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Bird's Point HSR MODEL
River Miles 5.8 – 0.0

HYDRAULIC SEDIMENT RESPONSE MODEL INVESTIGATION

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INTRODUCTION

The U.S. Army Corps of Engineers, St. Louis District, conducted a study of the flow and sediment transport conditions on the Mississippi River near Bird's Point between River Miles (RM) 5.8 and 0.0 near Cairo, Illinois. This study was funded by the Regulating Works Project for the Middle Mississippi River. The objective of the model study was to produce a report that outlined the results of an analysis of various river engineering measures, intended to reduce or eliminate the need for repetitive channel maintenance dredging between RM 3.0 and RM 0.0 without negatively affecting the navigation conditions near RM 2.0 to RM 1.0.

The study was conducted between February, 2011 and November, 2011 using a physical hydraulic sediment response (HSR) model at the Applied River Engineering Center, St. Louis District, in St. Louis, Missouri. The model study was performed by Mrs. Ashley Cox, Hydraulic Engineer, under direct supervision of Mr. Robert Davinroy, P.E., Chief of River Engineering Section for the St. Louis District. See Table 1 for other personnel involved in the study.

Table 1: Other Personnel Involved in the Study

Name	Position	District/Company
Leonard Hopkins, P.E.	Hydrologic and Hydraulic Branch Chief	St. Louis District
Rob Davinroy, P.E.	Chief of River Engineering Section	St. Louis District
Dave Gordon, P.E.	Chief of Hydraulic Design Section	St. Louis District
Michael Rodgers, P.E.	Project Manager for River Works Projects	St. Louis District
Jasen Brown, P.E.	Hydraulic Engineer	St. Louis District
Adam Rockwell	Cartographic Technician	St. Louis District
June Jeffries, P.E.	Chief of Environmental Engineering Section	St. Louis District
Brian Johnson	Chief of Environmental Planning Section	St. Louis District
Brandon Schneider	Biologist	St. Louis District
Jennifer Brown	Regulatory Project Manager	St. Louis District
Lance Engle	Dredging Project Manager	St. Louis District
Sarah Markenson	Real Estate	St. Louis District
Jason Floyd	Engineering Technician	St. Louis District
Dana Fischer	AREC Co-op	St. Louis District
Butch Atwood	Mississippi River Fisheries Biologist	Illinois Dept. of Natural Resources
Matt Mangan	Biologist	U.S. Fish & Wildlife Service
David Ostendorf	Resource Staff Scientist	Missouri Dept. of Conservation
Bernie Heroff	Port Captain	American River Transportation Co.
Shannon Hughes	River Field Port Captain	Kirby Inland Marine
Terry Wiltz	Chairman	Illinois River Carriers' Assocation

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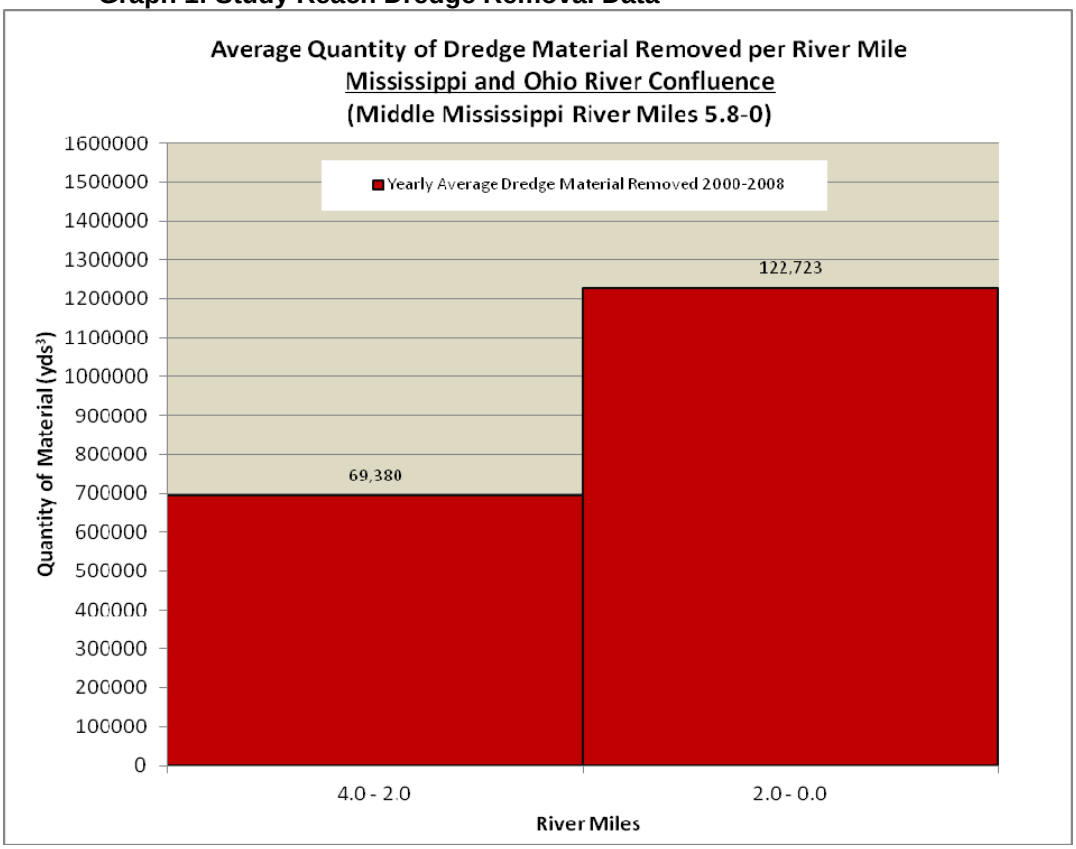
BACKGROUND

1. Problem Description

Dredging in the Mississippi River is commonly used to provide required navigation dimensions of depth, width, alignment, or a combination thereof. In the case of the Bird's Point reach, repetitive channel maintenance dredging is required for all three dimensions. Without dredging, the sandbar located along the LDB between River Mile (RM) 2.0 and RM 3.0 has grown in size and shoaling has occurred between RM 1.4 and RM 0.0, resulting in an unacceptable navigation approach through the U.S. – 60/62 Bridge (see Plate 3). On average, dredging in this area has been required nearly every year from 2000 - 2008. During that time frame, between RM 4.0 and RM 2.0, an average of 69,380 cubic yards (cy) has been dredged annually at a cost of $166,000. Between RM 2.0 and RM 0.0 an average of 122,723 cy has been dredged annually at a cost of $171,550. See Graph 1 for a comparative analysis of the dredge material removed in Bird's Point reach.

Graph 1: Study Reach Dredge Removal Data



2. Study Purpose and Goals

The purpose of this study was to find a river engineering solution to reduce or eliminate dredging at RM 4.0 - 0.0 while improving navigation conditions through the U.S. – 60/62 Bridge, and produce a report that communicates the results of the Hydraulic Sediment Response (HSR) model study.

The goals of this study were to:

i. Investigate and provide analysis on the existing flow mechanics causing the sedimentation and navigation alignment problems.

ii. Evaluate a variety of remedial measures utilizing an HSR model with the objective of identifying the most effective and economical plan to reduce or eliminate sedimentation at RM 4.0 - 0.0. In order to determine the best alternative, four criteria were used to evaluate each alternative.

   a. The alternative should reduce or eliminate sedimentation between RM 4.0 and RM 2.0 (more specifically RM 3.0 and RM 2.0).
   b. The alternative should reduce or eliminate sedimentation between RM 2.0 and RM 0.0 (more specifically RM 1.4 and RM 0.0).
   c. The alternative should maintain the navigation channel requirements of at least 9 foot of depth and 300 foot of width.
   d. The alternative should not worsen the navigation flow conditions through the U.S. – 60/62 Bridge.

iii. Communicate to other engineers, river industry personnel, and environmental agency personnel the results of the HSR model tests and the plans for improvements.

3. Study Reach

The study comprised a 5.8 mile stretch of the Mississippi River, between RM 5.8 – 0.0, passing through Mississippi County, Missouri and Alexander County, Illinois near Cairo. The Mississippi River and Ohio River confluence occurs just downstream of the area of interest, RM 3.0 - 0.0. Plate 1 is a location and vicinity map of the study reach. Plate 2 is a 2008 aerial photograph of the study reach. Discussed below are a variety of features found within the reach.

There were a total of 24 river training structures within the entire study reach and are shown on Plate 4. See Table 2 (page 10) for the river training structures' history and existing conditions. Revetment was in place along the entire RDB from RM 5.8 to RM 0.0. There have been no significant changes to the planform for this reach of the Mississippi River since 1928.

A majority of the property on the RDB side of the Mississippi River was used for agriculture. Cairo, Illinois is located on the LDB side of the river near RM 6.0. To the north and south of Cairo were agricultural fields. There were minimal hardwoods (i.e. cottonwoods and willows) found on either side of the Mississippi River. On the LDB side of the river was the Mound City to Cairo and Cairo to Cache River Diversion Channel Levee Systems. On the RDB side of the river was the Commerce to Birds Point Levee System. These systems are ultimately a part of the Mississippi River and Tributaries (MR&T) Levee System. Angelo Towhead was owned by Heartwood Forestland Fund VI at the time of the study.

The average annual suspended sediment discharge at the Thebes gage (RM 43.7) on the Mississippi is 262,000 tons per day, whereas the Lock and Dam 53 gage (RM 963.0) on the Ohio records 116,500 tons per day. The average discharge from the Mississippi River at the Thebes gage is 208,200 cubic feet per second (cfs) and 278,500 cfs on the Ohio River at the Metropolis gage (RM 946.0). (There was no discharge data available from the LD53 gage near Grand Chain, IL. The Metropolis gage discharge was used because it is just 17 miles upstream from LD53 and

covers a drainage basin only 100 square miles smaller than the LD53 gage drainage basin.)

