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Hydraulic Sediment Response Modeling, Replication Accuracy to the River

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Abstract: Hydraulic Sediment Response (HSR) modeling, formerly called Micro Modeling, is a small-scale physical mobile bed model technology that has been used by the United States Army Corps of Engineers (USACE) since 1994 for navigation design and environmental restoration on inland waterways of the United States. Continued advancements have been made to date to the operation of the model. This paper describes the ability of today's HSR model to replicate the observed bed response of the river. First, model operation is compared to large-scale coal bed models. Second, an earlier comprehensive study comparing older small-scale models directly to large-scale coal bed models used by USACE Engineer Research and Development Center (ERDC) is discussed. Thirdly, two study reaches of the Missouri and Mississippi Rivers containing a large number of training structures are presented showing results of recent HSR models. Natural variability of the bed response of the river is also examined. Results indicate that today's HSR models can replicate the bed response of the river with a high level of accuracy and within the observed natural variability of the river.

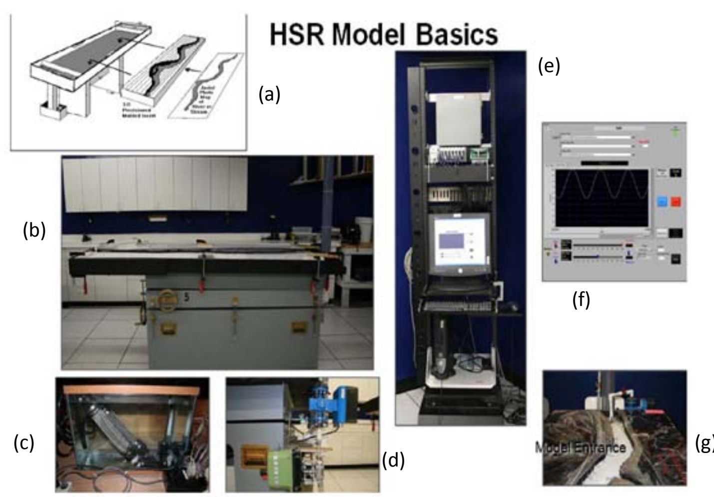
Introduction

The USACE has employed Hydraulic Sediment Response (HSR) modeling, formerly called Micro Modeling (Davinroy, 1994, Gaines 2002) since 1994 to address a variety of problems related to shoaling and scour on inland waterways in the United States (Davinroy 1999). Modeled waterways include the Mississippi, Atchafalaya, White, Missouri, Ohio, Brazos, and Kaskaskia Rivers. The small-scale physical models use synthetic bed material to simulate bed response, and use various materials to represent fixed boundary features such as banks, islands, dike structures, rock, and consolidated clay formations. Design alternatives have been developed from model output to solve problems such as repetitive maintenance dredging, side channel restoration, and other navigation related issues. HSR models replace the use of large scale coal bed models. The models examine sediment response in localized river reaches with fixed or minimal eroding banklines.

Model Setup Overview

The HSR model consists of a planform insert constructed from polyurethane foam fabricated to geo-referenced aerial photography. The insert is placed within a hydraulic flume that contains a reservoir, electronic control valves, pumps, a constant head pipe network, and flow meters, all interfaced with a computerized control system (Figure 1).

Figure 1



HSR operational schematic (a) Model insert, (b) Model flume, (c) Reservoir and pump, (d) Control valve and flow meter, (e) Computer rack, (f) User interface, and (g) Model insert with sediment.

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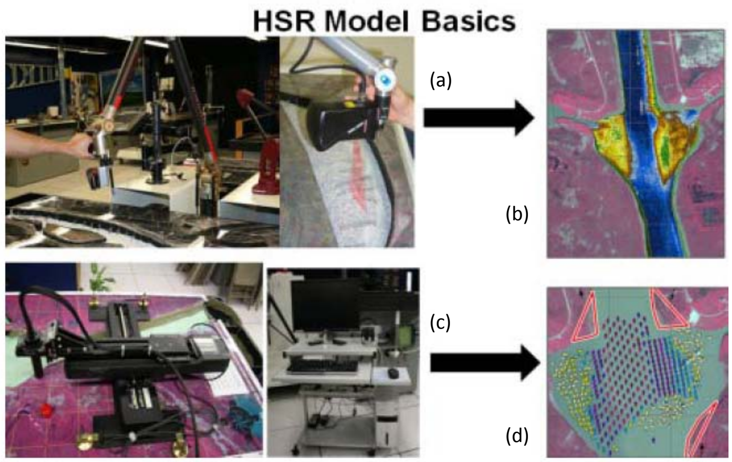
Discharge and sediment (granular plastic, urea, specific gravity 1.4) are simulated through the insert channel. A model coordinate system is established to collect all data. Lasers are used to collect detailed bathymetry and normalized velocity distribution (Cox et al. 2011) from the model for comparison to hydrographic surveys and Acoustic Doppler Current Profiles (ADCP) from the river (Figure 2). High definition cameras are also used for flow visualization and general model observation recording.

Figure 2



(a) Laser scanner, (b) Laser bathymetry, (c) Laser Doppler Velocimeter (LDV), and (d) LDV normalized velocity vector output.

Operational Similarities and Differences with Large Scale Coal Bed Models

Initial development of HSR models resulted from years of experience and observation of large-scale coal bed models used in the United States at the former Waterways Experiment Station (WES). These models were considered the standard in physical mobile bed models for USACE. Therefore their corresponding operation and expected accuracy in model bed response verification, as compared to the river, were carefully studied. Both of these small scale and large scale mobile bed models (Figure 3) do not follow rigid similitude scale ratios established from the Froude and Reynolds laws.

(a) Figure 3 (b)

(a) Large coal bed model, Dogtooth Bend, *scale 1:400 horizontal, 1:100 vertical*, and (b) HSR model, Atchafalaya River, *scale 1:7200 Horizontal, 1:1200 Vertical*.

Rather, these models focus on producing similarity of the three-dimensional bed response of the model as compared to hydrographic surveys of the river. This similarity is achieved through an empirical calibration process designed to ultimately produce "replication" in the HSR model case and"verification" in the large-scale coal bed model case.

The calibration process of the HSR model involves adjustments in the flow, model slope, model entrance conditions, model vertical scale, sediment volume, and fixed boundary conditions. The models are distorted linearly (horizontal to vertical scale) to generate sufficient forces necessary for bed movement. Distortion has varied from as small as 6 to as large as 22. Reynolds used a distortion of 33 in his well-publicized small-scale movable bed model of the River Mersey estuary (Reynolds 1887).

Two operational differences and one similarity between large-scale coal bed models and HSR models exist. First, the former employed segmented "above model" reference rails (Figure 4) that had variable slopes (Foster et al. 1978).

Figure 4

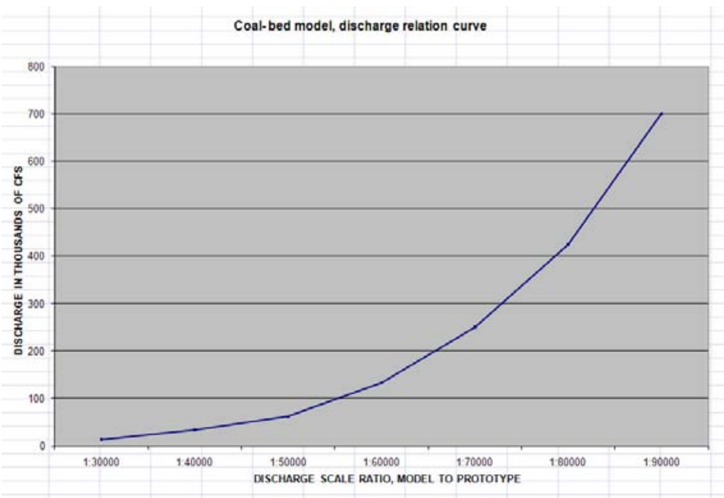
Railing system for large-scale coal bed models (U.S. Army Engineer Waterways Experiment 1937).

