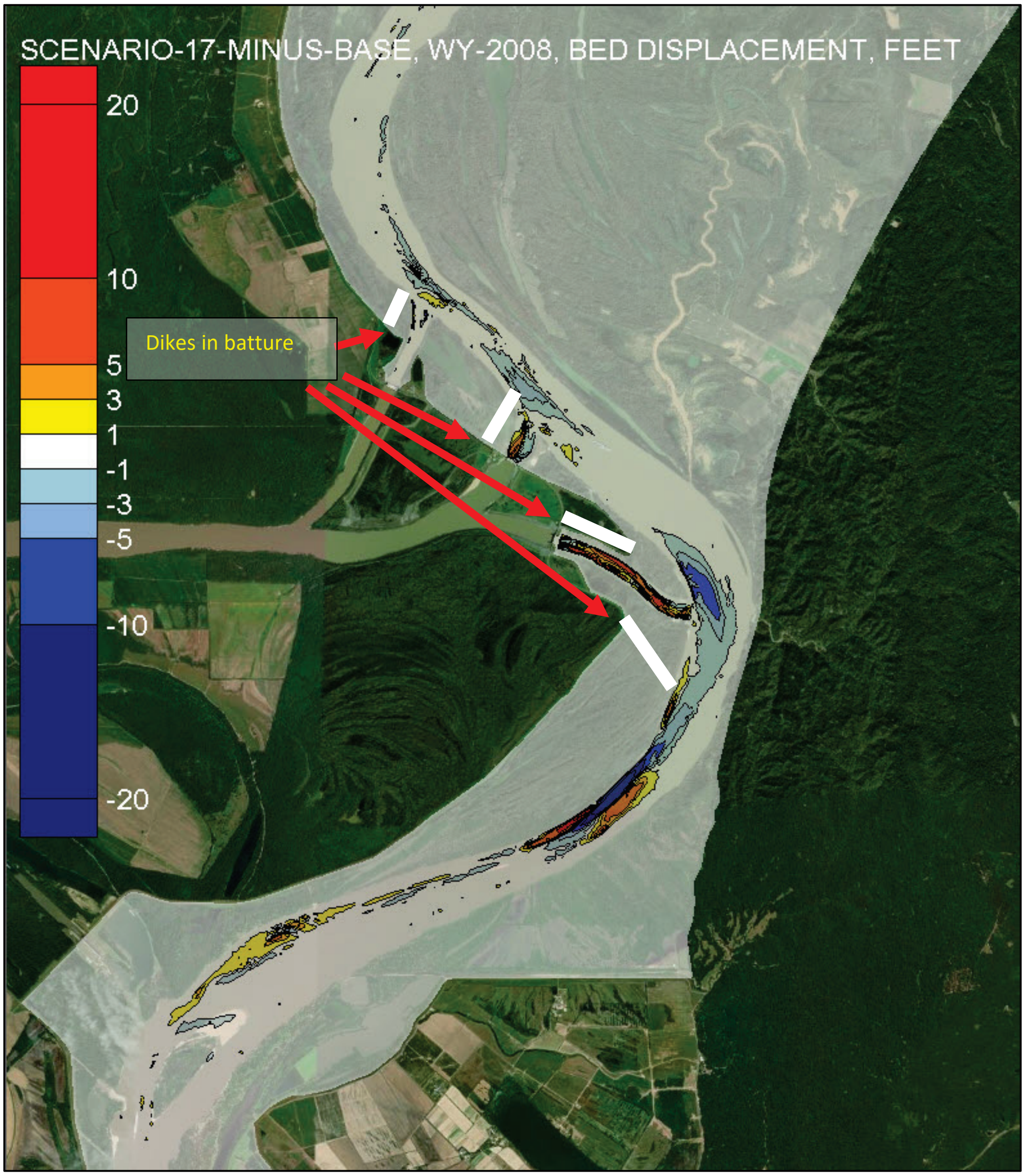
The bendway weirs in Scenario 15 tend to induce scour on the opposite bank, which is expected. The also induce deposition (relative to the base conditions) on the adjacent bank, at the hydropower intake. However, the deposition does not shallow the thalweg sufficiently to induce a significant increase in the sediment load entering the hydropower intake.

Figure 65. Bed displacement difference WY 2008: Scenario 16 minus Base.



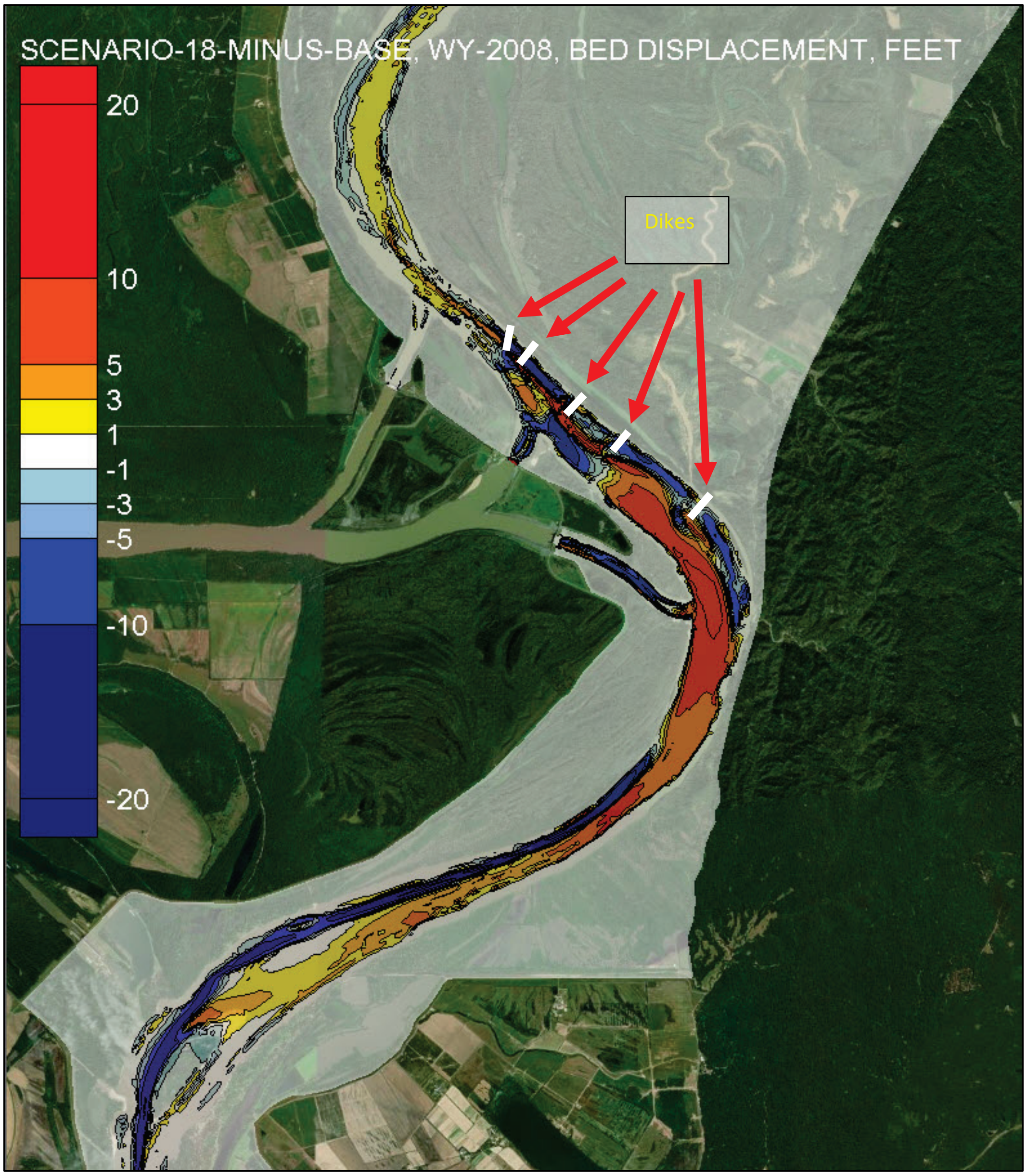
The single batture dike in Scenario 16 has little impact on the river morphology.