A. Geomorphology

To understand the planform of the river near Cairo, an investigation was conducted on the historical changes, both natural and manmade, that lead up to the present day condition. Plate 3 shows geomorphic planform changes from RM 26.0 to RM 0.0, encompassing the years from 1817 - 2003, and was sourced from "Geomorphology of the Middle Mississippi River", produced by the St. Louis District (2005). Based on this planform comparison, the time period between 1817 and 1881 marked the development of Angelo Towhead between RM 5.0 - 2.0. This formation occurred naturally, predating the use of river training structures in this river reach. The existence of Angelo Towhead and the corresponding chute are contributing factors to the repetitive dredging issues faced today. The formation of the towhead also decreased the width of the river roughly 2,400 ft at RM 3.6 while shifting the channel in an eastern direction. Less significant yet measureable shifts occurred in the time periods thereafter. A general widening trend of 1,850 ft at RM 4.0 and 530 ft at RM 3.0 with a southern direction shift was observed between years 1881 - 1928. According to Plate 4, revetment was placed along the RDB between RM 4.0 - 2.0 around 1928, resulting in a near stationary RDB between 1928 and 2003. The only change in the planform in this time span was a 1,055 ft southern shift along the unrevetted LDB.

Plates 4 - 10 consist of bathymetry and aerial photographs between 1928 and 1987 which provide a good overview of the characteristics and changes to the river between RM 5.8 to RM 0.0. As mentioned earlier, the 1928 aerial photograph (Plate 5) revealed that revetment was in place along the RDB of Greenfield Bend resulting in no significant bank line shift from 1928 - 2003. The photo also shows a half completed U.S. – 60/62 Bridge at RM 1.0. The 1942 map (Plate 5) shows completed river training structures at the inlet of Angelo Chute. Trail Dike 5.2 and Dike 4.2 were constructed to restrict flow in the chute and redirect that energy into the navigation channel due to problematic sedimentation issues experienced. Based on the

soundings of the 1939 - 1956 map (Plate 7), the navigation channel had become very narrow, a problem that was addressed by the construction of the trail dike at the entrance of Angelo Chute prior to 1946. Gradual changes to the bathymetry at RM 1.0 to RM 0.0 can be seen. Although Angelo Chute was rarely surveyed, the exit condition of that chute revealed the decrease in flow until 1976 - 1977 (Plate 9) with noticeable growth to the sand bar on the RDB at RM 1.0 – 0.0. The 1982 - 1983 soundings (Plate 10) show increased flow within the chute, a possible sign of training structure degradation at the inlet of Angelo Chute. Repair work to Trail Dike 5.0L was performed in 1985 and a slight increase in deposition at the chute exit was observed on the 1986 - 1987 soundings (Plate 11). Refer to Table 2 for a more detailed history of the river training structures.

Table 2: Study Reach River Structure History

River Training Structure	Description
Dike 5.4L	Constructed prior to the 1942 planform map. Repairs were performed in February 1980.
Dike 5.2L	Constructed prior to the 1942 planform map in conjunction with Trail Dikes 5.0L and Dike 4.7L. Repairs were performed in September 1984.
Trail Dike 5.0L	Constructed prior to the 1942 planform map in conjunction with Trail Dikes 5.2L and Dike 4.7L. Repairs were performed in September 1984. Spur dikes were added in August 2001.
Dike 4.7L	Constructed prior to the 1942 planform map in conjunction with Trail Dikes 5.2L and Dike 5.0L. Repairs were performed in September 1984.
Dike 4.4L	Constructed in September 1980. It was extended to 400 ft at a height of 290 – 292 ft with a 100 ft notch in 2009.
Dike 4.2L	Built prior to the 1942 planform map.
W Dike 4.0L	Completed in May 2010.
Dike 4.0L	Completed in April 2010.
Weirs 4.2R and 4.0R	Construction completed in January 2000.
Weirs 3.9R - 3.1R	Construction completed in February 1995.
Chevrons 2.80L - 2.60L	Proposed to be built in 2011.
Weirs 2.0R - 1.8R	Constructed in February 2000.
Dike 1.4R	Constructed prior to the1942 planform map. Repair work was carried out in January 1980.
Dike 1.3R	Constructed prior to the 1942 planform map. The structure was repaired in August 2001.
Dikes 0.8R – 0.1R	Dikes 0.8R and 0.1R were built between 1956 and 1971. Dike 0.8R was repaired in December of 1993 and in March 2001. Dikes 0.6R and 0.3R were built in March 2001. Proposed construction for the fiscal year 2011 includes length extensions of Dikes 0.8R – 0.3R

B. Channel Characteristics and General Trends

i. Bathymetry

Range line and multi-beam hydrographic surveys of the Mississippi River from 2001 to 2010 within the HSR Model extents, are shown on Plates 12 - 17. Plates 18 – 20 show pre-dredge conditions from 2006 – 2008. (Pre-dredge surveys from 2000 to 2008 show similar trends, so only the most recent surveys were included in the report.) For this study, the bathymetric data was referenced to the Low Water Reference Plane (LWRP).

Recent surveys were used to determine general trends because they showed the most recent construction and the resultant river bed changes. The following bathymetric trends remained relatively constant from 2001 - 2010 after comparison of the above mentioned hydrographic surveys:

Table 3: Study Reach Bathymetry Trends

River Miles	Description
5.8 - 4.8	The RDB bar ended at RM 5.5. The thalweg crossed from the LDB to the RDB over a distance of 1 river mile with depths between -10 and -30 ft LWRP.
4.8 - 3.0	The thalweg was located on the RDB over a series of bendway weirs with depths between -12 ft and -50 ft LWRP. The navigation channel was approximately 1,250 ft wide at RM 4.8 and decreased to 500 ft at RM 3.5 opposite of the LDB point bar. The LDB bar spanned the edge of Angelo Towhead and extended downstream to approximately RM 1.7(varied, from about 1,000 ft to 3,000 ft downstream of the tip of Angelo Towhead).
3.0 - 2.5	The thalweg remained on the RDB. Deposition occurred on the inside of the bend, narrowing the navigation channel and requiring annual dredging.
2.5 - 1.6	The thalweg was located on the RDB over 3 bendway weirs with depths between -12 ft and -50 ft LWRP. The navigable channel widened from approximately 750 ft at RM 1.9 to approximately 1,250 ft immediately downstream of Angelo Towhead near RM 1.5.
1.6 - 0.0	The thalweg crossed from the RDB through the main span of the U.S. Highway 60 Bridge to the LDB. The depth of the navigation channel through the main span of the bridge varied between -10 and -30 ft LWRP. The bar on the RDB between RM 1.3 and RM 0.0 decreased the channel width; at RM 0.8 the channel averaged 1,000 feet wide.

Even though the Ohio River was not studied, it was necessary to model the river for replication purposes. The formation of the scour hole at the confluence of the Mississippi and Ohio Rivers was critical, and would verify that the Mississippi River dominated the Ohio River in the HSR model.

ii. Velocity

An ADCP (Acoustic Doppler Current Profiler) survey of the Mississippi River, in the HSR Model extents, is shown on Plate 21. ADCP defines the velocity magnitude and direction of the water. The plate shows an ADCP survey from December 2007.

A comparison of velocity distribution using several cross sections of the channel was necessary to evaluate and compare flow trends. However, the value of the comparison is limited, due to only one year of ADCP collected. In order to compare the general velocity trends between the river and model, the velocities in each cross section were normalized. Normalization involved dividing the magnitudes from each transect by the highest magnitude in that particular transect. This created a velocity scale from 0 to 1 for both the collected river ADCP and the model Laser Doppler Velocimeter (LDV) data. The normalized data showed the magnitude distribution between the highest and lowest velocities in each cross section. The direction was unchanged and showed velocity patterns such as eddies and outdraft.

Table 4: Study Reach Velocity Trends

River Miles	Description
5.8 - 4.8	The highest velocities of the river were located near the middle of the channel and the RDB from RM 5.8 to RM 5.0. The energy distribution spread across the channel near RM 5.0 to RM 4.8.
4.8 - 3.0	The highest velocities crossed to the structures on the LDB from RM 4.8 to RM 4.0. The higher energy dissipated slightly as the river widened from RM 4.0 to RM 3.2.
3.0 - 2.5	At RM 3.1, the velocity magnitudes increased as the channel narrowed. The highest velocities crossed from the middle of the channel at RM 3.1 to the RDB near RM 2.0.
2.5 - 1.6	After passing over the weir field, the highest velocity magnitudes began to migrate to the middle of the channel.
1.6 - 0.0	The velocities that exited the side channel had minimal effects in the main channel. The highest energy passed through the 3rd and 4th spans (from the LDB) of the bridge and in the middle of the channel from RM 1.6 to RM 0.8. Near RM 0.8 the highest velocity magnitudes migrated towards the LDB and ultimately to the middle of the confluence near RM 0.5.

iii. Site Data

On August 1, 2011, the authors of this report visited the Bird's Point reach to examine bank lines, structures, and any data that could not otherwise be gathered in the office. At the Thebes' gage, the river stage was 29.11ft (329.11 ft in elevation). Because of the high stage, many hydraulic structures were submerged. The following observations were made:

- RM 0.0 – 0.3R: Caving bank conditions existed.

  Given the gradual slope of the bathymetry, this would be unusual; however, there had been long durations of high water prior to the field visit.
- Dike 1.3R: The exposed portion of the dike was in good condition.
- RM 1.4 – 1.5L: Caving bank conditions existed in an area of deposition.

  Sediment sampling in this vicinity revealed sand and gravel deposition (ideal pallid sturgeon habitat).

- Angelo Chute RDB: There was major bank line erosion immediately upstream of the revetment.
- Angelo Chute LDB: The LDB had gentle sloping bank lines with established vegetation.
- Dike 5.2L South Point: The dike itself and the shallow area on the east side of the dike had young vegetation. This suggested that an extended period of lower stages occurred recently.

Pictures from the site visit can be seen on Plates 22 – 23.

iv. Analysis of Existing Flow Mechanics

After thoroughly investigating the model reach through tow pilot interviews and ADCP surveys, it was determined that the study reach was very sensitive to the flows through Angelo Chute. Graphic 1 (Normal Flow) and Graphic 2 (High Flow) describe generalized flow conditions. Starting near RM 4.2, the velocities were dispersed evenly across the channel as a result of the RM 4.2 to RM 3.1R weir field. The flow increased upon exit of the weir field and constriction of the channel near RM 2.8. As the flow passed over the small weir field from RM 2.0 to RM 1.8R, the planform and weirs dispersed the energy and forced the direction of flow towards the center of the channel. At normal flows, the flow exiting Angelo Chute stayed near the LDB. The main channel flow was slightly angled towards the LDB as it passed through the bridge span. However, at high flows the velocities exiting the chute were strong enough to redirect the main channel flow towards the RDB as it passed through the bridge span. As a result, an alignment and slight outdraft problem existed near the bridge piers of the navigation span. Even at high flows, navigation through the bridge was not an area of concern for experienced pilots. However if pilots are not familiar with the reach, they may not know how to account for the flows exiting Angelo Chute. Accidents and difficulties navigating through this stretch of river have occurred when pilots unfamiliar with the reach underestimated the flows exiting the chute.