The rails were used to support sheet-metal templates or a survey rod setup for the creation of interpolated or "molded" bed contours between cross sections related to a scaled, hydrographic survey of the river. During testing, if a particular localized area of the bed did not develop properly at the right elevation,
supplementary slope was applied (Franco 1978) by adjusting these rails and molded bed.

HSR models do not use rails, bed molding, or localized slope adjustments. Engineers experimented with these procedures and realized that any artificial molding of the bed or localized changing of slope with rails was temporary and limited the model bed from forming on its own. Therefore the HSR model relies on hydrodynamics and sediment transport to develop its own equilibrium bed response and resultant three-dimensional bed configuration within the channel. The calibration parameters previously described ensure that the water surface and the reference plane used for data collection of the bed are parallel. This procedure helps establish a repeatable bed response that can then be compared directly to hydrographic surveys of the river.

Second, coal bed models used an exponentially varying discharge relation curve between the model and the prototype (Franco 1978) when running flow hydrographs (Figure 5). This was required to control model stages. The strict application of theoretical scale ratios to the usual movable bed model resulted in insufficient movement of the model bed material at the lower stages and in too violent movement at high stages (WES Rep, 1953). An exit tailbay weir was raised and lowered in combination with adjusted entrance flows to produce a scaled stage hydrograph. Sediment was introduced at the entrance to the model and measured at the exit of the model prior to and after the adjusted hydrograph was run and checked for model bed load stability.

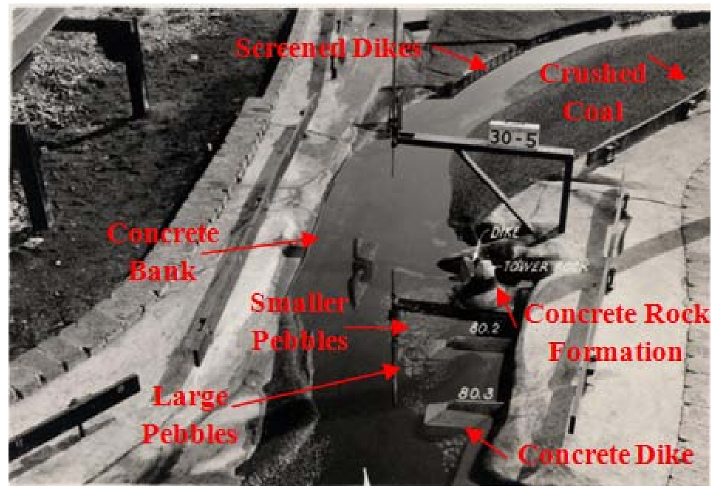
Figure 5



Discharge relation curve scale for large-scale coal bed model.

This method of running scaled stages and using an exponential discharge relation curve was intensely studied in HSR models, but engineers discovered that operating with scaled stages did not produce a realistic energy response or appropriate bed movement in the models. By raising and lowering the exit weir and adjusting discharge to produce scaled stages, the bed of the model would aggrade and degrade accordingly. This affected the model bed response and made it impossible to isolate the effects on the bed of design alternatives tested such as training structures, dredging, or other modifications. Therefore, the exit weir is held fixed and the models are run in dynamic sediment equilibrium utilizing a sediment recirculation system while applying a steady dominant flow. The flow and stages are not directly scalable. Rather, they represent a controlled energy response used to realistically fluidize the bed and produce similar deposition and scour as observed in the river. Floods are not simulated. The goal of the operation of the model is to simulate the channel forming bed response/discharge response that best develops the observed bed response of the river. Refinements in control valves, pumps, and maintaining a constant head have been made over the years to improve model bed response accuracy. Lastly, the coal bed models and the HSR models both employ various materials to simulate roughness and boundary effects. In large coal bed models, a variety of different materials in one model have been used used for representing both training structures and non-erodible features within the channel (Wes Rep 1937, Figure 6).

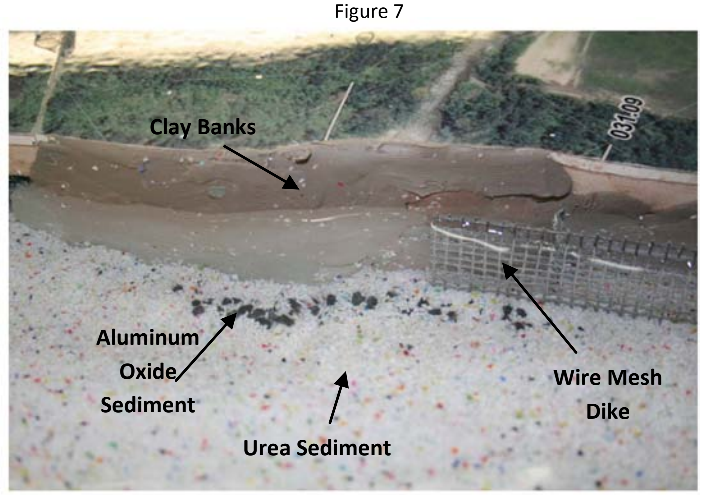
Figure 6



Non-erodible materials used on large coal bed model.

Common materials used are concrete, various sizes of pebbles and gravel, haydite, metal screen, and sheet metal. In the HSR models, galvanized screen is used for training structures, clay and polymesh for banks, and fine aluminum oxide gravel for non-erodibles such as rock and consolidated clay occurring within the channel (Figure 7).

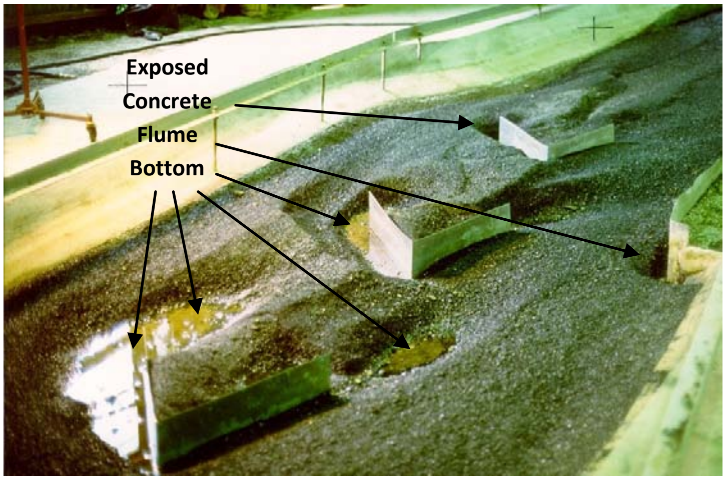
Figure 7



Non-erodible materials used on HSR Model.

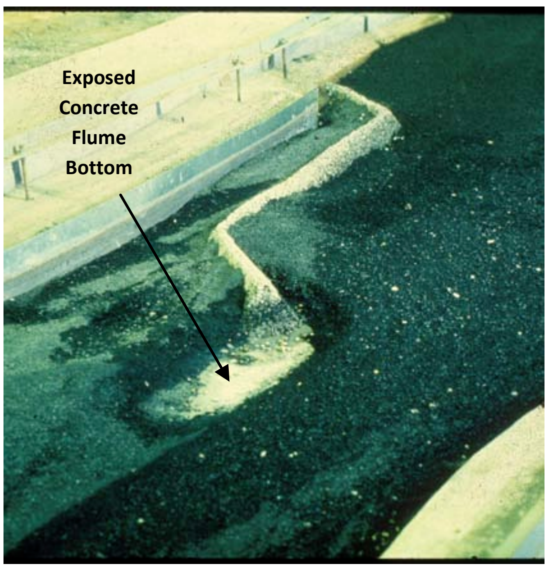
One of the most important aspects of the HSR model is the ability to reproduce the three-dimensional bed response effects of training structures. In the USACE St. Louis District experience with the large coal bed models used for river engineering studies between the 1980s and 90s, several different types of solid non-pervious materials were used to represent dikes, including sheet metal and a cement-pebble conglomerate (Davinroy 1986, Figures 8 and 9).

Figure 8



Sheet metal dikes in St. Louis Harbor Model and exposed concrete flume bottom (Davinroy 1986).

Figure 9



Pebble conglomerate dike in St. Louis Harbor Model and concrete flume exposed from scour (Davinroy 1986).