Figure 66. Bed displacement difference WY 2008: Scenario 17 minus Base.



The series of batture dikes in Scenario 17 induce local scour at the low sill and auxiliary intakes, due to the focusing of the flow when the river is out of bank. The change in flow pattern also readjusts the location of deposition downstream shifting it from the western bar to the center of the channel.

Figure 67. Bed displacement difference WY 2008: Scenario 18 minus Base.



The dike field in Scenario 18 has significant effects on the bed displacement. The displacement difference plot shows an increase in net deposition upstream of the dikes, and both deposition and scour in the inflow channels and downstream of the dikes. To better understand the reasons for these, it is useful to plot the absolute bed displacements for the Base and Scenario 18 simulations (Figure 68) and to plot the difference in water surface elevation between Scenario 18 and Base simulations (Figure 69).

Figure 68. Bed displacement for Base and Scenario 18 for WY 2008.

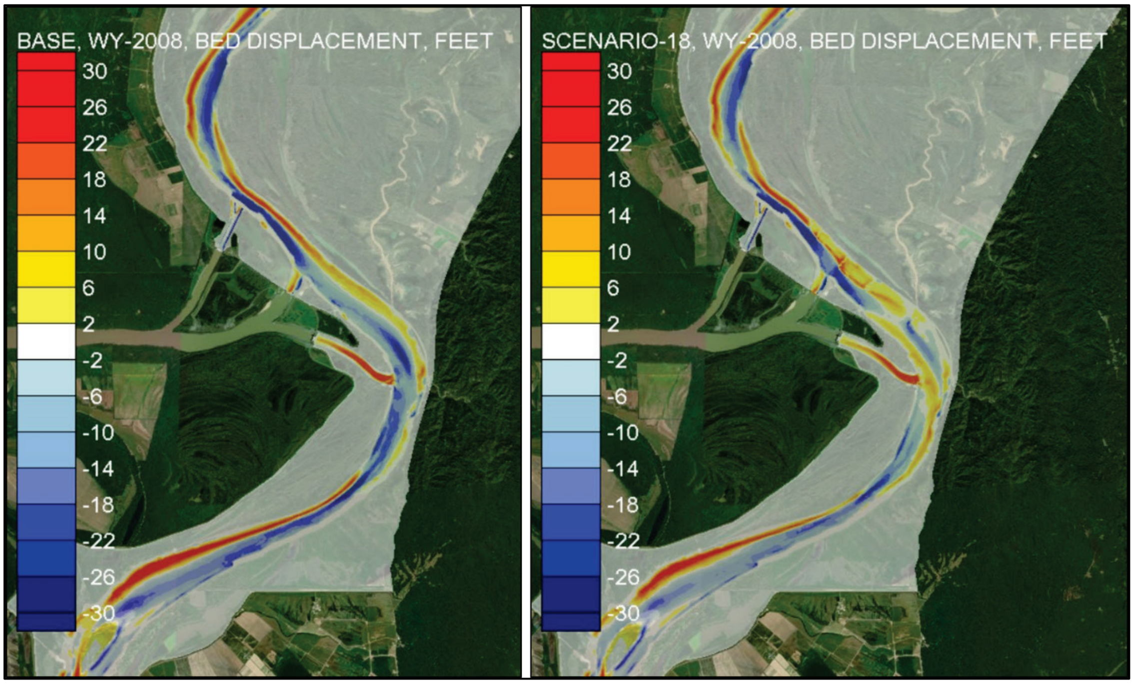
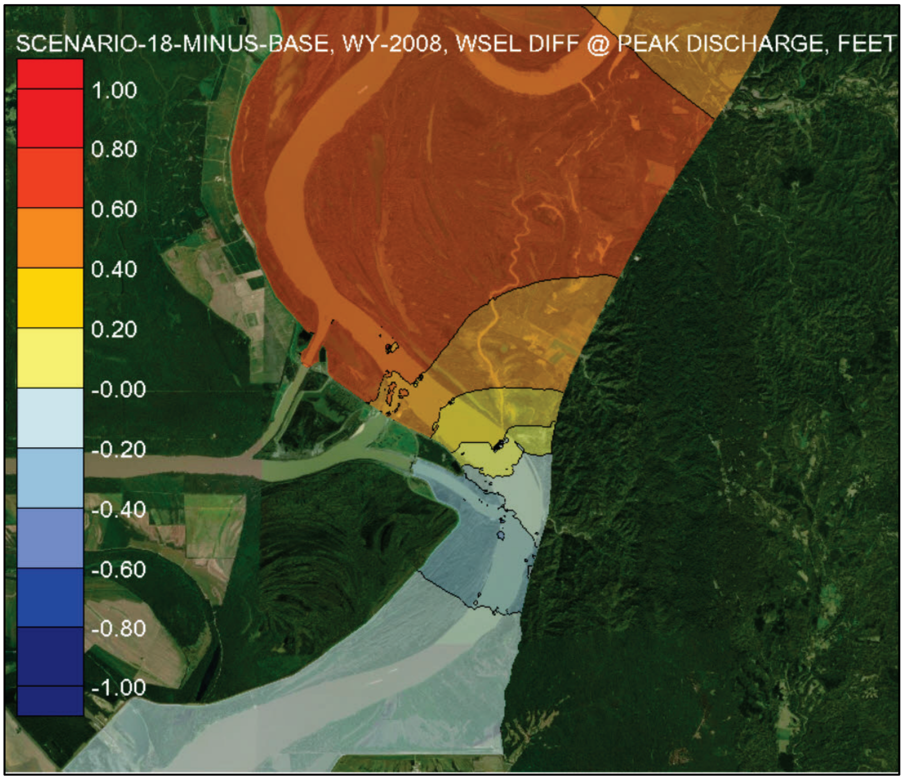