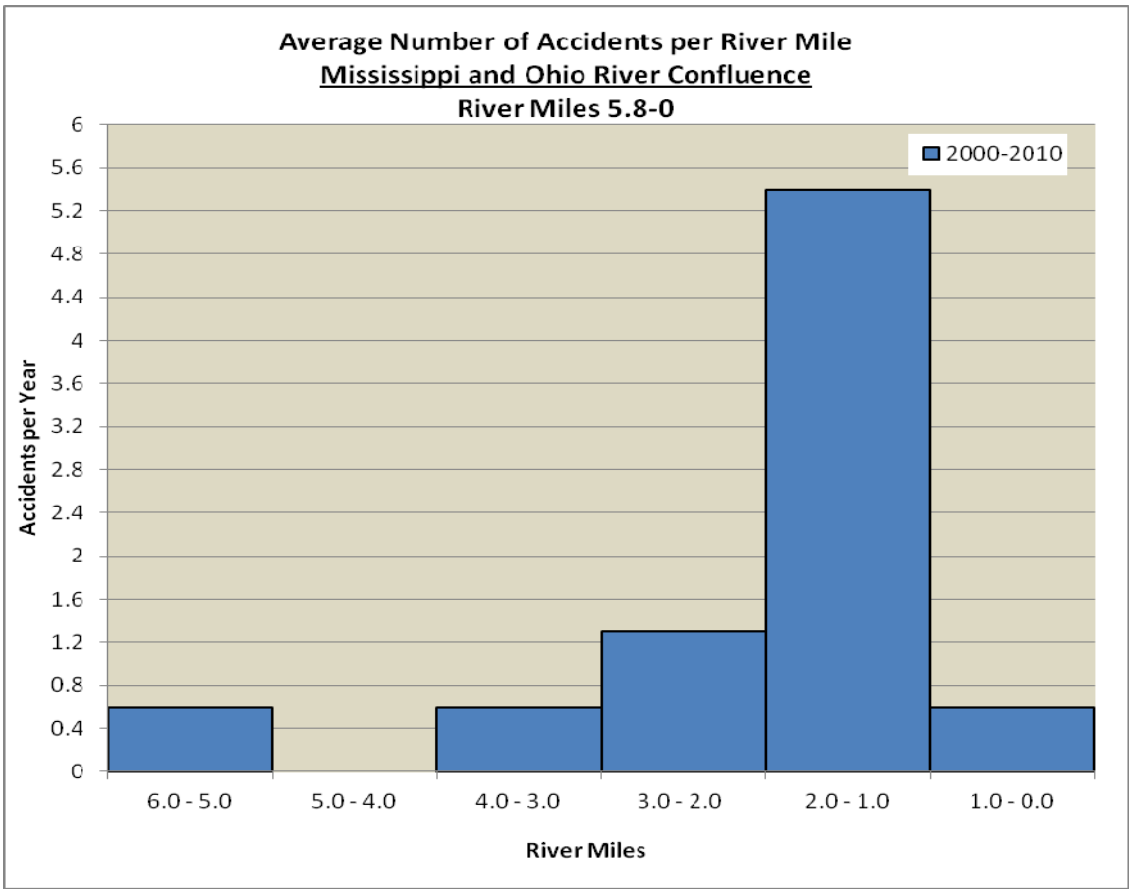
Graphic 1: Study Reach with General (Normal) Flow Trends as Indicated by Pilot Interviews and ADCP Surveys

Graphic 2: Study Reach with General (High) Flow Trends as Indicated by Pilot Interviews and ADCP Surveys

v. Accident Data

During higher Mississippi River discharges, barge tow pilots have reported that flow exiting Angelo Chute directs the main channel flow towards the RDB pier of the navigation span. This has been shown to be a safety hazard. The available accident data for RM 3.0 to RM 0.0, provided by Coast Guard District 8, reveals that the average number of accidents per year is 5.4 near RM 1.0 (Graph 2). These accidents are associated with the U.S. - 60/62 Bridge.

Graph 2: Study Reach Accident Data



HSR MODELING

1. Model Calibration and Replication

The HSR modeling methodology employed a calibration process designed to replicate the general conditions in the river at the time of the model study. Replication of general prototype conditions in the model was achieved during calibration and involved a three step process.

First, planform “fixed” boundary conditions of the study reach, i.e. banklines, islands, side channels, tributaries and other features were established according to the most recent available high resolution aerial photographs. Various other fixed boundaries were also introduced into the model including any channel improvement structures, underwater rock, clay and other non-mobile boundaries. These boundaries were based off of documentation (such as plans and specifications) provided by the St. Louis District.

Second, “loose” boundary conditions of the model were replicated. Bed material was introduced into the channel throughout the model to an approximate level plane. The combination of the fixed and loose boundaries served as the starting condition of the model.

Third, model tests were run using steady state discharge. Adjustment of the discharge, sediment volume, model slope, fixed boundaries, and entrance conditions were refined during these tests as part of calibration. The bed progressed from a static, flat, arbitrary bed into a fully-formed, dynamic, three dimensional mobile bed. Repeated tests were simulated for the assurance of model stability and repeatability. When the general trends of the model bathymetry were similar to observed recent river bathymetry, the model was considered calibrated and alternative testing began.

One important parameter to note was that in calibration, non-erodible bed material of higher specific gravity was used in some localized areas on the model riverbed to better replicate likely areas of non-erodible material observed in the prototype.

Because the non-erodible was required for calibration, the non-erodible remained in the model throughout the rest of the study (ie during alternative testing).

2. Scales and Bed Materials

The model employed a horizontal scale of 1 inch = 900 feet, or 1:10,800, and a vertical scale of 1 inch = 68 feet, or 1:816, for a 13 to 1 distortion ratio of linear scales. This distortion supplied the necessary forces required for the simulation of sediment transport conditions similar to those observed in the prototype. The bed material was granular plastic urea, Type II, with a specific gravity of 1.40.

3. Appurtenances

The HSR model planform insert was constructed according to the 2008 low water high-resolution aerial photography of the study reach. The insert was then mounted in a standard HSR model flume. The riverbanks of the model were routed into dense polystyrene foam and modified during calibration with clay and polymesh. Adjustable leveling casters were used to modify the slope of the model. The measured slope of the insert and flume was approximately 0.01 inch/inch. River training structures in the model were made of galvanized steel mesh to generate appropriate scaled roughness. A picture of the HSR model can be seen on Plate 24.

4. Flow Control

Flow into the model was regulated by customized computer hardware and software interfaced with an electronic control valve and submersible pump. This interface was used to control the flow of water and sediment into the model. Sediment distribution for the Ohio and Mississippi River was controlled so that the Mississippi River received the majority of the sediment. For all model tests, flow entering the model was held steady at 1.01 Gallons per Minute (GPM) for the Mississippi River side and 0.93 GPM for the Ohio River side. This served as the average expected energy response of the river. Because of the constant variation experienced in the river, this steady state flow was used to replicate existing general conditions and analyze the ultimate expected sediment response that could occur from future alternative actions.

5. Data Collection

Data from the HSR model was collected with a three dimensional (3D) laser scanner and a Laser Doppler Velocimeter (LDV). The operation of this equipment is described below.

A. 3D Laser Scanner

The river bed in the model was surveyed with a high definition, 3D laser scanner that collects a dense cloud of xyz data points. These xyz data points were then georeferenced to real world coordinates and triangulated to create a 3D surface. The surface was then color coded by elevation using standard color tables that were also used in color coding prototype surveys. This process allowed a direct comparison between HSR model bathymetry surveys and prototype bathymetry surveys.

B. Laser Doppler Velocimeter (LDV)

The magnitude (speed) and direction of flow in the model was measured with the LDV. The data was then processed to produce velocity vector transects. Each velocity vector transect was normalized to the highest vector magnitude in the transect. The resulting normalized vectors were then sized and color coded using standard vector arrow sizes and color tables used in displaying prototype velocity surveys (also normalized). This allowed for a direct comparison between HSR model velocity surveys and prototype velocity surveys.

6. Replication Test

Once the model adequately replicated general prototype trends, the resultant bathymetry served as a benchmark for the comparison of all future model alternative tests. In this manner, the actions of any alternative, such as new channel improvement structures, realignments, etc, were compared directly to the replicated condition. General trends were evaluated for any major differences, positive or negative, between the alternative test and the replication test by comparing the surveys of the two and also carefully observing the model while the actual testing was taking place.

A. Replication Bathymetry

Bathymetric trends were recorded from the model using a 3D Laser Scanner. Calibration was achieved after numerous favorable bathymetric comparisons of the prototype surveys were made to several surveys of the model. The resultant bathymetry served as the replication for the model and is shown on Plate 25.

Results of the HSR model replication bathymetry and a comparison to the 2001 through 2010 prototype surveys indicated the following trends:

Table 5: Study Reach and Prototype Bathymetry Trend Comparison

River Miles	Description
5.8 – 4.8	The model and the prototype surveys showed a point bar ending at RM 5.5. In both the model and the prototype, the crossing was observed between RM 5.8 and RM 4.8. Like the prototype, the model showed thalweg depths from -10 to -30 feet LWRP.
4.8 – 3.0	In both the model and the prototype, the thalweg remained on the RDB throughout the bendway weir field with depths between -12 to -50 feet LWRP. The model and prototype navigation channel widths at RM 4.8 to RM 3.5 were approximately the same. The LDB bar, in both the model and the prototype, spanned the edge of Angelo Towhead and extended downstream.
3.0 - 2.5	The thalweg was on the RDB in both the model and prototype. In the model, deposition occurred in the dredge removal areas, as shown on Plate 3.
2.5 – 1.6	In both the model and the prototype, the thalweg remained on the RDB throughout the bendway weir field with depths between -12 to -50 feet LWRP. The model's navigable channel also widened from approximately 775 ft at RM 1.9 to approximately 1,300 ft immediately downstream of Angelo Towhead near RM 1.5.
1.6 – 0.0	Like the prototype, the model survey showed the thalweg migration towards the LDB through the main span of the bridge. In both the prototype and model, the depth of the navigation channel through the main span of the bridge was about -10 to -30 ft LWRP. The bar on the RDB between RM 1.3 and RM 0.0 decreased the channel width in both the model and prototype.