In many cases, the response of the bed observed around these structures was not representative of what was observed in the river. Excessive scour around sheet metal and rock structures were noted in several coal bed model studies. In both cases, scour was so great around the structures that the bottom of the concrete flume became exposed. Furthermore, the scour off the end of the model dikes wrapped around and upstream of the structures, exactly opposite of what was observed in the river. In the early years of HSR modeling development, rock dikes were represented in the model by using thin impervious sheet metal and plastic. The same scour response was observed in the early micro model studies. As in the large coal bed models, the exaggerated scour around the training structures was accepted as a limitation of the model. The underlying philosophy with the large coal bed models was that as long as the general trends of the overall river were observed, one could still make general trend conclusions about the effectiveness of dikes in the model. That same philosophy was used for the early small-scale models.

However, through continued HSR research, it has been found that if training structure response is not properly simulated, the ability to replicate the river bed response becomes extremely difficult. Through flume experimentation, galvanized steel mesh structures (Figure 10) have proven to be extremely effective in reproducing the bed responses of solid dike structures observed in the river and are now widely used in the HSR model. The porosity of these mesh structures enables a relative lowering of the hydraulic roughness and conversely a reduction in turbulence, force, and shear stress applied to the mobile bed of the model. Other improvements in reducing model roughness have been made on the bank and island boundaries including polymesh, and other pervious materials.

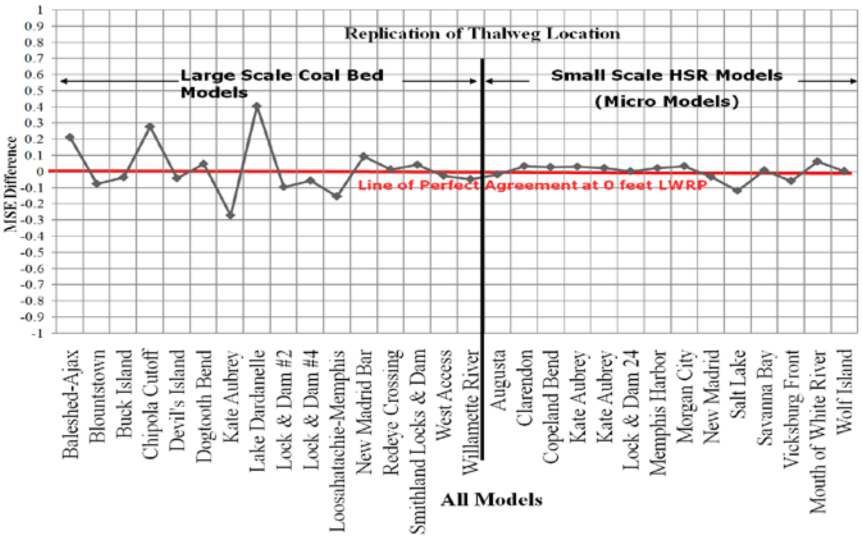
Figure 10

Galvanized wire mesh dikes in HSR model.

Major Difference in Loose Boundary Starting Conditions

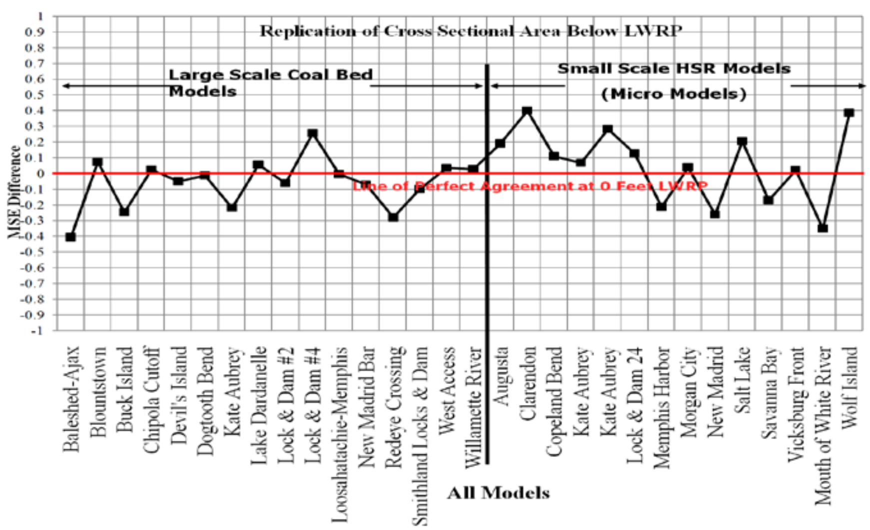
The HSR model relies on hydrodynamics to replicate the starting "loose boundary" condition of the river, unlike numerical sediment models or large scale mobile bed physical models. For the latter, the existing bathymetry of the river is fixed as a starting "loose boundary" (Raudkivi 1990) condition. The HSR modeling methodology employs a calibration process designed to replicate the river's loose boundary condition at the time of the model study. Replication is defined as the ability of the model to reproduce the mobile bed response of the river. It is achieved during model calibration and involves a three-step process. First, fixed planform boundary conditions of the study reach, i.e. banklines, islands, side channels, tributaries, and other features are established according to the most recent available high-resolution aerial photographs and topography. Various other fixed boundaries that exist in the river are also defined including river training structures, submerged rock, consolidated clay, and other non-mobile boundaries. Second, loose boundary conditions of the model are developed. Synthetic channel bed material is introduced throughout the model in an arbitrary amount to an

Figure 11



Mean square error analysis, large-scale coal bed models versus HSR models, thalweg location.

Figure 12



Mean square error analysis, large-scale coal bed models versus HSR models, cross section.

approximate level plane. Steady-state dominant discharge and sediment transport are then simulated through the model channel. During simulation, adjustments of the discharge, sediment volume, model vertical scale, model table slope, and entrance conditions are refined. Utilizing the natural physics of hydrodynamics and sediment transport, the goal of the model is to develop the initial static, flat bed into a fully formed, dynamic, three-dimensional mobile bed response, reproducing the bed response observed in the river. After numerous discharge simulations, the resultant model bed configuration is surveyed each time by the laser during the calibration phase and compared to hydrographic surveys of the river. Multiple runs are simulated for the assurance of model stability and repeatability. When the general trends of the model bed bathymetry are similar to observed recent river bathymetry, i.e. sand bars and scour holes are developed to acceptable dimensions and elevations, channel crossings and the thalweg trace are at the right locations, and these dimensional trends are repeatable and in dynamic equilibrium from run to run, the model is considered replicated and design alternative testing for future imposed changes may then proceed.

Replication and Correlation Accuracy, Past and Present

The replication and correlation accuracy of the HSR model, i.e. how well the model's bed response correlates or compares to the bed response of the river, has been studied since the introduction of the model technology in 1994. Modifications and refinements over the years to the modeling methodology have been made and continue to improve response accuracy. Every river reach under study imposes challenges and complexities. These are imposed from: the amount of available survey data, including bathymetry, ADCP, and discharge measurements, the amount of known and unknown non-erodible features that may exist in the reach, the effects of repetitive dredging and disposal, and the amount of natural bed response variance that occurs in the reach. A research effort conducted by USACE (Gaines et al. 2002) documented that randomly selected small-scale HSR models (horizontal scale greater than 1:3600) performed just as well as the large-scale coal bed models (horizontal scale less than 1:600) in replicating river bed response. A total of 30 models were studied. Variability between the model and river was expressed using the mean square error. This was defined as the squared difference between the model survey and hydrographic surveys of the river divided by the hydrographic surveys of the river, and then averaged for all ranges established along each individual model selected.

Five morphological variables were evaluated at the Low Water Reference Plane (LWRP, 97 % exceedance) including thalweg and cross section comparison. Results indicated that 14 HSR were in the same order of morphologic similarity and agreement with the actual river as compared to 16 large scale coal bed models. The HSR models varied in horizontal scales between 1:3600 to 1:20,000 and vertical distortions between 6 and 20. The large scale models varied in horizontal scales between 1:72 to 1:600 and vertical distortions between 1 and 10. Figure 11 shows that small-scale models performed better than the large-scale models in reproducing thalweg location. Figure 12 shows that small-scale models varied slightly more than large-scale models in reproducing cross sections. The relative mean square values evaluated were extremely conservative as the analysis examined channel response at or below the LWRP, which is approximately 25 to 30 percent of the total typical channel cross sectional area at bankful stage (Lauth 2011).