Figure 69. Water surface elevation difference WY 2008: Scenario 18 minus Base.



The displacement plots illustrate that the presence of the dikes tends to rearrange the deposition patterns, such that some of the net deposition seen in Figure 68 is actually a transition from scour to deposition.

The water surface elevation difference plot indicates that much of the upstream deposition is due the backwater condition caused by the flow construction at the dike field. This locally reduces the upstream stream power, resulting in net deposition.

4.6.2 Quantitative analysis of structural scenarios and Mississippi River morphologic response

Figure 70 through Figure 72 depict the coarse sediment load diverted through the ORCC for each structural scenario. The loads for each control structure are identified. There is a separate figure for each WY.

Figure 70. Simulated coarse sediment load diverted through the ORCC for the structural scenarios: WY 2008.

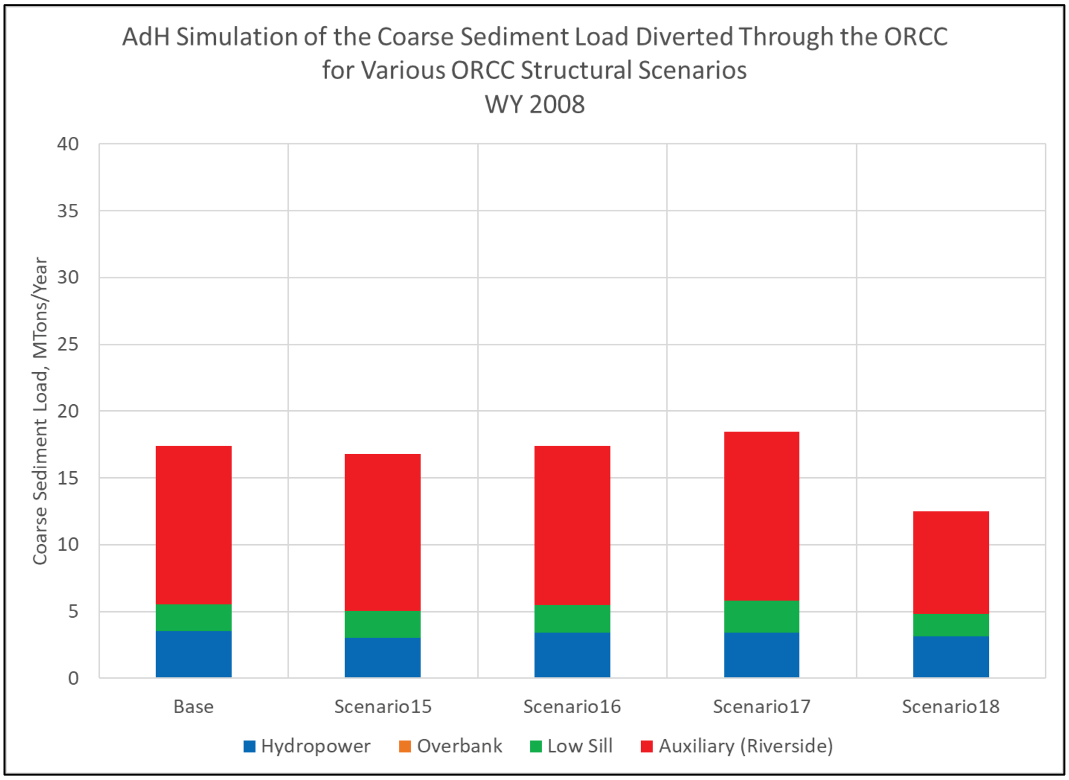


Figure 71. Simulated coarse sediment load diverted through the ORCC for the structural scenarios: WY 2012.