Even though the Ohio River was not studied, it was necessary to model the river for replication purposes. The formation of the scour hole at the confluence of the

Mississippi and Ohio Rivers was critical, and verified that the Mississippi River dominated the Ohio River in the HSR model.

B. Replication Velocity

Once favorable bathymetric trends were observed in the model, a Laser Doppler Velocimeter (LDV) profile was collected from the replication test conditions in the model to compare with ADCP data collected on the river. After comparisons of the prototype ADCP were made to LDV surveys of the model and the trends were similar, this further verified that the model was replicated. The resultant LDV normalized velocity distributions served as the velocity replication test for the model and is shown on Plate 26.

The profile for the LDV was determined based upon the previously collected prototype transects, but limited to a ten inch by ten inch grid. (This was due to the traverse extents of the LDV). The LDV could have been moved for additional data collection, however this was not pursued due to time and budget restrictions. Results of the HSR model replication test were compared to the 2007 prototype ADCP survey and indicated the following trends:

Table 6: Model and Prototype Velocity Trend Comparison

River Miles	Description
2.7-1.6	In both the model and the prototype the high velocities crossed from the middle of the channel towards the RDB. The models high velocities reached the RDB further upstream, near RM 2.20 (prototype near RM 2.0). After passing over the weir field, the highest velocity magnitudes in the model and the prototype began to migrate to the middle of the channel.
1.6-1.1	The model and prototype velocities that exited the side channel had minimal effects in the main channel. In both the model and the prototype, the highest energy passed through the 3rd and 4th spans (from the LDB) of the bridge and in the middle of the channel from RM 1.6 to 0.8. The velocity through the bridge spans was one of the focuses of the study.

In addition to monitoring the bed changes with the 3D Laser Scanner for each alternative, the LDV was used to monitor the velocity changes between RM 2.7 to RM 1.0.

7. Design Alternative Tests

The testing process consisted of modeling alternative measures in the HSR model followed by analyses of the bathymetry and velocity results. The goal was to reduce or eliminate the sedimentation at RM 3.0 and RM 0.0 without negatively affecting the navigation conditions through the U.S. -60/62 Bridge. Evaluation of each alternative was accomplished through a qualitative comparison to the model replication test bathymetry (deposition) and model replication test velocity (LDV) data (alignment).

Alternative 1:

Type of Structure	River Mile	LDB or RDB	Dimensions (Feet)	Structure Top Elevation (ft in LWRP)
Chevron	2.8	LDB	300 x 300	+18.5
Chevron	2.6	LDB	300 x 300	+18.5

Results: *Bathymetry (Plate 27) and Velocity (Plate 28) Analysis*

Reduced Deposition at RM 3.0 – 2.0	Reduced Deposition at RM 1.4 – 0.0	Worsened Alignment through RM 1.8 – 1.0	Additional Comments
No	No	Yes	The channel slightly deepened (from -8 ft to -10 ft LWRP) and widened (from 0 ft to 200 ft) from RM 2.7 to RM 2.2. The velocities increased near RM 2.7 (next to the chevrons). There was a minimal increase in the velocities' angle and magnitude on the LDB side of the channel from RM 1.9 – 1.5.

Alternative 2:

Type of Structure	River Mile	LDB or RDB	Dimensions (Feet)	Structure Top Elevation (ft in LWRP)
Chevron	2.8	LDB	300 x 300	+18.5
Chevron	2.6	LDB	300 x 300	+18.5
Dike Extension	0.8	RDB	370	+18.5
Dike Extension	0.6	RDB	645	+18.5
Dike Extension	0.3	RDB	930	+18.5

Results: *Bathymetry (Plate 29) and Velocity (Plate 30) Analysis*

Reduced Deposition at RM 3.0 – 2.0	Reduced Deposition at RM 1.4 – 0.0	Worsened Alignment through RM 1.8 – 1.0	Additional Comments
No	No	Yes	The channel slightly deepened (from -8 ft to -10 ft LWRP) and widened (from 0 ft to 200 ft) from RM 2.7 to RM 2.2. There was a minimal increase in depth in the crossing near RM 1.1. There were no significant changes in the RDB bar. There was a minimal increase in the angle of the velocities on the LDB side of the channel from RM 1.9 – 1.5.

Alternative 3:

Type of Structure	River Mile	LDB or RDB	Dimensions (Feet)	Structure Top Elevation (ft in LWRP)
Weir	3.0	RDB	475	-15
Weir	2.9	RDB	545	-15

Results: *Bathymetry (Plate 31) and Velocity (Plate 32) Analysis*

Reduced Deposition at RM 3.0 – 2.0	Reduced Deposition at RM 1.4 – 0.0	Worsened Alignment through RM 1.8 – 1.0	Additional Comments
No	No	Yes	There were no significant bathymetry changes. The new weirs did disperse the energy across the channel near RM 2.7. The flow on the LDB side of the channel from RM 2.7 to RM 2.3 no longer aimed directly towards the RDB as it did in the replication test. There was a minimum increase on the LDB side of the channel from RM 1.9 to RM 1.5. There was no significant change to the alignment near the bridge (RM1.5 to RM 1.3).

Alternative 4:

Type of Structure	River Mile	LDB or RDB	Dimensions (Feet)	Structure Top Elevation (ft in LWRP)
Weir (Shorten Existing)	3.3	RDB	120	Existing Bed Elevation
Weir (Shorten Existing)	3.1	RDB	260	Existing Bed Elevation

*Note: Degrade to current river bed elevation.

Results: *Bathymetry (Plate 33) and Velocity (Plate 34) Analysis*

Reduced Deposition at RM 3.0 – 2.0	Reduced Deposition at RM 1.4 – 0.0	Worsened Alignment through RM 1.8 – 1.0	Additional Comments
No	No	Yes	As a result of the shortened weirs, from RM 3.3 to RM 3.0, the bar extended further toward the RDB. The navigation channel was still nearly 800 ft wide. (The extra energy was not expended at the tips of the weirs.) The shortened weirs did disperse the energy across the channel near RM 2.7. The flow on the LDB side of the channel from RM 2.7 to RM 2.3 no longer aimed directly towards the RDB as it did in the replication test. There was a minimal increase in the velocities on the LDB side of the channel from RM 1.9 – 1.5.

Alternative 5:

Type of Structure	River Mile	LDB or RDB	Dimensions (Feet)	Structure Top Elevation (ft in LWRP)
Weir (Shorten Existing)	3.3	RDB	120	Existing Bed Elevation
Weir (Shorten Existing)	3.1	RDB	260	Existing Bed Elevation
Weir	3.0	RDB	475	-15
Weir	2.9	RDB	545	-15

*Note: Degrade to current river bed elevation.

Results: *Bathymetry (Plate 35) and Velocity (Plate 36) Analysis*

Reduced Deposition at RM 3.0 – 2.0	Reduced Deposition at RM 1.4 – 0.0	Worsened Alignment through RM 1.8 – 1.0	Additional Comments
No	No	Yes	As a result of the shortened weirs, from RM 3.3 to RM 3.0, the bar extended further toward the RDB. The navigation channel was still nearly 800 ft wide. (The extra energy was not expended at the tips of the weirs.) The new/shortened weirs did disperse the energy across the channel near RM 2.7. The flow on the LDB side of the channel from RM 2.7 to RM 2.3 no longer aimed directly towards the RDB as it did in the replication test. The velocities' magnitude and angles increased on the LDB side of the channel from RM 1.9 to RM 1.5.

Alternative 6:

Type of Structure	River Mile	LDB or RDB	Dimensions (Feet)	Structure Top Elevation (ft in LWRP)
Weir (Shorten Existing)	3.3	RDB	120	Existing Bed Elevation
Weir (Shorten Existing)	3.1	RDB	260	Existing Bed Elevation
Weir	3.0	RDB	475	-15
Weir	2.9	RDB	545	-15
Chevron	2.8	LDB	300 x 300	+18.5
Chevron	2.6	LDB	300 x 300	+18.5
Dike Extension	0.8	RDB	370	+18.5
Dike Extension	0.6	RDB	645	+18.5
Dike Extension	0.3	RDB	930	+18.5

*Note: Degrade to current river bed elevation.

Results: *Bathymetry (Plate 37) and Velocity (Plate 38) Analysis*

Reduced Deposition at RM 3.0 – 2.0	Reduced Deposition at RM 1.4 – 0.0	Worsened Alignment through RM 1.8 – 1.0	Additional Comments
Yes	Yes	Yes	As a result of the shortened weirs, from RM 3.3 to RM 3.0, the bar extended further toward the RDB. The navigation channel was still nearly 800 ft wide. (The extra energy was not expended at the tips of the weirs.) The constriction of the channel due to the chevrons resulted in less deposition from RM 3.0 to RM 2.0, increasing the width of the navigable channel. The dike extensions reduced the deposition from RM 0.8 to RM 0.1. The new/shortened weirs did disperse the energy across the channel near RM 2.7. The flow on the LDB side of the channel from RM 2.7 to RM 2.3 no longer aimed directly towards the RDB as it did in the replication test. The velocities increased and were angled more towards the LDB from RM 1.8 to RM 1.3. This could worsen the alignment through the bridge and/or could cause issues for the fleeting on the LDB near RM 1.0.