The three Kate Aubrey (KA) models shown in Figures 11 and 12 were evaluated to assess effects of model scale. A previous large scale coal bed model at KA had 1:300 and 1:100 scales horizontal and vertical, respectively. Two KA micro models (Gaines et al 2002) had scales of 1:8000 H and 1:600 V (KA #1) and 1:16000H and 1:900 V (KA #2). The different model approaches and model scales represented in the three KA models yielded essentially the same degree of model and river agreement for verification (coal bed model) or replication (HSR models).

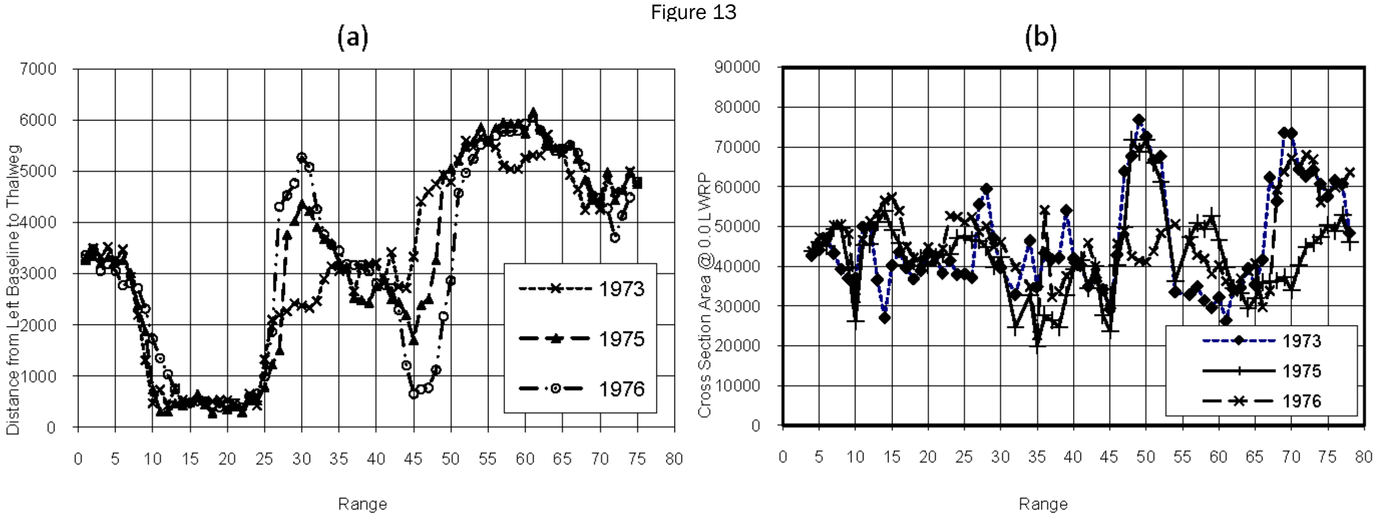
It is significant to note that natural variations in river conditions must be considered in assessing model-river agreement. This is true in the case of the large scale coal-bed models that use pre-molded bed and variable stage-sediment hydrographs as well as with small scale HSR models that use a sediment transport equilibrium approach. Table 1 shows values for five morphologic parameters at KA calculated by arithmetic average, reach weighting, and cumulative frequency methods. Natural variations in river bed response seen in hydrographic surveys over the span of one to ten or more years may be significant. In the case of KA reach, variability in cross-section area averaged for the entire river study reach was on the order of 10 to 15% between 1975 and 1976. The degree or magnitude of river bed response variation from year to year is site dependent. Localized conditions within a single reach (Figure 13a and 13b) can exhibit large changes over a relatively short time span.

Many of the model studies evaluated in the 2002 study, both large and small scale, used impervious solid materials representing banks and training works. It is suspected that this is the main reason why some of the models were above or below the perfect line of agreement evaluated at LWRP. One critical evaluation that was not performed was studying the deviation in the mean standard error between two or more river surveys (natural variation) and comparing this back against the model mean standard error. This evaluation would have helped define the highly dynamic, variable reaches that were studied and have provided another parameter by which to compare to the models.

To capture modeling advances since the 2002 study, two recent case studies are presented from 2011 HSR modeling efforts. The resulting replication correlation to the river is examined to further document the ability of today's HSR models to replicate bed load response. A direct cross-sectional comparative analysis of the bed responses of the models to the actual hydrographic surveys obtained in the river is used. Also, a similar comparison is made between river surveys to gain an understanding of the variability occurring in the river with no major planform or construction changes.

The analyses involves defining cross sectional information from established range lines, computing the cross sectional area below a + 10 ft LWRP, and computing the percent difference between the model and river and also between two river surveys taken over the same reach.

Figure 13



(a) Prototype Thalweg Position, Kate Aubrey Reach of Mississippi River, (b) Prototype Cross-Section Area, Kate Aubrey Reach of Mississippi River

Table 1

Reach Morphologic Parameter Values by Three Methods

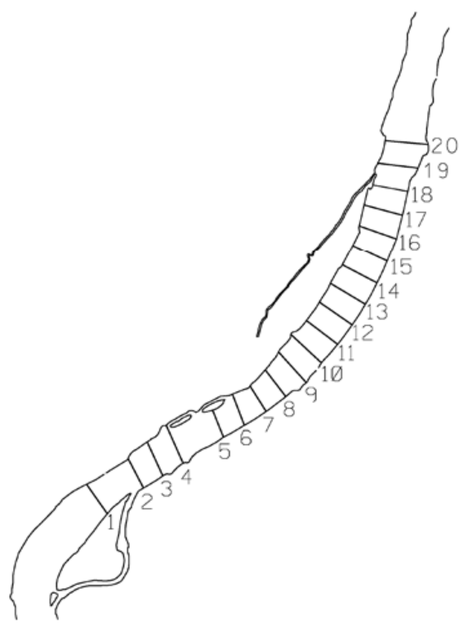
Reach Morphologic Parameter Values - Kate Aubrey Reach, Mississippi River								
Survey	Case	Method for Determining Reach Value	Number of Ranges	Area (sq. ft.)	Hydraulic Depth (ft.)	Width (ft.)	Width / Depth	Thalweg Position
1:300 Model	Verification	Arithmetic	28	26501	13.6	2107	211	na
		Reach Weighted		26195	12.4	2108	170	na
		CF		26832	14.0	2072	213	4708
1975 Prototype		Arithmetic	28	33394	13.7	2696	252	na
		Reach Weighted		34116	12.1	2823	234	na
		CF		33472	13.5	2669	258	5424
1976 Prototype		Arithmetic	28	38064	16.6	2644	227	na
		Reach Weighted		38058	14.2	2687	190	na
		CF		37987	16.6	2632	235	5370
1:8,000 Micromodel	Calibration	Arithmetic	71	35540	15.6	2385	182	na
		Reach Weighted		35993	15.2	2375	157	na
		CF		35040	15.7	2376	184	3309
1973 Prototype		Arithmetic	71	45839	16.3	2983	209	na
		Reach Weighted		45937	15.3	3010	197	na
		CF		46136	16.3	2976	207	3227
1975 Prototype		Arithmetic	71	42688	18.4	2488	159	na
		Reach Weighted		42333	16.6	2556	154	na
		CF		42257	18.4	2470	159	3208
1976 Prototype		Arithmetic	71	46372	19.8	2509	148	na
		Reach Weighted		46493	17.9	2603	146	na
		CF		46102	19.7	2513	147	3195
1:16,000 Micromodel	Calibration	Arithmetic	75	51034	17.5	3030	213	na
		Reach Weighted		51490	16.9	3041	180	na
		CF		50667	17.6	3067	219	3314
1973 Prototype		Arithmetic	75	45054	16.1	2973	213	na
		Reach Weighted		45482	15.3	2981	195	na
		CF		46136	16.3	2976	207	3227
1975 Prototype		Arithmetic	75	42323	18.1	2508	164	na
		Reach Weighted		42199	16.6	2540	153	na
		CF		42257	18.4	2470	159	3208
1976 Prototype		Arithmetic	75	46065	19.5	2552	157	na
		Reach Weighted		46206	17.8	2596	146	na
		CF		46102	19.7	2513	147	3195

Case Study One, Missouri River at St. Charles, Missouri

An HSR model study of the Missouri River was conducted for the City of St. Charles Missouri, from RM 31.1 to 29.0. The model was constructed to a horizontal scale of 1 inch = 300 ft, or 1:3600, and a vertical scale of 1 inch = 27 feet, or 1:324, for an 11 to 1 distortion ratio. Model replication bathymetry is compared directly to a 2007 hydrographic survey (Figure 14). A total of 20 cross sections were established along the study reach (Figure 15).