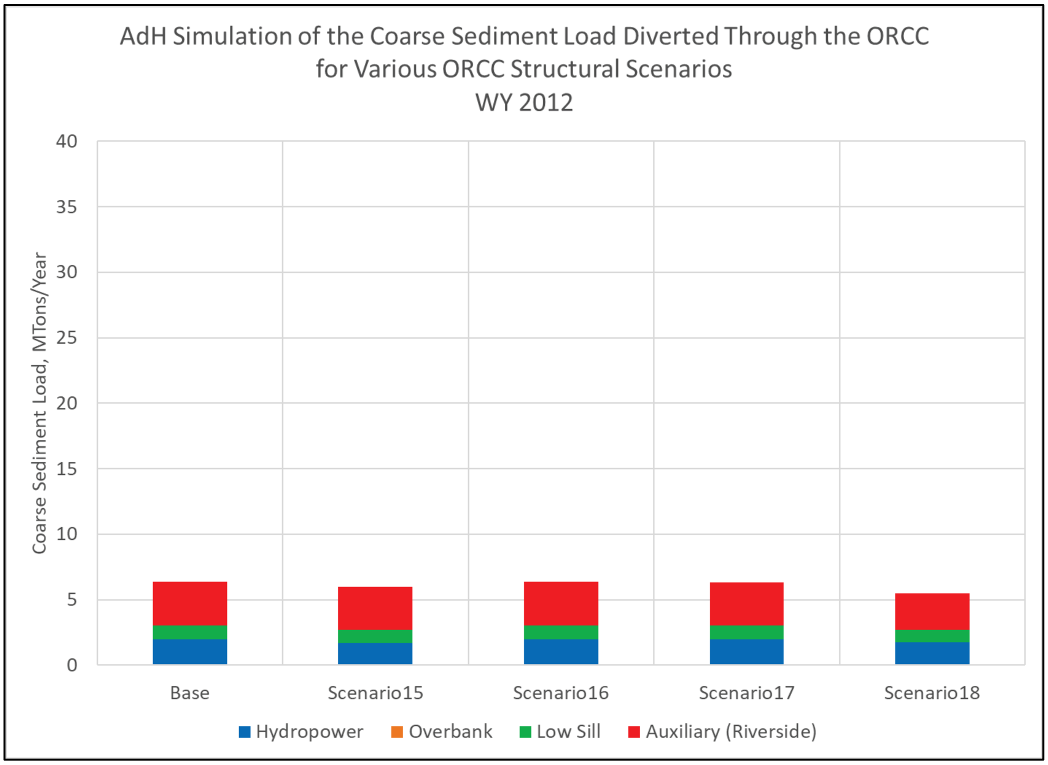
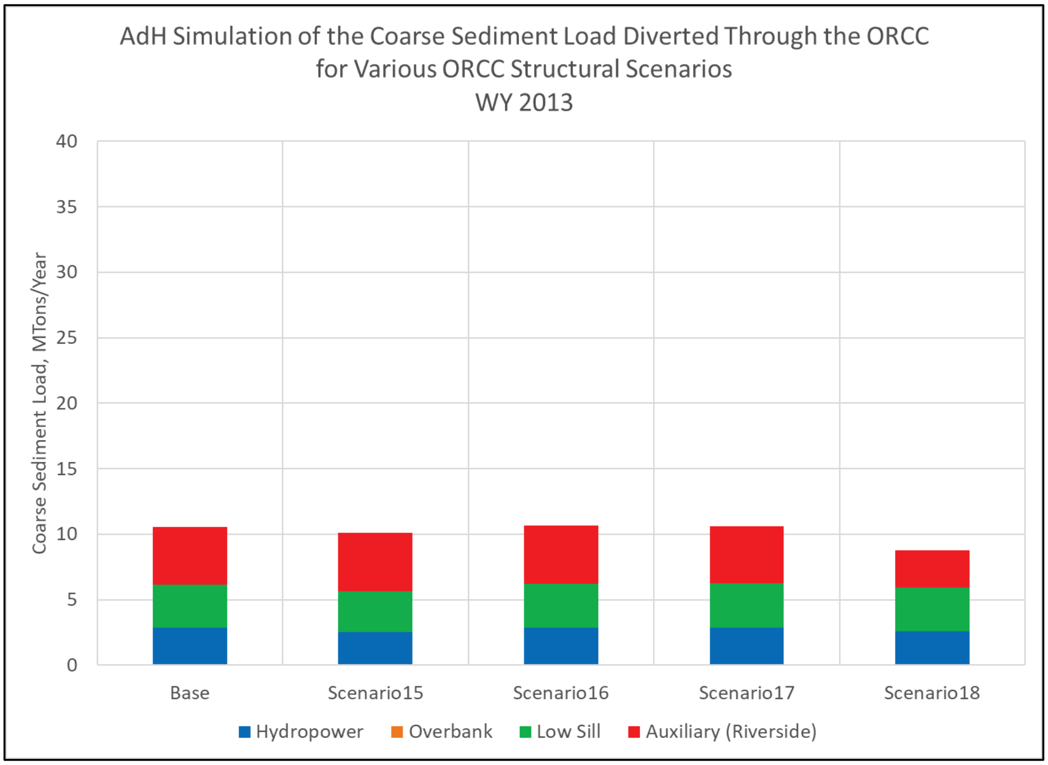


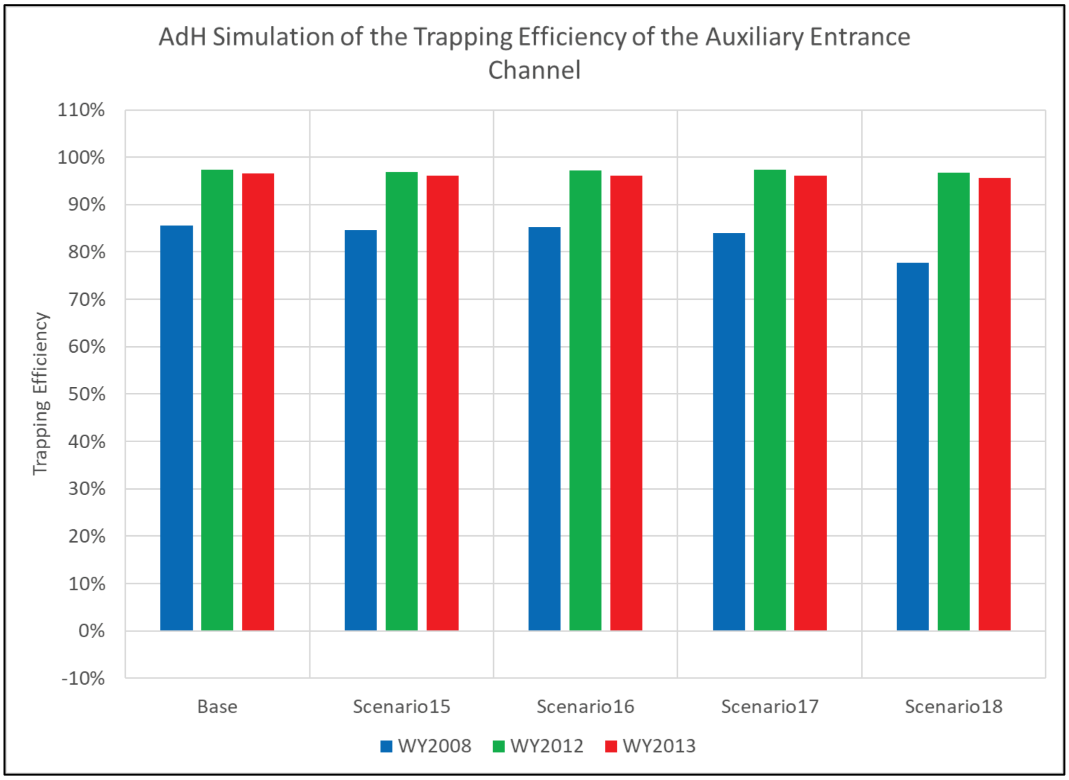
Figure 72. Simulated coarse sediment load diverted through the ORCC for the structural scenarios: WY 2013.