Alternative 7:

Type of Structure	River Mile	LDB or RDB	Dimensions (Feet)	Structure Top Elevation (ft in LWRP)
Weir	3.0	RDB	475	-15
Weir	2.9	RDB	545	-15
Chevron	2.8	LDB	300 x 300	+18.5
Chevron	2.6	LDB	300 x 300	+18.5
Dike Extension	0.8	RDB	370	+18.5
Dike Extension	0.6	RDB	645	+18.5
Dike Extension	0.3	RDB	930	+18.5

Results: *Bathymetry (Plate 39) and Velocity (Plate 40) Analysis*

Reduced Deposition at RM 3.0 – 2.0	Reduced Deposition at RM 1.4 – 0.0	Worsened Alignment through RM 1.8 – 1.0	Additional Comments
No	Yes	Yes	The constriction of the channel due to the chevrons resulted in less deposition from RM 3.0 to RM 2.0, increasing the width of the navigable channel. The dike extensions reduced the deposition from RM 0.8 to RM 0.1. The new weirs did disperse the energy across the channel near RM 2.7. The flow on the LDB side of the channel from RM 2.7 to RM 2.3 no longer aimed directly towards the RDB as it was in the replication test. On the LDB side of the channel, the velocities were angled more towards the LDB from RM 1.9 to RM 1.3. This could worsen the alignment through the bridge and/or could cause issues for the fleeting on the LDB near RM 1.0.

Alternative 8:

Type of Structure	River Mile	LDB or RDB	Dimensions (Feet)	Structure Top Elevation (ft in LWRP)
Weir	3.0	RDB	475	-15
Weir	2.9	RDB	545	-15
Chevron	2.8	LDB	300 x 300	+18.5
Chevron	2.6	LDB	300 x 300	+18.5
Dike Extension	0.8	RDB	370	+18.5
Dike Extension	0.6	RDB	645	+18.5
Dike Extension	0.3	RDB	930	+18.5

*Note: Compared to Alternative 7, the chevrons were placed farther away from Angelo Towhead, while still leaving 1,100 ft of navigation channel.

Results: *Bathymetry (Plate 41) and Velocity (Plate 42) Analysis*

Reduced Deposition at RM 3.0 – 2.0	Reduced Deposition at RM 1.4 – 0.0	Worsened Alignment through RM 1.8 – 1.0	Additional Comments
Yes	No	Yes	The constriction of the channel due to the chevrons resulted in less deposition from RM 3.0 to RM 2.0, increasing the width of the navigable channel. The dike extensions reduced the deposition from RM 0.8 to RM 0.1. The new weirs did disperse the energy across the channel near RM 2.7. The flow on the LDB side of the channel from RM 2.7 to RM 2.3 no longer aimed directly towards the RDB as it was in the replication test. On the LDB side of the channel, the velocities were angled more towards the LDB from RM 1.9 to RM 1.3. This could worsen the alignment through the bridge and/or could cause issues for the fleeting on the LDB near RM 1.0.

Alternative 9:

Type of Structure	River Mile	LDB or RDB	Dimensions (Feet)	Structure Top Elevation (ft in LWRP)
Chevron	2.8	LDB	300 x 300	+18.5
Chevron	2.6	LDB	300 x 300	+18.5

*Note: The chevrons were placed in the same location as Alternative 8.

Results: *Bathymetry (Plate 43) and Velocity (Plate 44) Analysis*

Reduced Deposition at RM 3.0 – 2.0	Reduced Deposition at RM 1.4 – 0.0	Worsened Alignment through RM 1.8 – 1.0	Additional Comments
Yes	No	Yes	The channel slightly deepened (from -8 ft to -10 ft LWRP) and widened (from 0 ft to 250 ft) from RM 2.7 to RM 2.2. The velocities increased near RM 2.7 (next to the chevrons). There was an increase in the velocities on the LDB side of the channel from RM 1.9 to RM 1.5.

Alternative 10:

Type of Structure	River Mile	LDB or RDB	Dimensions (Feet)	Structure Top Elevation (ft in LWRP)
Chevron	2.8	LDB	300 x 300	+18.5
Chevron	2.6	LDB	300 x 300	+18.5

*Note: Compared to Alternative 9, the chevrons were placed closer farther away from Angelo Towhead, while still leaving 950 ft of navigation channel.

Results: *Bathymetry (Plate 45) and Velocity (Plate 46) Analysis*

Reduced Deposition at RM 3.0 – 2.0	Reduced Deposition at RM 1.4 – 0.0	Worsened Alignment through RM 1.8 – 1.0	Additional Comments
Yes	No	Yes	The constriction of the channel due to the chevrons resulted in less deposition from RM 3.0 to RM 2.0. The channel slightly deepened (from -8 ft to -10 ft LWRP) and widened (from 0 ft to 200 ft) from RM 2.7 to RM 2.2. The flow on the LDB side of the channel from RM 2.7 to RM 2.3 no longer aimed directly towards the RDB as it was in the replication test. On the LDB side of the channel, the velocities increased and were angled more towards the LDB from RM 1.9 to RM 1.3. This could worsen the alignment through the bridge and/or could cause issues for the fleeting on the LDB near RM 1.0.

Alternative 11:

Type of Structure	River Mile	LDB or RDB	Dimensions (Feet)	Structure Top Elevation (ft in LWRP)
Rootless Dike	2.9	LDB	350	+18.5
Rootless Dike	2.7	LDB	455	+18.5

*Note: Dikes should start 100 ft from LDB.

Results: *Bathymetry (Plate 47) and Velocity (Plate 48) Analysis*

Reduced Deposition at RM 3.0 – 2.0	Reduced Deposition at RM 1.4 – 0.0	Worsened Alignment through RM 1.8 – 1.0	Additional Comments
Yes	No	Yes	The channel slightly deepened (from -8 ft to -10 ft LWRP) and widened (from 0 ft to 300 ft) from RM 2.7 to RM 2.2. The velocities increased near RM 2.7 (next to the dikes). The flow on the LDB side of the channel from RM 2.7 to RM 2.3 no longer aimed directly towards the RDB as it was in the replication test. On the LDB side of the channel, the velocities were angled more towards the LDB from RM 2.0 to RM 1.5.

Alternative 12:

Type of Structure	River Mile	LDB or RDB	Dimensions (Feet)	Structure Top Elevation (ft in LWRP)
Weir	3.0	RDB	475	-15
Weir	2.9	RDB	545	-15
Weir	2.8	RDB	500	-15
Weir	2.7	RDB	235	-15
Weir	2.6	RDB	365	-15
Weir	2.5	RDB	390	-15
Weir	2.4	RDB	415	-15
Weir	2.3	RDB	410	-15
Weir	2.2	RDB	530	-15

Results: *Bathymetry (Plate 49) and Velocity (Plate 50) Analysis*

Reduced Deposition at RM 3.0 – 2.0	Reduced Deposition at RM 1.4 – 0.0	Worsened Alignment through RM 1.8 – 1.0	Additional Comments
No	No	No	There were no significant bathymetry changes. The new weirs did disperse the energy across the channel near RM 2.7. The flow on the LDB side of the channel from RM 2.7 to RM 2.3 no longer aimed directly towards the RDB as it did in the replication test. The velocities slightly decreased on the LDB side of the channel from RM 1.8 to RM 1.3. There was no significant change to the alignment near the navigation span (RM1.5 to RM 1.3).

Alternative 13:

Type of Structure	River Mile	LDB or RDB	Dimensions (Feet)	Structure Top Elevation (ft in LWRP)
Weir	3.0	RDB	475	-15
Weir	2.9	RDB	545	-15
Weir	2.8	RDB	500	-15
Notched Dike	2.8	LDB	475	+18.5
Weir	2.7	RDB	235	-15
Weir	2.6	RDB	365	-15
Weir	2.5	RDB	390	-15
Weir	2.4	RDB	415	-15
Weir	2.3	RDB	410	-15
Weir	2.2	RDB	530	-15

*Note: The shallow notch is 100 ft wide and should begin 145 ft from Angelo Towhead.

Results: *Bathymetry (Plate 51) and Velocity (Plate 52) Analysis*

Reduced Deposition at RM 3.0 – 2.0	Reduced Deposition at RM 1.4 – 0.0	Worsened Alignment through RM 1.8 – 1.0	Additional Comments
No	No	No	The channel deepened (from -8 ft to -14 ft LWRP) and widened (from 0 ft to 250 ft) from RM 2.4 to RM 2.3. The channel slightly deepened (from -8 ft to -10 ft LWRP) and widened (from 0 ft to 250 ft) from RM 1.2 to RM 0.7. The new weirs did disperse the energy across the channel near RM 2.7. The flow on the LDB side of the channel from RM 2.7 to RM 2.3 no longer aimed directly towards the RDB as it did in the replication test. The velocities slightly decreased on the LDB side of the channel from RM 1.8 to RM 1.3. There was no significant change to the alignment near the navigation span (RM1.5 to RM 1.3).

Alternative 14:

Type of Structure	River Mile	LDB or RDB	Dimensions (Feet)	Structure Top Elevation (ft in LWRP)
Weir	3.0	RDB	475	-15
Rootless Dike	2.9	LDB	350	+18
Weir	2.9	RDB	545	-15
Weir	2.8	RDB	500	-15
Rootless Dike	2.7	LDB	455	+18.5
Weir	2.7	RDB	235	-15
Weir	2.6	RDB	365	-15
Weir	2.5	RDB	390	-15
Weir	2.4	RDB	415	-15
Weir	2.3	RDB	410	-15
Weir	2.2	RDB	530	-15

*Note: Dikes should start 100 ft from LDB. The location of the dikes leaves approximately 1,100 ft of navigation channel.

Results: *Bathymetry (Plate 53) and Velocity (Plate 54) Analysis*

Reduced Deposition at RM 3.0 – 2.0	Reduced Deposition at RM 1.4 – 0.0	Worsened Alignment through RM 1.8 – 1.0	Additional Comments
Yes	No	No	The channel deepened (from -8 ft to -14 ft LWRP) and widened (from 0 ft to 400 ft) from RM 2.8 to RM 2.2. The channel only slightly deepened (from -8 ft to -10 ft LWRP) and widened (from 0 ft to 250 ft) from RM 1.2 to RM 0.6. The new weirs did disperse the energy across the channel near RM 2.7. The flow on the LDB side of the channel from RM 2.7 to RM 2.3 no longer aimed directly towards the RDB as it did in the replication test. The velocities slightly decreased on the LDB side of the channel from RM 1.8 to RM 1.3. There was no significant change to the alignment near the navigation span (RM1.5 to RM 1.3).