Over 40 training structures exist in the study reach. Cross sectional comparison plots are generated and then compared along the reach (Figure 16). From the computed calculations, the average difference in cross sectional area is 6.6%, using the absolute value of the percent difference in area for all ranges between the model replication bathymetry and the actual river bathymetry. In addition, comparison between 1998 and 2007 hydrographic surveys are compared (Figure 17), with no planform changes or structural modifications in the channel occurring, and the average difference in cross sectional area is 6.4%. This represents a very high level of agreement between the model and the river.

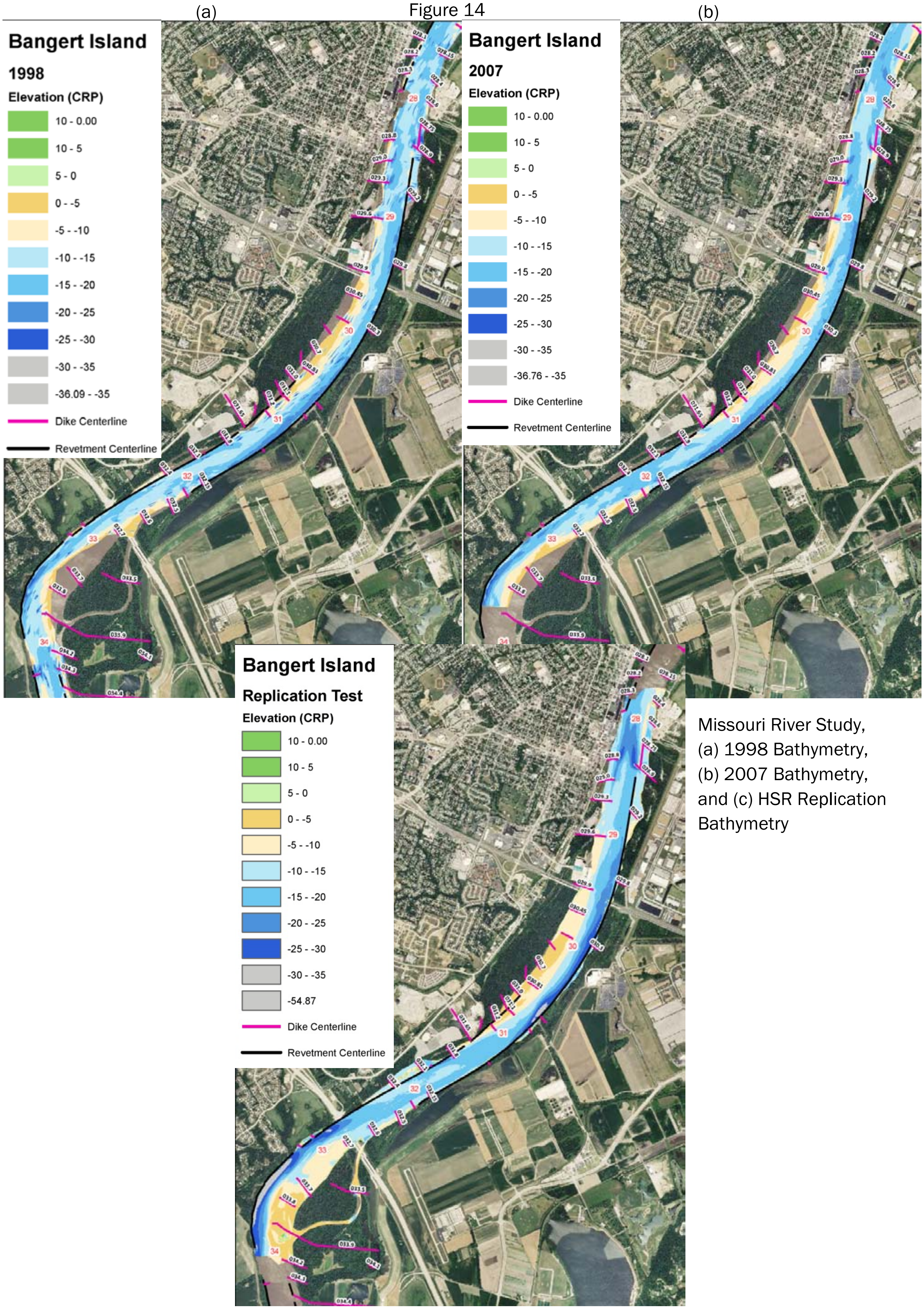
Figure 15



Bangert cross section locations for analysis.

Figure 14

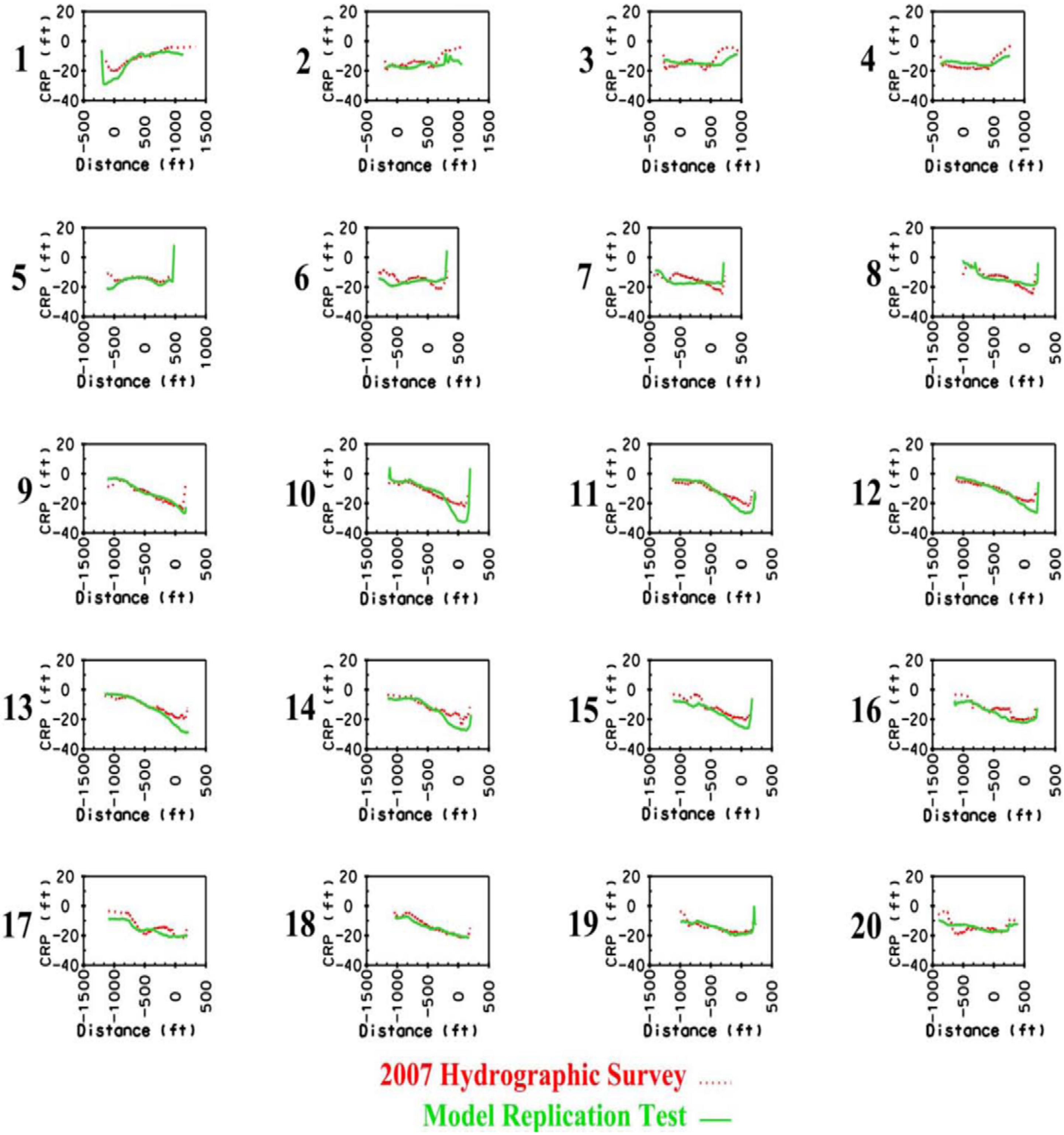
(a) (b)