Note that the volume diverted through all the structures is reduced for Scenario 18. This is due to the reduction in sediment supply from upstream caused by the backwater effect at the constriction.

The sediment trapping efficiency for the Auxiliary Entrance Channel for each structural simulation is given in Figure 73.

Figure 73. Simulated trapping efficiency of the Auxiliary Entrance Channel: structural scenarios.



The trapping efficiency of the auxiliary channel is essentially unchanged for the structural scenarios.

To understand the influence of the structural scenarios on the local Mississippi River bed morphology and on the Mississippi River sediment flux downstream of the ORCC, it is useful to perform a mass balance computation. For this mass balance, the control volume is the Mississippi River between Union Point and Tarbert Landing. It is bounded on the west by the ORCC. The western boundary for the Auxiliary Entrance Channel is the riverside location (i.e., the junction of the Auxiliary channel and the Mississippi River). Hence, the mass balance reveals the influence of the operations on the Mississippi River between Union Point and Tarbert

Landing, excluding the Auxiliary Entrance Channel. The mass balance plots are shown in Figure 74 through Figure 76.

Figure 74. Coarse sediment mass balance for Mississippi River between Union Point and Tarbert Landing: WY 2008.

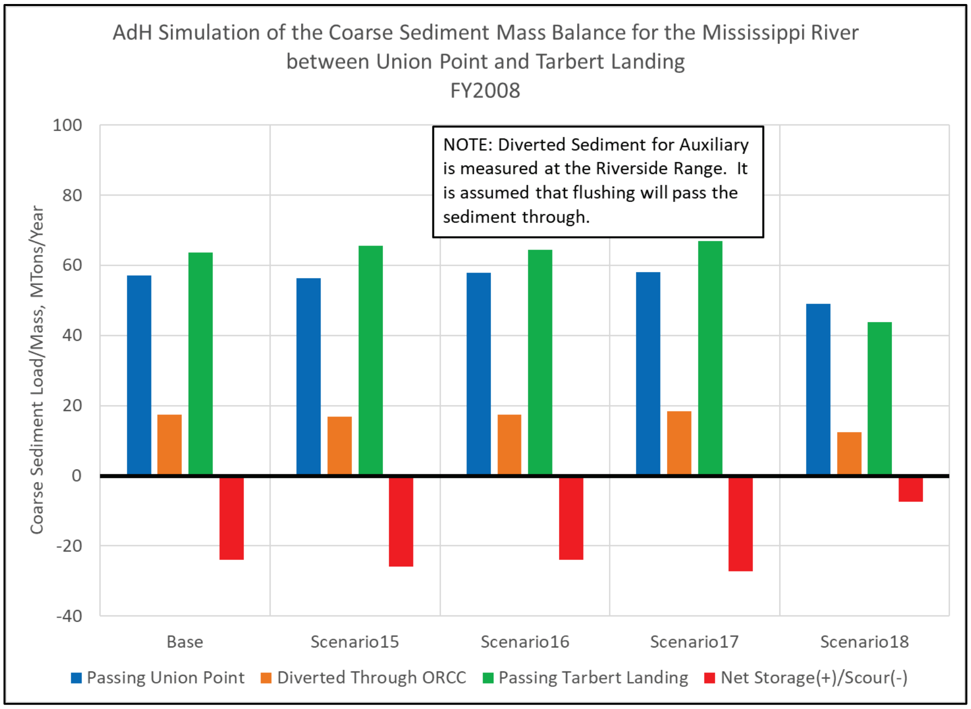


Figure 75. Coarse sediment mass balance for Mississippi River between Union Point and Tarbert Landing: WY 2012.

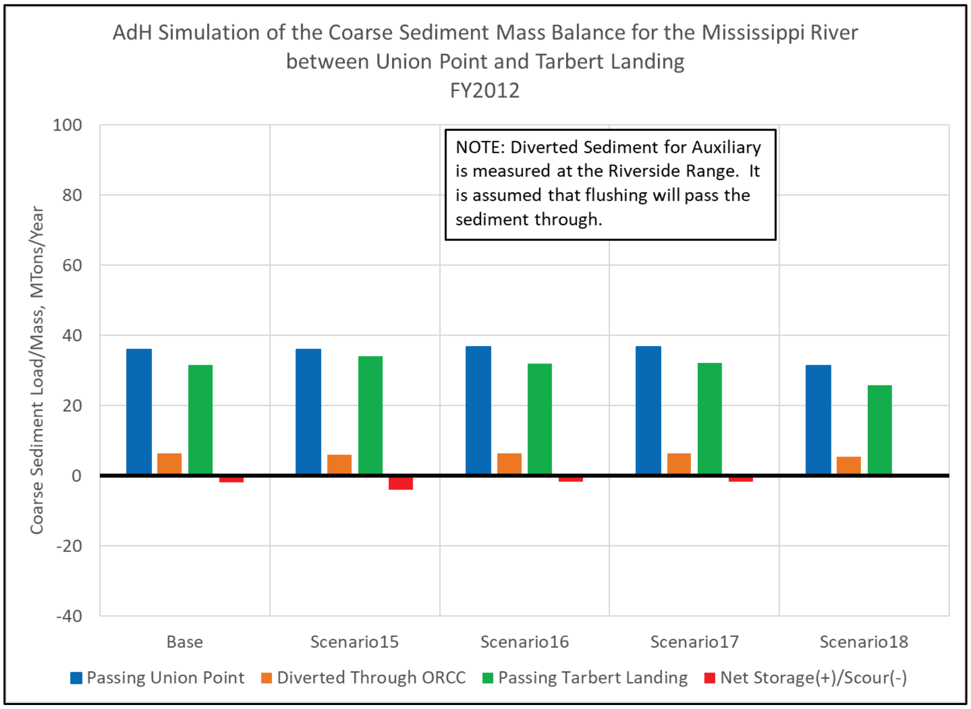
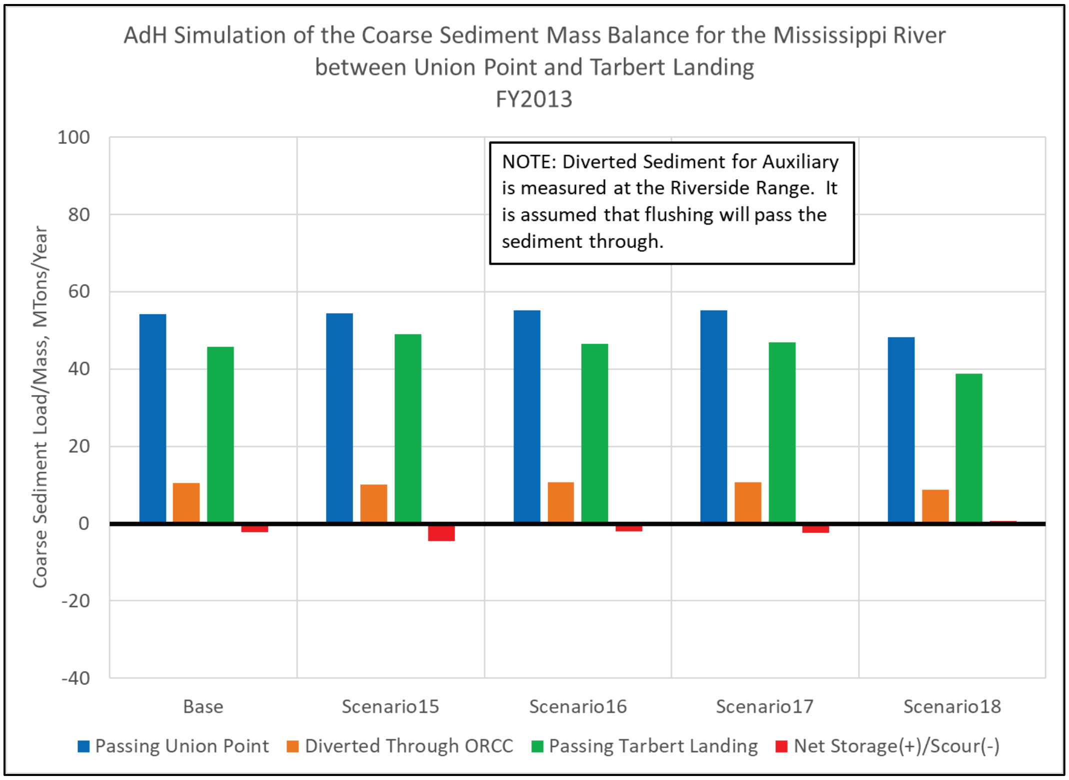