Alternative 15:

Type of Structure	River Mile	LDB or RDB	Dimensions (Feet)	Structure Top Elevation (ft in LWRP)
Weir	3.0	RDB	475	-15
Rootless Dike	2.9	LDB	350	+18.5
Weir	2.9	RDB	545	-15
Weir	2.8	RDB	500	-15
Rootless Dike	2.7	LDB	455	+18.5
Weir	2.7	RDB	235	-15
Weir	2.6	RDB	365	-15
Weir	2.5	RDB	390	-15
Weir	2.3	RDB	410	-15
Weir	2.2	RDB	530	-15

*Note: Dikes should start 100 ft from LDB. The location of the dikes leaves approximately 1,100 ft of navigation channel.

Results: *Bathymetry (Plate 55) and Velocity (Plate 56) Analysis*

Reduced Deposition at RM 3.0 – 2.0	Reduced Deposition at RM 1.4 – 0.0	Worsened Alignment through RM 1.8 – 1.0	Additional Comments
Yes	No	No	There were no significant bathymetry changes compared to Alternative 14. There also were no significant velocity changes compared to Alternative 14. (See Alternative 14 Additional Comments).

Alternative 16:

Type of Structure	River Mile	LDB or RDB	Dimensions (Feet)	Structure Top Elevation (ft in LWRP)
Rootless Dike	2.9	LDB	350	+18.5
Weir	2.9	RDB	545	-15
Weir	2.8	RDB	500	-15
Rootless Dike	2.7	LDB	455	+18.5
Weir	2.6	RDB	365	-15
Weir	2.5	RDB	390	-15
Weir	2.3	RDB	410	-15
Weir	2.2	RDB	530	-15

*Note: Dikes should start 100 ft from LDB. The location of the dikes leaves approximately 1,100 ft of navigation channel.

Results: *Bathymetry (Plate 57) and Velocity (Plate 58) Analysis*

Reduced Deposition at RM 3.0 – 2.0	Reduced Deposition at RM 1.4 – 0.0	Worsened Alignment through RM 1.8 – 1.0	Additional Comments
Yes	No	No	The channel deepened (from -8 ft to -14 ft LWRP) and widened (from 0 ft to 300 ft) from RM 2.8 to RM 2.2. The channel only slightly deepened (from -8 ft to -10 ft LWRP) and widened (from 0 ft to 200 ft) from RM 1.2 to RM 0.6. The new weirs did disperse the energy across the channel near RM 2.7. The flow on the LDB side of the channel from RM 2.7 to RM 2.3 no longer aimed directly towards the RDB as it did in the replication test. The velocities slightly decreased on the LDB side of the channel from RM 1.8 to RM 1.4. There was no significant change to the alignment near the navigation span (RM1.5 to RM 1.3).

Alternative 17:

Type of Structure	River Mile	LDB or RDB	Dimensions (Feet)	Structure Top Elevation (ft in LWRP)
Notched Dike	3.0	LDB	670	+18.5
Weir	2.9	RDB	545	-15
Weir	2.8	RDB	500	-15
Weir	2.6	RDB	365	-15
Weir	2.5	RDB	390	-15
Weir	2.3	RDB	410	-15
Weir	2.2	RDB	530	-15

*Note: The shallow notch is 100 ft wide and should begin 300 ft from Angelo Towhead.

Results: *Bathymetry (Plate 59) and Velocity (Plate 60) Analysis*

Reduced Deposition at RM 3.0 – 2.0	Reduced Deposition at RM 1.4 – 0.0	Worsened Alignment through RM 1.8 – 1.0	Additional Comments
Yes	No	No	The channel deepened (from -8 ft to -14 ft LWRP) and widened (from 0 ft to 350 ft) from RM 2.8 to RM 2.2. The new weirs did disperse the energy across the channel near RM 2.7. The flow on the LDB side of the channel from RM 2.7 to RM 2.3 no longer aimed directly towards the RDB as it did in the replication test. The velocities slightly decreased on the LDB side of the channel from RM 1.8 to RM 1.4. There was no significant change to the alignment near the navigation span (RM1.5 to RM 1.3).

Alternative 18:

Type of Structure	River Mile	LDB or RDB	Dimensions (Feet)	Structure Top Elevation (ft in LWRP)
Chevron	3.0	LDB	300 x 300	+18.5
Weir	2.9	RDB	545	-15
Weir	2.8	RDB	500	-15
Weir	2.6	RDB	365	-15
Weir	2.5	RDB	390	-15
Weir	2.3	RDB	410	-15
Weir	2.2	RDB	530	-15

Results: *Bathymetry (Plate 61) and Velocity (Plate 62) Analysis*

Reduced Deposition at RM 3.0 – 2.0	Reduced Deposition at RM 1.4 – 0.0	Worsened Alignment through RM 1.8 – 1.0	Additional Comments
Yes	No	No	The channel deepened (from -8 ft to -14 ft LWRP) and widened (from 0 ft to 325 ft) from RM 2.8 to RM 2.2. The channel only slightly deepened (from -8 ft to -10 ft LWRP) and widened (from 0 ft to 225 ft) from RM 1.2 to RM 0.6. The new weirs did disperse the energy across the channel near RM 2.7. The flow on the LDB side of the channel from RM 2.7 to RM 2.3 no longer aimed directly towards the RDB as it did in the replication test. The velocities slightly decreased on the LDB side of the channel from RM 1.8 to RM 1.4. There was no significant change to the alignment near the navigation span (RM1.5 to RM 1.3).

Alternative 19:

Type of Structure	River Mile	LDB or RDB	Dimensions (Feet)	Structure Top Elevation (ft in LWRP)
Chevron	3.0	LDB	300 x 300	+18.5
Weir	2.6	RDB	365	-15
Weir	2.5	RDB	390	-15
Weir	2.3	RDB	410	-15
Weir	2.2	RDB	530	-15

Results: *Bathymetry (Plate 63) and Velocity (Plate 64) Analysis*

Reduced Deposition at RM 3.0 – 2.0	Reduced Deposition at RM 1.4 – 0.0	Worsened Alignment through RM 1.8 – 1.0	Additional Comments
Yes	No	No	The channel deepened (from -8 ft to -14 ft LWRP) and widened (from 0 ft to 275 ft) from RM 2.8 to RM 2.2. The flow did increase as a result of the structure at RM 3.0L. The weirs dispersed the flow across the channel, but not as efficiently as previous alternatives with weirs near RM 2.9 and 2.8. The flow on the LDB side of the channel from RM 2.7 to RM 2.3 no longer aimed directly towards the RDB as it did in the replication test. The velocities slightly decreased on the LDB side of the channel from RM 1.8 to RM 1.4. There were no significant velocity changes from RM 1.8 to RM 1.3.

Alternative 20:

Type of Structure	River Mile	LDB or RDB	Dimensions (Feet)	Structure Top Elevation (ft in LWRP)
Rootless Dike	3.0	LDB	615	+18.5
Weir	2.6	RDB	365	-15
Weir	2.5	RDB	390	-15
Weir	2.3	RDB	410	-15
Weir	2.2	RDB	530	-15

*Note: Dike should start 100 ft from LDB.

Results: *Bathymetry (Plate 65) and Velocity (Plate 66) Analysis*

Reduced Deposition at RM 3.0 – 2.0	Reduced Deposition at RM 1.4 – 0.0	Worsened Alignment through RM 1.8 – 1.0	Additional Comments
Yes	No	No	The channel deepened (from -8 ft to -14 ft LWRP) and widened (from 0 ft to 250 ft) from RM 2.8 to RM 2.2. The flow did increase as a result of the structure at RM 3.0L. The weirs dispersed the flow across the channel as did the previous alternatives, but it seemed to be slightly more effective near RM 2.5 to RM 2.3. The flow on the LDB side of the channel from RM 2.7 to RM 2.3 no longer aimed directly towards the RDB as it did in the replication test. There were no significant velocity changes from RM 1.8 to RM 1.3.

*Note: Additional velocity (LDV) data was collected from RM 3.5 to RM 2.8 to determine if the existing weirs at RM 3.3R and 3.1R should be modified. Because this alternative was the preferred alternative and would most likely go to construction in FY13, additional upstream velocity data was collected for "pre-existing weir modification" conditions. See Plate 78 for velocity results from RM 3.5 to RM 1.0. The higher velocities were along the RDB from RM 3.5 to RM 2.8. After passing over the weirs, the flow's direction was angled slightly more towards the LDB or middle of the channel from RM 3.1 to RM 2.8. The higher velocities tend to spread across the channel (towards the LDB) from RM 3.0 to RM 2.8. There was no significant deflection of flow or angle change at the tips of the weirs at RM 3.3R and 3.1R.

Alternative 21:

Type of Structure	River Mile	LDB or RDB	Dimensions (Feet)	Structure Top Elevation (ft in LWRP)
Rootless Dike	3.0	LDB	615	+18.5
Weir	2.85	RDB	540	-15
Weir	2.55	RDB	390	-15
Weir	2.25	RDB	535	-15

Results: *Bathymetry (Plate 67) and Velocity (Plate 68) Analysis*

Reduced Deposition at RM 3.0 – 2.0	Reduced Deposition at RM 1.4 – 0.0	Worsened Alignment through RM 1.8 – 1.0	Additional Comments
Yes	No	No	The channel deepened (from -8 ft to -14 ft LWRP) and widened (from 0 ft to 250 ft) in some locations throughout RM 2.8 to RM 2.2. The flow did increase as a result of the structure at RM 3.0L. The weirs dispersed the flow across the channel, but not as efficiently as in Alternative 20. The flow on the LDB side of the channel from RM 2.7 to RM 2.3 no longer aimed directly towards the RDB as it did in the replication test. There were no significant velocity changes from RM 1.8 to RM 1.3.

Alternative 22:

Type of Structure	River Mile	LDB or RDB	Dimensions (Feet)	Structure Top Elevation (ft in LWRP)
Chevron	3.0	LDB	300 x 300	+18.5
Weir	2.85	RDB	540	-15
Weir	2.55	RDB	390	-15
Weir	2.25	RDB	535	-15

Results: *Bathymetry (Plate 69) and Velocity (Plate 70) Analysis*

Reduced Deposition at RM 3.0 – 2.0	Reduced Deposition at RM 1.4 – 0.0	Worsened Alignment through RM 1.8 – 1.0	Additional Comments
Yes	No	No	The channel deepened (from -8 ft to -14 ft LWRP) and widened (from 0 ft to 200 ft) in some locations throughout RM 2.8 to RM 2.2. The flow did increase as a result of the structure at RM 3.0L. The weirs dispersed the flow across the channel, but not as efficiently as in Alternative 20. The flow on the LDB side of the channel from RM 2.7 to RM 2.3 no longer aimed directly towards the RDB as it did in the replication test. There were no significant velocity changes from RM 1.8 to RM 1.3.