(c)

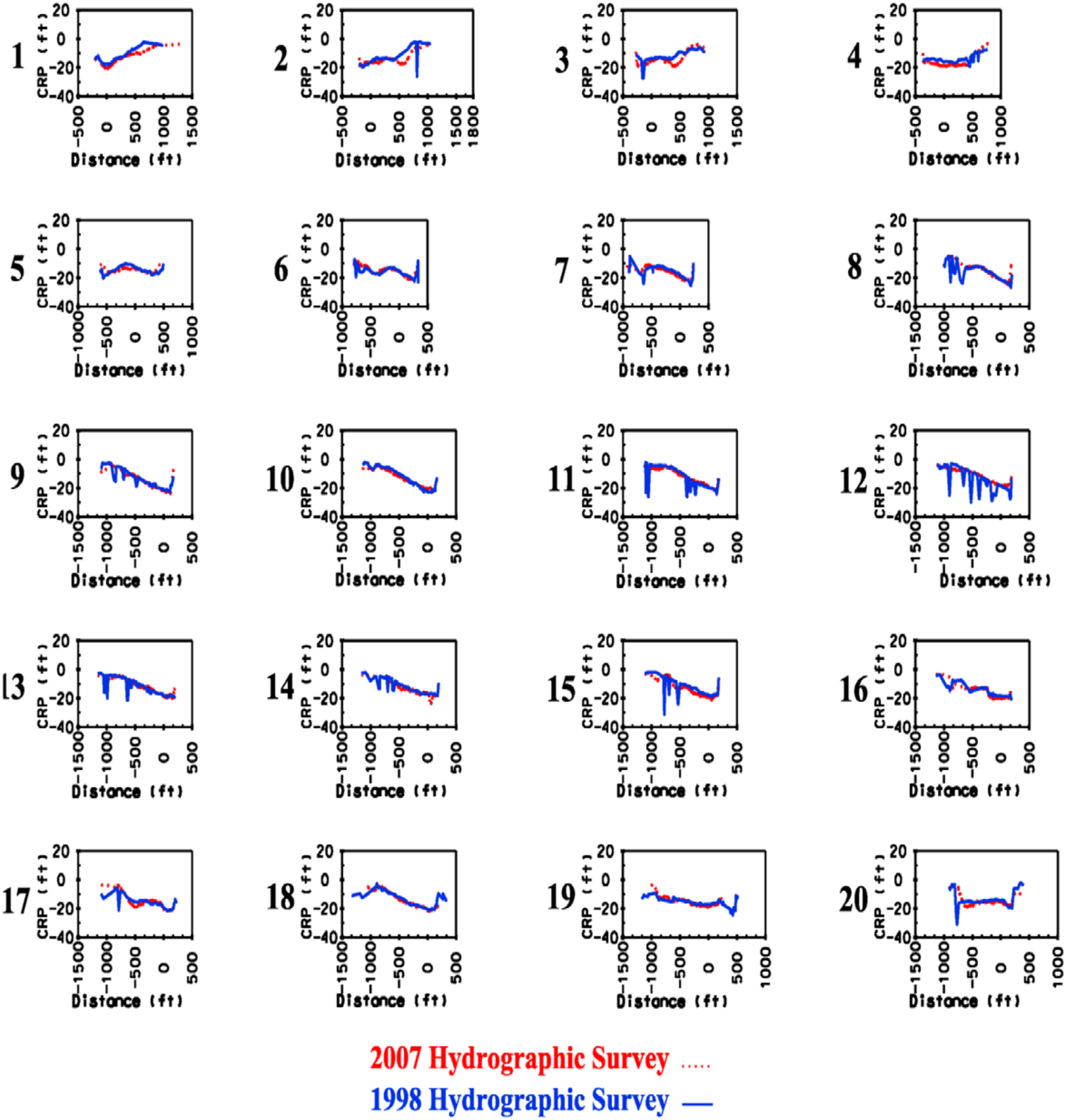
Missouri River Study, (a) 1998 Bathymetry, (b) 2007 Bathymetry, and (c) HSR Replication Bathymetry

Figure 16



Bangert's cross section plots from 2007 hydrographic survey versus HSR model replication.

Figure 17



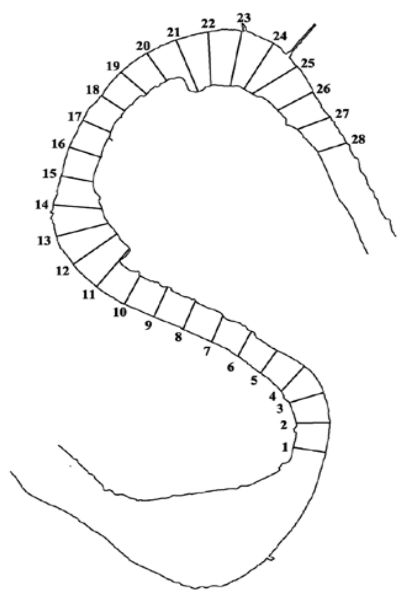
Bangert's cross section plots from 2007 hydrographic survey versus 1998 hydrographic survey

Case Study Two, Mississippi River at Grand Lake Towhead

An HSR model study of the Mississippi River was conducted for USACE St. Louis District, from RM 26.0 to 10.5. The model was constructed to a horizontal scale of 1 inch = 800 ft, or 1:9600, and a vertical scale of 1 inch = 37 feet, or 1:444, for a 21.5 to 1 distortion ratio. Model replication bathymetry is compared directly to a 2005 hydrographic survey (Figure 18). A total of 28 cross sections were established along the study reach (Figure 19).