Figure 76. Coarse sediment mass balance for Mississippi River between Union Point and Tarbert Landing. WY 2013.



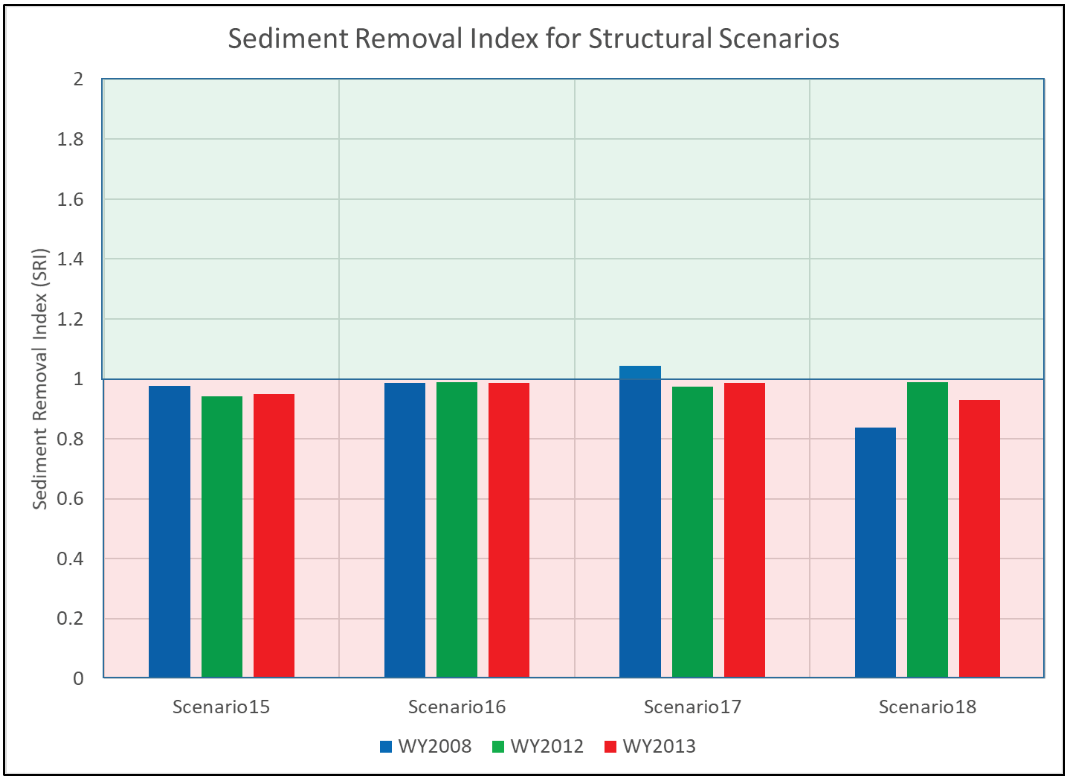
NOTE: Diverted Sediment for Auxiliary is measured at the Riverside Range. It is assumed that flushing will pass the sediment through.

Note that Scenario 18 results show a decrease in the sediment inflow at Union Point, resulting in a general reduction in sediment fluxes. It is expected that this would be a temporary adjustment: once the upstream morphology has adapted to the presence of the dikes, the sediment flux should recover to near base flow conditions.

To summarize all the structural model results, it is useful to perform a SRI analysis. This analysis indicates how much sediment is removed from the river for each scenario, relative to base conditions. Since the index is computed as a function of the sediment inflow for each scenario, it minimizes the local adjustment effects that are seen in the mass balance analyses. Hence, it is a measure of the long-term performance of the scenarios.

Figure 77 is a plot of the SRI analysis for the structural scenarios. The plot is shaded red for values below 1 (i.e., scenarios that divert less sediment as a proportion of the incoming load than the base) and shaded green for values above 1 (i.e., scenarios that divert more sediment as a proportion of the incoming load than the base).

Figure 77. The SRI for the structural scenarios.



The SRI analysis shows that the structural scenarios have little impact on the sediment removal. Only Scenario 18 shows some reduction in sediment diversion efficiency, especially for high flow years.

4.7 Summary of Base conditions and scenario analyses

4.7.1 Summary of Base conditions

There were three historical flow years selected to be representative high, typical, and low flow years. These are 2008, 2013, and 2012, respectively.