Alternative 23:

Type of Structure	River Mile	LDB or RDB	Dimensions (Feet)	Structure Top Elevation (ft in LWRP)
Rootless Dike	3.0	LDB	615	+18.5
Weir	2.9	RDB	545	-15
Weir	2.8	RDB	500	-15
Weir	2.7	RDB	365	-15
Weir	2.6	RDB	390	-15
Weir	2.3	RDB	410	-15
Weir	2.2	RDB	530	-15

*Note: Dike should start 100 ft from LDB.

Results: *Bathymetry (Plate 71) and Velocity (Plate 72) Analysis*

Reduced Deposition at RM 3.0 – 2.0	Reduced Deposition at RM 1.4 – 0.0	Worsened Alignment through RM 1.8 – 1.0	Additional Comments
Yes	No	No	The channel deepened (from -8 ft to -14 ft LWRP) and widened (from 0 ft to 100 ft) in some locations throughout RM 2.8 to RM 2.2. The flow did increase as a result of the structure at RM 3.0L. The weirs dispersed the flow across the channel, but not as efficiently as in Alternative 20 near RM 2.6 to RM 2.3. The flow on the LDB side of the channel from RM 2.7 to RM 2.3 no longer aimed directly towards the RDB as it did in the replication test. However, the velocities wrap around and angle more towards the LDB near RM 2.25. There were no significant velocity changes RM 1.8 to RM 1.3.

Alternative 24:

Type of Structure	River Mile	LDB or RDB	Dimensions (Feet)	Structure Top Elevation (ft in LWRP)
Rootless Dike	3.0	LDB	615	+18.5
Weir	2.7	RDB	365	-15
Weir	2.6	RDB	390	-15
Weir	2.3	RDB	410	-15
Weir	2.2	RDB	530	-15

*Note: Dike should start 100 ft from LDB.

Results: *Bathymetry (Plate 73) and Velocity (Plate 74) Analysis*

Reduced Deposition at RM 3.0 – 2.0	Reduced Deposition at RM 1.4 – 0.0	Worsened Alignment through RM 1.8 – 1.0	Additional Comments
Yes	No	No	The channel deepened (from -8 ft to -14 ft LWRP) and widened (from 0 ft to 200 ft) in some locations throughout RM 2.8 to RM 2.3. The flow did increase as a result of the structure at RM 3.0L. The weirs dispersed the flow across the channel, but not as efficiently as in Alternative 20 near RM 2.7 to RM 2.3. The flow on the LDB side of the channel from RM 2.7 to RM 2.3 no longer aimed directly towards the RDB as it did in the replication test. The magnitudes of the velocities did decrease on the LDB side of the channel from RM 1.8 to RM 1.4. There were no significant velocity changes RM 1.8 to RM 1.3.

Alternative 25:

Type of Structure	River Mile	LDB or RDB	Dimensions (Feet)	Structure Top Elevation (ft in LWRP)
Rootless Dike	3.0	LDB	615	+18.5
Weir	2.75	RDB	365	-15
Weir	2.65	RDB	310	-15
Weir	2.43	RDB	390	-15
Weir	2.35	RDB	410	-15
Weir	2.2	RDB	530	-15

*Note: Dike should start 100 ft from LDB.

Results: *Bathymetry (Plate 75) and Velocity (Plate 76) Analysis*

Reduced Deposition at RM 3.0 – 2.0	Reduced Deposition at RM 1.4 – 0.0	Worsened Alignment through RM 1.8 – 1.0	Additional Comments
Yes	No	No	The channel deepened (from -8 ft to -14 ft LWRP) and widened (from 0 ft to 150 ft) from RM 2.4 to RM 2.2. (This was not as efficient in removing the deposition as Alternative 20). The flow did increase as a result of the structure at RM 3.0L. The weirs dispersed the flow across the channel, but it seemed to be slightly less effective than Alternative 20. This was determined because there was higher flows (more red arrows) across the transects in Alternative 20, compared to 25. The flow on the LDB side of the channel from RM 2.7 to RM 2.3 no longer aimed directly towards the RDB as it did in the replication test, however the direction of the arrows were slightly more angled towards the RDB than Alternative 20. There were no significant velocity changes from RM 1.8 to RM 1.3.

Alternative 26:

Type of Structure	River Mile	LDB or RDB	Dimensions (Feet)	Structure Top Elevation (ft in LWRP)
Weir (Shorten Existing)	3.3	RDB	120	Existing Bed Elevation
Weir (Shorten Existing)	3.1	RDB	260	Existing Bed Elevation
Rootless Dike	3.0	LDB	615	+18.5
Weir	2.75	RDB	365	-15
Weir	2.65	RDB	310	-15
Weir	2.43	RDB	390	-15
Weir	2.35	RDB	410	-15
Weir	2.2	RDB	530	-15

*Note: Dike should start 100 ft from LDB.

Results: *Bathymetry (Plate 77) and Velocity (Plate 78) Analysis*

Reduced Deposition at RM 3.0 – 2.0	Reduced Deposition at RM 1.4 – 0.0	Worsened Alignment through RM 1.8 – 1.0	Additional Comments
Yes	No	No	The channel deepened (from -8 ft to -14 ft LWRP) and widened (from 0 ft to 250 ft) from RM 2.8 to RM 2.2. The bathymetry results as well as the velocity results (from RM 3.5 to RM 2.8) did not show any significant changes compared to Alternative 20. The higher velocities were along the RDB from RM 3.5 to RM 2.8. After passing over the weirs, the flow's direction was angled slightly more towards the LDB or middle of the channel from RM 3.1 to RM 2.8. The higher velocities tend to spread across the channel (towards the LDB) from RM 3.0 to RM 2.8. There was no significant deflection of flow or angle change at the tips of the weirs at RM 3.3R and 3.1R. The flow did increase as a result of the structure at RM 3.0L. The weirs dispersed the flow across the channel as did the previous alternatives, but it seemed to be slightly more effective near RM 2.5 to RM 2.3. The flow on the LDB side of the channel from RM 2.7 to RM 2.3 no longer aimed directly towards the RDB as it did in the replication test. There were no significant velocity changes from RM 1.8 to RM 1.3.

*Note: Additional velocity (LDV) data was collected from RM 3.5 to RM 2.8 to determine if the existing weirs at RM 3.3R and 3.1R should be modified. See Plate 78 for Alternative 20 vs Alternative 26 velocity results.

CONCLUSIONS

1. Evaluation and Summary of the Model Tests

Alternatives	**Reduced Deposition at RM 3.0 – 2.0**	**Reduced Deposition at RM 1.4 – 0.0**	**Worsened Alignment through RM 1.8 – 1.0**	**Positive Overall Impact on Study Reach**
Alternative 1	No	No	Yes	No
Alternative 2	No	No	Yes	No
Alternative 3	No	No	Yes	No
Alternative 4	No	No	Yes	No
Alternative 5	No	No	Yes	No
Alternative 6	Yes	Yes	Yes	No
Alternative 7	No	Yes	Yes	No
Alternative 8	Yes	No	Yes	No
Alternative 9	Yes	No	Yes	No
Alternative 10	Yes	No	Yes	No
Alternative 11	Yes	No	Yes	No
Alternative 12	No	No	No	No
Alternative 13	No	No	No	No
Alternative 14	Yes	No	No	Yes
Alternative 15	Yes	No	No	Yes
Alternative 16	Yes	No	No	Yes
Alternative 17	Yes	No	No	Yes
Alternative 18	Yes	No	No	Yes
Alternative 19	Yes	No	No	Yes
Alternative 20	**Yes**	**No**	**No**	**Yes**
Alternative 21	Yes	No	No	Yes
Alternative 22	Yes	No	No	Yes
Alternative 23	Yes	No	No	Yes
Alternative 24	Yes	No	No	Yes
Alternative 25	Yes	No	No	Yes
Alternative 26	Yes	No	No	Yes

In order to determine the best alternative, certain criteria, based on the study purpose and goals, were used to evaluate each alternative. The first and most important consideration was that the alternative had to sufficiently reduce or eliminate the dredging at RM 3.0 to RM 0.0. The second condition was that the alternative had to maintain the navigation channel requirements of at least 9 foot of depth and 300 foot of width. Lastly, the alternative should improve the navigation flow conditions through the U.S. – 60/62 Bridge. Although there were a number of alternatives that showed reduced deposition in the problem areas while maintaining the navigation channel requirements, they were not recommended. These alternatives were not recommended primarily because the alternative did not successfully improve the flow conditions near RM 2.7 to RM 2.0 or maintain the existing flow conditions in the navigation span of the bridge. Some of the alternatives that met the criterion but were not chosen were alternatives 15 - 26.

2. Recommendations

Alternative 20, Plates 65, 66, and 78, was recommended as the most desirable alternative because of its observed ability to significantly reduce the dredging at RM 3.0 – 2.0. This alternative could considerably reduce the deposition near RM 3.0 to RM 2.0 and improve the flow conditions from RM 2.7 to RM 2.0, while maintaining the existing alignment from RM 1.8 to RM 1.0. By reducing the deposition, this alternative increased the width of the navigable channel from RM 2.8 to RM 2.2. According to the LDV results, the velocities around the bend from RM 2.5 to RM 2.3 were more dispersed across the navigation channel, as well as the angle at which flow was directed towards the RDB was notably reduced. This would allow the pilots the freedom to navigate their tows more towards the center of the channel, instead of hugging the RDB line. Also, it should make for better conditions in the waiting area just upstream of the Bird's Point grain elevator (RM 2.3 to RM 2.1). This alternative also maintained the flow conditions, angled slightly towards the LDB navigation span pier, from RM 1.8 to 1.0. Even though the existing flow conditions were not ideal, the goal was to maintain those conditions because the tow pilots are accustomed to them. Overall, this alternative greatly reduced the dredging and

enhanced the navigation safety for industry while providing a self maintaining channel.