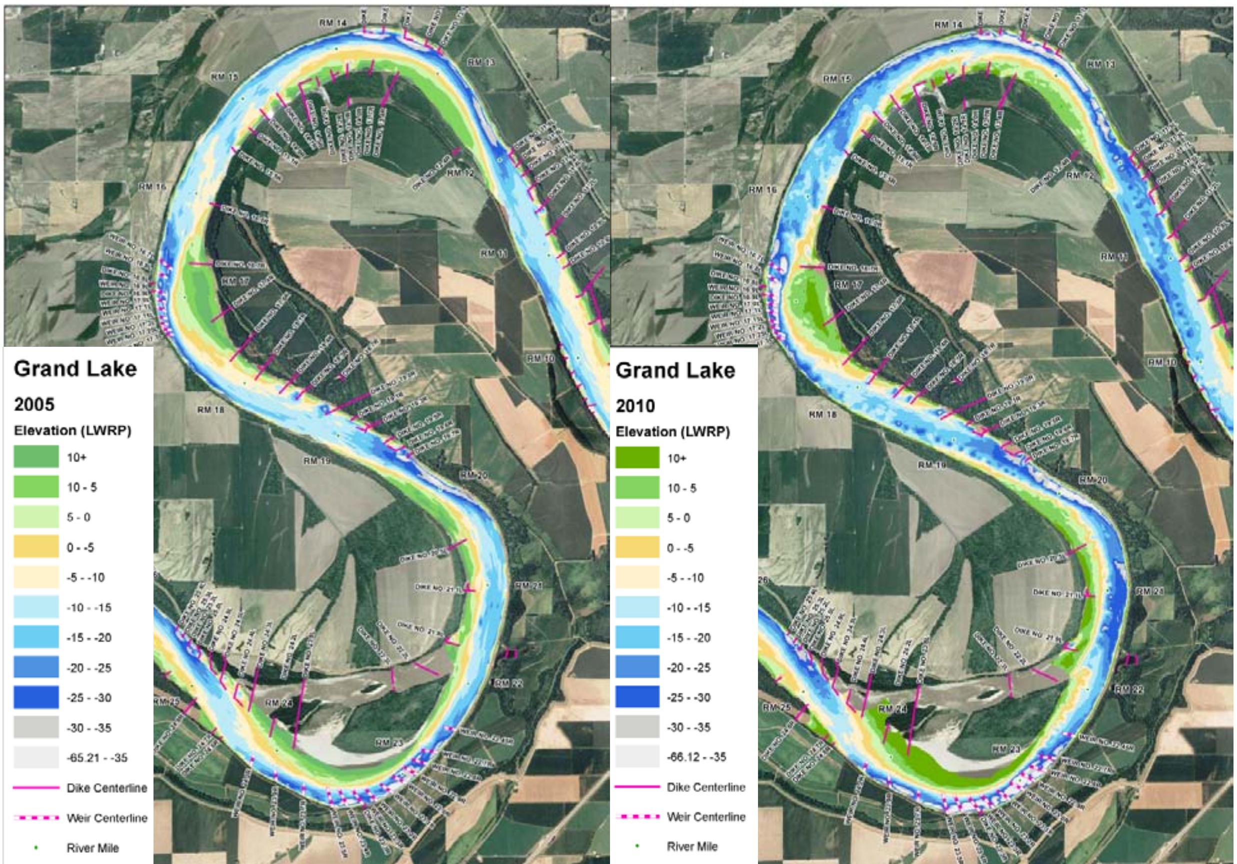
Over 106 training structures exist in the study reach. From computed values, the average difference in cross sectional area is 16% (Figure 20). The same comparison between a 2005 and 2010 hydrographic survey is 14.2 % (Figure 21). As with Case Study One, this represents a high level of aggrment, model to river. It should be noted that a large amount of repetitive dredging, including both dredge cuts and dredge disposal (Figure 22), occurred in the river over the study reach. This negates the ability of the river to ever develop its ultimate bed response within the channel. If left un-dredged the channel would have a tendency to be shallower in many locations. The modeler must take this factor into consideration during the calibration and replication phase of the project.

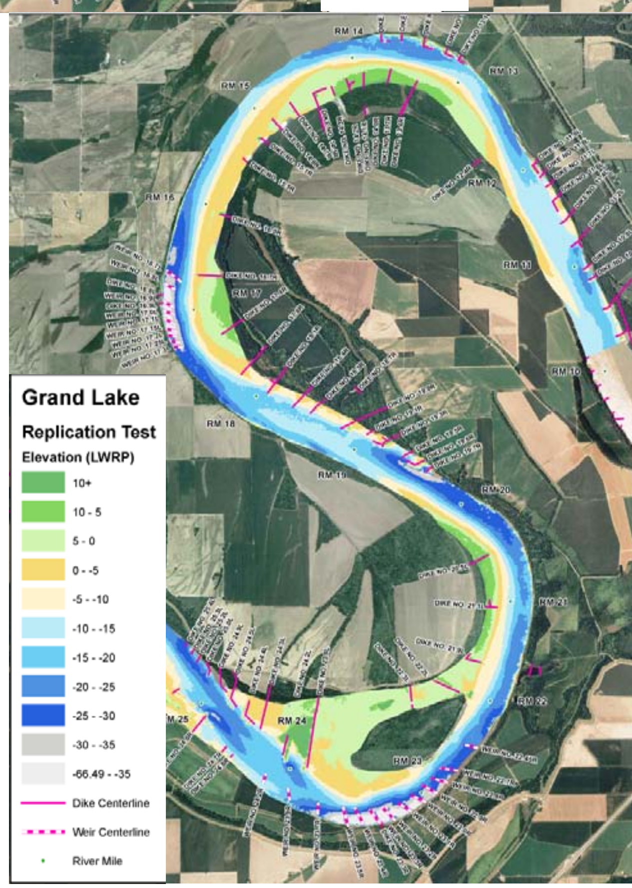
Figure 19



Grand Lake cross section locations for analysis.

(a) Figure 18 (b)

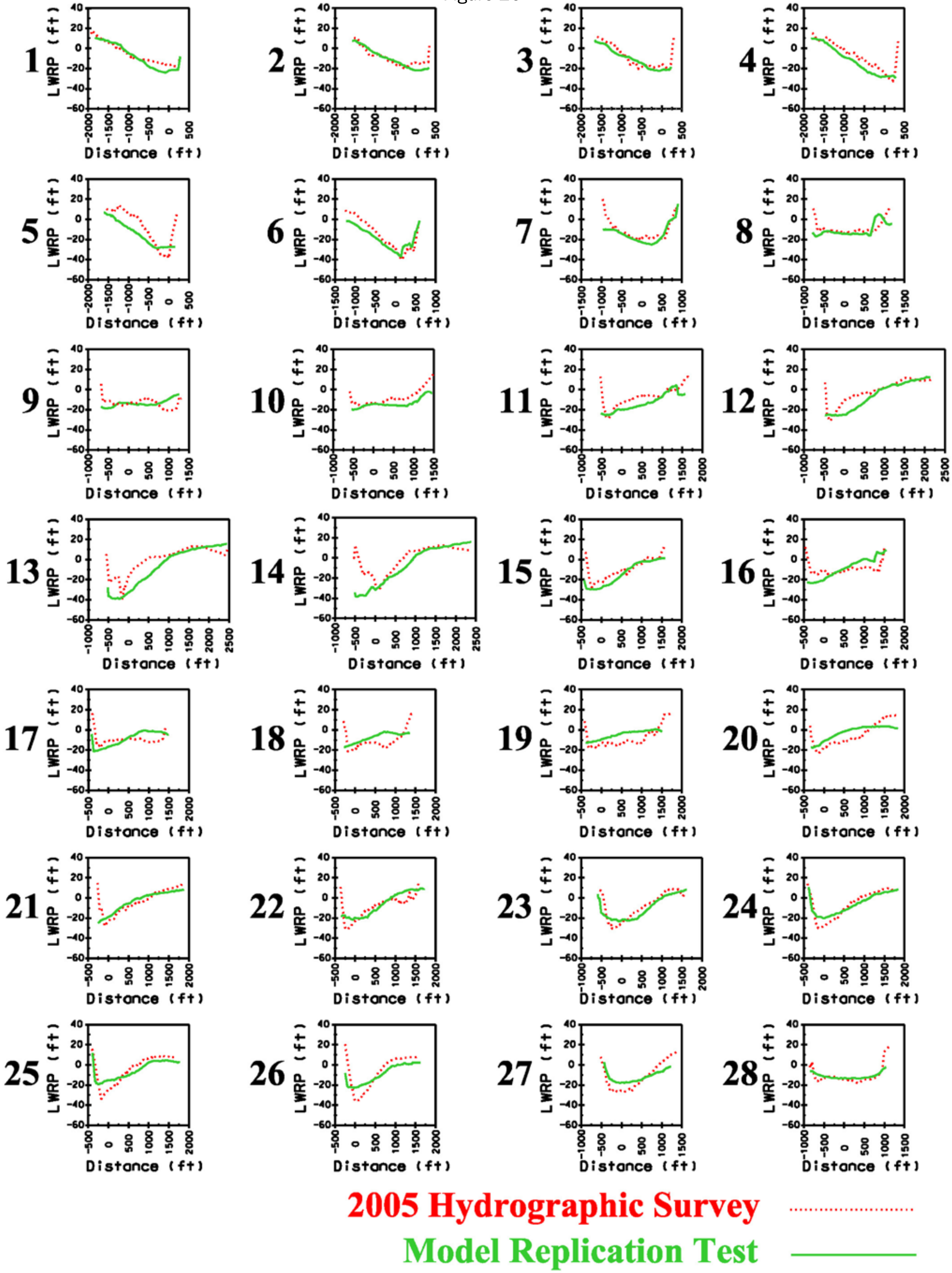




Grand Lake, Mississippi River, (a) 2005 Bathymetry, (b) 2010 Bathymetry, (c) HSR Replication Bathymetry