SDC were calculated for each of the ORCC structures to quantify their sediment diversion characteristics.

The ORCC complex is essentially a manifold system. It takes advantage of the natural hydraulic sorting associated with the river bends to preferentially exclude and/or extract sediment, depending on the proportion of water diverted at each of the structures.

- The Hydropower Channel is located on the outside of the bend, perched over the deep thalweg of the Mississippi River Channel. It diverts a relatively low concentration of sand.
- The Overbank Structure is a perched structure located well away from the river, in the batture. It is essentially a clear-water diversion.
- The Low Sill Channel is located in the crossing. It is located next to a shoal in the channel that forms downstream of the Hydropower channel diversion, due to the loss of stream power to that diversion. It tends to divert a larger proportion of sand than the Hydropower Channel.
- The Auxiliary Entrance Channel is located on the inside of a river bend, at a shoal formed as a result of channel expansion, the point bar associated with the bend, and shoaling downstream of the Low Sill diversion. It diverts a relatively high concentration of sand.
- The Auxiliary Structure SDC values are much lower than the Auxiliary Entrance SDC values. This indicates sediment trapping in the Auxiliary Entrance Channel.

There are 17 scenarios analyzed for each of three design flow years. These 17 scenarios consist of 9 operational scenarios, 4 dredging scenarios, and 4 structural scenarios. A summary of each is given in the following.

4.7.2 Summary of operational scenarios (Scenarios 3–10)

The operational scenarios demonstrate that the sediment diversion characteristics of the ORCC are most heavily influenced by two factors:

1. The proportion of water diverted to the Low Sill and Auxiliary structures. These structures divert proportionally greater sediment than does the hydropower structure, so scenarios that divert more water to these structures divert more sediment.
2. The total diversion volume. For example, an increase in the lateral flow distribution from the 70/30 split to a 60/40 split significantly increases the sediment diverted at the complex.

Since the simulated effects in this study are only for 1 yr intervals, there are local morphological effects that have significant influence on the results. These local morphological effects are discussed in detail in the main text.

The SRI helps to account for these effects by calculating the ratio of the sediment removed to the sediment introduced.

For example, the SRI analysis shows that the increase in discharge is not as effective at increasing long-term sediment diversion as it appears to be in the annual analysis. This is because some of the increase in diverted sediment is due to a temporary increase in the inflowing sediment concentration caused by the increased drawdown in the Mississippi River (due to the flow acceleration).

4.7.3 Summary of dredging scenarios (Scenarios 11–14)

The dredging scenario analysis demonstrates that the sediment diverted by the complex is not significantly affected by dredging in the Mississippi River in the vicinity of the complex. Since the amount diverted is essentially unchanged in each scenario, once the river adjustments for the local morphologic changes are complete the downstream sediment load adjustment is essentially just equal to the Base load minus the dredged amount.

4.7.4 Summary of structural scenarios (Scenarios 15–18)

The structural scenarios have little impact on the sediment removal. They have some impact on the river hydraulics, resulting in some local adjustments to the morphology. Only one scenario (Scenario 18) shows some reduction in ORCC sediment diversion efficiency, especially for high flow years.

5 Conclusions and Recommendations

The report details the results of a multi-dimensional model analysis of the hydrodynamic and geomorphological impacts of various proposed scenario analyses for the ORCC. The conclusions are confined to Mississippi River geomorphic responses. The results do address changes to the amount of sediment diverted, but this report does not address the impacts of these changes to the ORCC outflow complex or the Atchafalaya River.

5.1 Conclusions

The conclusions are cast in terms of responses to the Steering Committee charge questions that this task was designed to address. The questions are given below, followed by the responses.

1. How much sediment is currently being diverted through the ORCC? This model study analyzed the sediment diversion for three separate historic flow years: high flow (WY 2008), typical flow (WY 2013), and low flow (WY 2012). For each of these years, the mass of sediment diverted was measured in two ways:

1. The sediment diverted from the Mississippi River (i.e., sediment passing from the river though the entrance channels of the diversion structures)
2. The sediment diverted to the ORCC outfall complex (i.e., the sediment passing though the diversion structures).

The difference between these can be very significant. This is because most of the sediment diverted through into the Auxiliary Entrance Channel (85%–95%) is stored in the channel (Figure 46). It must be removed from the channel by dredging and/or flushing operations.

Table 9 shows the simulated mass of sediment diverted for each flow year, using both methods of accounting.

Table 9. Simulated mass of sand diverted from the Mississippi River through the ORCC.

Design Flow Year	Mass of Sand Diverted from the River (Mtons/yr)	Mass of Sand Diverted through the Structures (Mtons/yr)
WY 2012 (Low Flow)	5.4	2.7
WY 2013 (Typical Flow)	8.9	5.2
WY 2008 (High Flow)	14.4	5.6

If it is assumed that flushing operations are employed with sufficient frequency to maintain the capacity of the channel, then the mass of sand diverted from the Mississippi River is the best long-term measure of the amount of sand being transferred to the ORCC outfall over time. However, if dredging is utilized to remove sand from the Auxiliary Entrance Channel, and that sediment is returned to the Mississippi River, then the mass of sand that is transferred to the ORCC outfall must be decremented by that amount.

2. What are the impacts of sedimentation on the operation of the ORCC and the Morganza Structure? Diversion theory, based on fundamental hydraulic and geomorphic principles (Letter et al. 2008; Brown et al. 2013) indicates that the introduction of a diversion will induce a morphodynamic response in the river from which water and sediment are being diverted. Typically, this response includes upstream scour and downstream deposition.

If the diversion is an uncontrolled diversion (i.e., the flow is unregulated [e.g., the original old river diversion at Shreve's Cut]), the continuing increase in diversion flow and consequent increase in downstream deposition in the river can potentially result in the full avulsion of the river at the diversion site.

However, if the diversion is a controlled diversion (i.e., the flow rate is regulated [e.g., the ORCC]) then the morphodynamic response in the river will be limited in scale and finite in duration. Once the river has adjusted to the new flow regime, the morphodynamic response will stop.

Modeling using the 1D HEC6T model, conducted for another task within the OMAR Assessment, indicates that the time scale for these adjustments in the Mississippi River is on the order of 30 yr.

Therefore, since the last significant modification to the ORCC was the introduction of the hydropower facility in 1990, it is expected that most of the morphodynamic adjustments of the Mississippi River to the operation of the hydropower facility are complete.