The recommended design included the following:

- RM 3.0L: Construct new 615 ft rootless dike
  - Structure top elevation = +18.5 ft (LWRP)
- RM 2.6R: Construct new 365 ft weir
  - Structure top elevation = -15 ft (LWRP)
- RM 2.5R: Construct new 390 ft weir
  - Structure top elevation = -15 ft (LWRP)
- RM 2.3R: Construct new 410 ft weir
  - Structure top elevation = -15 ft (LWRP)
- RM 2.2R: Construct new 530 ft weir
  - Structure top elevation = -15 ft (LWRP)

For future consideration, the dike extensions at RM 0.8R, RM 0.6R, and RM 0.3R showed that they could reduce the deposition from RM 1.0 to RM 0.0 (see Plates 37 and 39). Because the dredging was not a significant problem and because environmental partners voiced concern about the RDB bar in this reach, the dike extensions were not included in the final recommended alternative.

3. Interpretation of Model Test Results

In the interpretation and evaluation of the model test results, it should be remembered that these results are qualitative in nature. Any hydraulic model, whether physical or numerical, is subject to biases introduced as a result of the inherent complexities that exist in the prototype. Anomalies in actual hydrographic events, such as prolonged periods of high or low flows are not reflected in these results, nor are complex physical phenomena, such as the existence of underlying rock formations or other non-erodible variables. Water surfaces were not analyzed and flood flows were not simulated in this study.

This model study was intended to serve as a tool for the river engineer to guide in assessing the general trends that could be expected to occur in the Mississippi River from a variety of imposed design alternatives. Measures for the final design may be modified based upon engineering knowledge and experience, real estate and construction considerations, economic and environmental impacts, or any other special requirements.

FOR MORE INFORMATION

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APPENDIX

A. Report Plates

1. Location and Vicinity Map
2. 2008 Aerial Photograph – 1:24,000
3. Dredge Removal – 1:24,000
4. Geomorphology Planform 1817 – 2003 – 1:24,000
5. 1928 Aerial Photograph Overlay – 1:24,000
6. 1942 Planform Map Overlay – 1:24,000
7. 1939 – 1956 Hydrographic Survey Overlay – 1:24,000
8. 1968 – 1971 Hydrographic Survey Overlay – 1:24,000
9. 1976 – 1977 Hydrographic Survey Overlay – 1:24,000
10. 1982 – 1983 Hydrographic Survey Overlay – 1:24,000
11. 1986 – 1987 Hydrographic Survey Overlay – 1:24,000
12. 2001 Hydrographic Survey – 1:24,000
13. 2002 Multi-Beam Hydrographic Survey – 1:24,000
14. 2005 Hydrographic Survey – 1:24,000
15. July 2007 Hydrographic Survey – 1:24,000
16. 2007 Multi-Beam Hydrographic Survey – 1:24,000
17. 2010 Hydrographic Survey – 1:24,000
18. August 2006 Pre-Dredge Hydrographic Survey – 1:24,000
19. November 2007 Pre-Dredge Hydrographic Survey – 1:24,000
20. October 2008 Pre-Dredge Hydrographic Survey – 1:24,000
21. December 2007 Normalized ADCP – 1:24,000
22. Birds Point Field Photographs
23. Birds Point Field Photographs
24. Birds Point HSR Model
25. Replication Test: Bathymetry Results – 1:24,000
26. Replication Test: LDV Results – 1:24,000
27. Alternative 1: Bathymetry Results – 1:35,000
28. Alternative 1: LDV Results – 1:16,500
29. Alternative 2: Bathymetry Results – 1:35,000
30. Alternative 2: LDV Results – 1: 16,500
31. Alternative 3: Bathymetry Results – 1:35,000

32. Alternative 3: LDV Results – 1: 16,500
33. Alternative 4: Bathymetry Results – 1:35,000
34. Alternative 4: LDV Results – 1: 16,500
35. Alternative 5: Bathymetry Results – 1:35,000
36. Alternative 5: LDV Results – 1: 16,500
37. Alternative 6: Bathymetry Results – 1:35,000
38. Alternative 6: LDV Results – 1: 16,500
39. Alternative 7: Bathymetry Results – 1:35,000
40. Alternative 7: LDV Results – 1: 16,500
41. Alternative 8: Bathymetry Results – 1:35,000
42. Alternative 8: LDV Results – 1: 16,500
43. Alternative 9: Bathymetry Results – 1:35,000
44. Alternative 9: LDV Results – 1: 16,500
45. Alternative 10: Bathymetry Results – 1:35,000
46. Alternative 10: LDV Results – 1: 16,500
47. Alternative 11: Bathymetry Results – 1:35,000
48. Alternative 11: LDV Results – 1: 16,500
49. Alternative 12: Bathymetry Results – 1:35,000
50. Alternative 12: LDV Results – 1: 16,500
51. Alternative 13: Bathymetry Results – 1:35,000
52. Alternative 13: LDV Results – 1: 16,500
53. Alternative 14: Bathymetry Results – 1:35,000
54. Alternative 14: LDV Results – 1: 16,500
55. Alternative 15: Bathymetry Results – 1:35,000
56. Alternative 15: LDV Results – 1: 16,500
57. Alternative 16: Bathymetry Results – 1:35,000
58. Alternative 16: LDV Results – 1: 16,500
59. Alternative 17: Bathymetry Results – 1:35,000
60. Alternative 17: LDV Results – 1: 16,500
61. Alternative 18: Bathymetry Results – 1:35,000
62. Alternative 18: LDV Results – 1: 16,500
63. Alternative 19: Bathymetry Results – 1:35,000
64. Alternative 19: LDV Results – 1: 16,500

65. Alternative 20: Bathymetry Results – 1:35,000
66. Alternative 20: LDV Results – 1: 16,500
67. Alternative 21: Bathymetry Results – 1:35,000
68. Alternative 21: LDV Results – 1: 16,500
69. Alternative 22: Bathymetry Results – 1:35,000
70. Alternative 22: LDV Results – 1: 16,500
71. Alternative 23: Bathymetry Results – 1:35,000
72. Alternative 23: LDV Results – 1: 16,500
73. Alternative 24: Bathymetry Results – 1:35,000
74. Alternative 24: LDV Results – 1: 16,500

B. October 13, 2011 Bird's Point HSR Model Meeting Minutes

C. HSR Model Theory

APPENDIX B. October 13, 2011 Bird's Point HSR Model Meeting Minutes

Ashley provided background information and a brief discussion of the features in the study reach.

Ashley then provided a thorough explanation of the alternatives that were tested and the preferred alternative. She explained the criteria she used to evaluate the alternatives and why she recommended Alternative 20.

Shannon Hughes noted that the weirs from Alternative 20 located at RM 2.6 and RM 2.5 were located in the "waiting area" for the Bird's Point grain elevator. The pilots voiced concern that the proposed weirs in Alternative 20 might cause turbulent water and draw their tows away from the RDB towards the channel. Shannon then suggested to test some alternatives with no weirs in the waiting area (approximately RM 2.57 to RM 2.4).

Following, the next discussion focused on the existing weirs at RM 3.3R and RM 3.1R. There was concern that these weirs were too long, and that they were the cause of the deposition near RM 3.0 to RM 2.0. As a result, Ashley said that once the final recommended alternative was agreed upon, she would run additional LDV and bathymetry tests to see if shortening the two existing weirs had any positive effects.

She also asked the environmentally focused attendees which structure they preferred, a notched dike, rootless dike, or chevron near RM 3.0L. Ashley pointed out that there was a small amount of flow between Angelo Towhead and the point bar, and that the rootless dike would allow that flow to continue without an abrupt stop. The environmental partners stated that they would prefer either the rootless dike or a chevron.

After the open discussion, Ashley confirmed with the group, which consisted of both industry, corps members, and environmental partners, that Alternative 20 did show promising results. She then told the group that she would run Alternatives 23 and 24 (changing the location of weirs in combination with a rootless dike) and inform the group of the results. Once an alternative was agreed upon, then she would try shortening the two existing weirs. Everybody thought that was a good plan of action.

Attendees:

Jasen Brown	Katherine Clancey	Ashley Cox	Rob Davinroy
Dave Gordon	Shannon Hughes (RIAC)	Brian Johnson	Brad Krischel
Matt Mangan	Sarah Markenson	Ivan Nguyen	David Ostendorf
Adam Rockwell	Kip Runyon	Brandon Schneider	Terry Wiltz (IRCA)

APPENDIX C. HSR Model Theory

The principle behind the use of a hydraulic sediment response model is similitude, the linking of parameters between a model and prototype so that behavior in one can predict behavior in the other.

There are two different types of similitude; mathematical similitude and empirical similitude. Mathematical similitude is founded on the scale relationship between all linear dimensions (geometric similarity), a scale relationship between all components of velocity (kinematic), or both geometric and kinematic similarity with the ratio of all common point forces equal (dynamic similarity).

In contrast to mathematical similitude, empirical similitude is based on the belief that the laws of mathematical similitude can be relaxed as long as other more fundamental relationships are preserved between the model and the prototype. All physical models used in the past by USACE employed, to some degree, empirical similitude. Numerous definitions of what relationships must be preserved have been put forward concerning physical sediment models. These relationships often deal with the scalability of elements of sediment transport processes or surface or structure roughness. Hydraulic sediment response models depend on similitude in the morphologic response, i.e. the ability of the model to replicate known prototype parameters associated with the bed response in the river under study. Bed response includes thalweg location, scour and deposition within the channel and at various river structures, and the overall resultant bed configuration. These parameters are directly compared to what is observed from prototype surveys.

Detailed cross-sectional analysis of prototype and model surveys defining bed response and bed configuration have shown that HSR model variation from the prototype is often approximately that of the natural variation observed in the prototype. This correspondence allows hydraulic engineers to use the HSR model with confidence and introduce alternatives in the model to approximate the bed response that can be expected to occur in the prototype.

HSR models were developed from empirical large scale coal bed models utilized by the USACE Waterways Experiment Station (Environmental Research and Development Center). These models were used by MVS from 1940 to the mid 1990s. For a more thorough explanation of the HSR model development, please refer to the following link:
http://www.mvs.usace.army.mil/arec/reports/Hydraulic%20Sediment%20Response%20Modeling,%20Replication%20Accuracy,%20TPM53.pdf