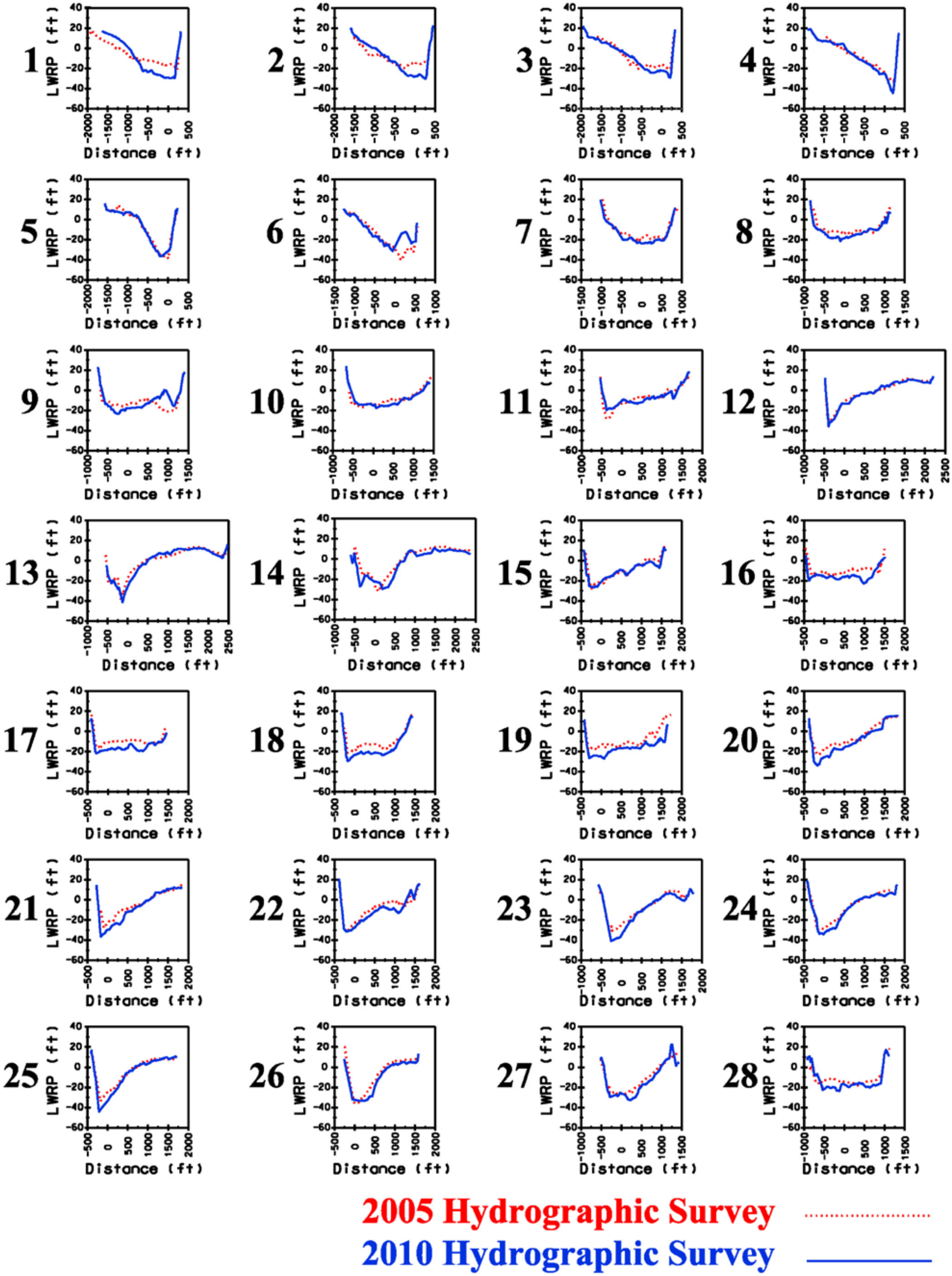
(c)

Figure 20



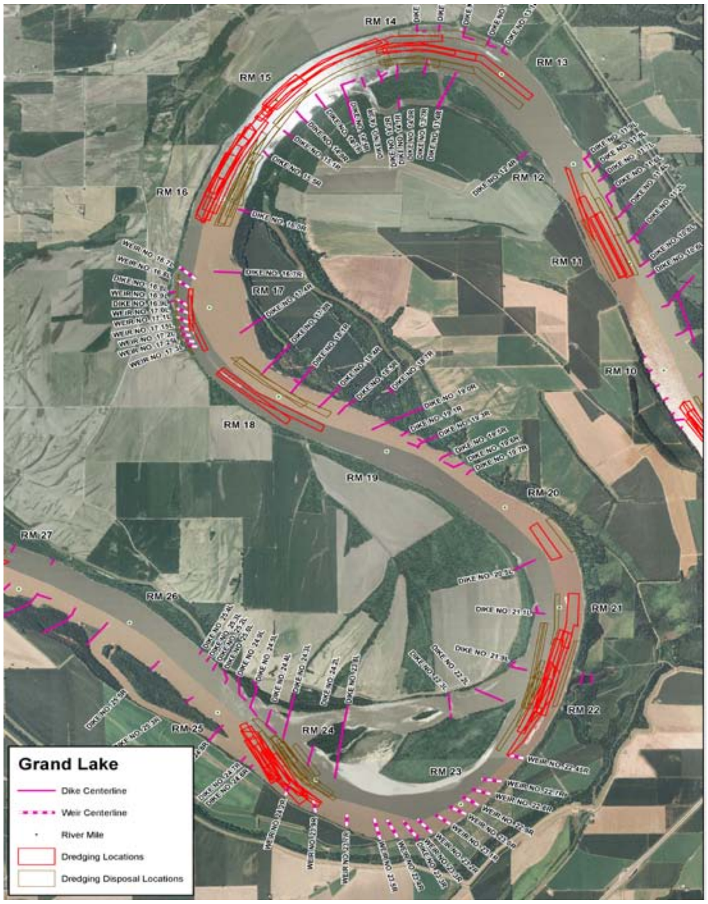
Grand Lake's cross section plots from 2005 hydrographic survey versus the replication test.

Figure 21



Grand Lake's cross section plots from 2010 hydrographic survey versus 2005 hydrographic survey.

Figure 22



Grand Lake historical dredge cut and disposal locations.

Conclusions

A 2002 comprehensive comparison study comparing large scale coal bed models to HSR models was performed in order to gauge the relative response scale effects had on the ability of the model to reproduce the trends observed in the river. This study demonstrated that the previous small scale and large scale movable bed models studied and compared against each other were on the same order of magnitude in their ability to reproduce the observed bed response of the river. Since that study, further improvements have been to improve accuracy, including more accurate and repeatable flow and sediment control and reduction in model roughness boundaries. To capture the success of these improvements, detailed cross-sectional comparisons between two recent HSR model replication surveys were compared to hydrographic surveys of the Missouri and Mississippi Rivers. The same comparisons were also made between different sets of hydrographic surveys to examine natural variation. The models chosen each contained a large number of existing training works structures (40 on the Missouri River model and 106 on the Mississippi River model). Even with this many structures in the models and their corresponding high influence on bed response, results showed both HSR models produced excellent replication agreement with the river and were consistent with the natural variability of bed response observed in the river over relatively short time periods (nine years on the Missouri and five years on the Mississippi).

Many training structure projects for navigation improvement, reduction in dredging, and environmental restoration have been successfully implemented in the Mississippi River as a result of HSR model studies. HSR modeling has been shown to reproduce the river's bed response and is a valid procedure for addressing the impacts of navigation structures on river geometry.

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