This means that, barring further modifications to the ORCC, future morphodynamic trends in the Mississippi River in the vicinity of the ORCC and the Morganza Structure should be primarily associated with forcing mechanisms other than the ORCC.

For estimates of what these trends are, please see the reports associated with the 1D HEC-6T sedimentation modeling and the Geomorphic Analysis tasks that are associated with the OMAR Assessment.

3. How much sediment could be diverted by USACE operations if the Hydroelectric Station was not operated? This question is addressed via the Scenario 3 results. These results utilize Ratio 1 operations. Ratio 1 operations divert all flows at the ORCC through either the Low Sill Structure or the Auxiliary Structure. The resulting diverted sediment loads are shown in Table 10. This table is identical to the one given in Table 9 for the existing (base) flows. For reference, the base loads are also included in this table, in **blue**.

Table 10. Mass of sand diverted from the Mississippi River through the ORCC for Ratio 1 operations.

Design Flow Year	Mass of Sand Diverted from the River (Mtons/yr); Base values in blue.	Mass of Sand Diverted through the Structures (Mtons/yr); Base values in blue.
WY 2012 (Low Flow)	9.1 5.4	4.3 2.7
WY 2013 (Typical Flow)	17.4 8.9	10.0 5.2
WY 2008 (High Flow)	21.8 14.4	11.8 5.6

Note that the sediment loads shown in Table 10 are somewhat inflated by the fact that the increase in flow diversion at Low Sill and Auxiliary induces scouring of the shoal downstream of the hydropower channel. This scouring, therefore, is a local and temporary effect that increases the diverted sediment load. If these operations were maintained for multiple years, the river morphology would adjust to the new conditions and the additional sediment associated with this local scour would not be diverted.

4. How can water control operations be optimized to improve sediment transfer based on improved understanding of water flow and sediment transport in the system? Section 4.4 of this report details the effects of various potential changes to operations at the ORCC.

The operational scenarios demonstrate that the sediment diversion characteristics of the ORCC are most heavily influenced by two factors:

- The proportion of water diverted to the Low Sill and Auxiliary Structures. These structures divert proportionally greater sediment than does the hydropower structure, so scenarios that divert more water to these structures divert more sediment.
- The total diversion volume. For example, an increase in the lateral flow distribution from the 70/30 split to a 60/40 split significantly increases the sediment diverted at the complex.

Since the simulated effects in this study are only for 1 year periods, there are local morphological effects that have significant influence on the results. These local morphological effects are discussed in detail in the main text.

5. How much sediment must be diverted to bring the Mississippi at ORCC into dynamic equilibrium? The answer to this question is contingent on the definition of *equilibrium*.

From Chapter 3, the analytic value of the equilibrium SDCE is approximately 1.7. This equilibrium value is, by definition, the value of the SDC necessary to maintain equal river channel dimensions both upstream and downstream of the diversion.

This means that if the downstream channel has already adjusted to the presence of a diversion with a SDC lower than the equilibrium value, then changing the diversion to the equilibrium SDC will scour the downstream channel.

The ORCC is just such a diversion. The estimated value of the SDC for ORCC is ~0.9 (see Section 3.2.3).

The ORCC, and before that the uncontrolled diversion at Shreve's Cut, has existed for many decades. The Mississippi River has largely adjusted to the presence of these diversions.

Hence, with respect to the ORCC, the river is already likely in equilibrium.

However, if one defines *equilibrium* in terms of the overall morphodynamic equilibrium of the river, rather than in terms of the relationship between the ORCC and the river, then the answer is different. In this case, the object is to use the ORCC as a tool to compensate for larger morphodynamic trends in the river.

This aspect of this charge question is not addressed by the study results in this report, but it has been addressed by the geomorphic assessment and 1D HEC-6T modeling tasks associated with the OMAR Assessment. The reader is referred to these tasks for quantitative estimates of the changes required to ORCC operations to bring the Mississippi River into dynamic equilibrium.

6. What are the long-term impacts (i.e., change in flowline) above and below ORCC on the Mississippi River for the various operational and dredging management options evaluated? Qualitative and short-term trends in changes to water surface elevation associated with various scenarios are discussed in Sections 4.4 and 4.5 of this report. Long-term effects on flowline are addressed quantitatively in the 1D modeling report (Copeland and Lewis 2022).

7. Are there potential structural solutions on either side of the ORCC that could facilitate sediment transport through the system? The structural solutions investigated here are shown to have limited effects on the sediment transport efficiency of the ORCC. Detailed results are found in Section 4.6 of this report

5.2 Recommendations

The scenario analyses presented here are of use in identifying large trends and making general assessments of the potential impacts of various proposed changes to the ORCC.

However, if any of these scenarios were to be analyzed for possible implementation at the ORCC, there should be significant additional modeling conducted to inform this decision. This modeling should include 1D modeling for long-term and large-scale impacts and multi-dimensional modeling for local impacts and to assess project performance.

The multi-dimensional models should have these characteristics, among others:

- They should be validated to sequential comprehensive bathymetric surveys, if possible.
- They should be simulated for multiple sequential years (on the order of 10 yr).
- They should be simulated using multiple sets of forcing conditions, each of which is perturbed about the estimated uncertainty of the model parameters. These simulations can then be used to generate estimated uncertainty bounds for the results.
- All reporting of results should be expressed in terms of these uncertainties.

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Abbreviations

1D	One-dimensional
2D	Two-dimensional
3D	Three-dimensional
AdH	Adaptive Hydraulics
CHL	Coastal and Hydraulics Laboratory
ERDC	US Army Engineer Research and Development Center
MR&T	Mississippi River and Tributaries
OMAR	Old River, Mississippi River, Atchafalaya River, and Red River
ORCC	Old River Control Complex
ORCS	Old River Control Structure
SDC	Sediment diversion coefficient
SDCE	Sediment diversion coefficient equilibrium
SRI	Sediment removal index
SRR	Sediment removal ratio
STE	Sediment trapping efficiency
USACE	US Army Corps of Engineers
USGS	US Geological Survey
VFS	Very fine sand
WY	Water year

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This report is part of the (OMAR) Assessment (defined herein), intended to provide a comprehensive assessment of the interconnected Mississippi, Red, and Atchafalaya Rivers, and the potential results of various changes. This report details the multi-dimensional modeling efforts undertaken to characterize the hydrodynamic and morphodynamic response of the Mississippi River to both the existing configuration and to various proposed operational, dredging, and structural scenarios.

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