# SUPPLEMENTAL INVESTIGATION OF THE INFLUENCE OF RIVER TRAINING STRUCTURES ON FLOOD STAGES FROM RIVERMILE 179.5 TO 190.0 OF THE MIDDLE MISSISSIPPI RIVER

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Jesse A. Piotrowski, Nathan C. Young
and Larry J. Weber

IIHR – Hydroscience & Engineering
College of Engineering
The University of Iowa
Iowa City, Iowa 52242-1585

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## ABSTRACT

The United States Army Corps of Engineers (USACE) St. Louis District previously contracted IIHR- Hydroscience & Engineering (IIHR) to perform a series of hydrodynamic simulations of a navigation project constructed on the Middle Mississippi River adjacent to St. Louis, Missouri in 2009, which included a chevron dike field and a dike extension. Results indicated the chevron dikes and dike extension have minimal reach-scale impact on water surface elevations. Effects of the new and modified structures could not be distinguished from those associated with the mobile river bed. Based on study results, USACE contracted IIHR to improve model fidelity in the vicinity of river training structures and bridge piers and determine variability in water surface elevation due to the mobile river bed.

Two-dimensional hydrodynamic simulations were performed for a 10.5-mile reach of the Middle Mississippi River (MMR) adjacent to St. Louis, Missouri to characterize the effects of river training structures on flood stages. Simulations were performed using United States Bureau of Reclamation Sedimentation and River Hydraulics Two-Dimensional (SRH-2D) modeling software. The model was calibrated by adjusting roughness coefficients to closely reproduce water surface elevations measured by USACE. The model was validated using a separate USACE water surface elevation survey. Simulations were performed over a range of flow conditions using both pre- and post-dike construction river geometries – created using USACE bathymetric survey data.

Results indicated structures did not cause significant differences in reach-scale water surface elevations. Localized increases in water surface elevation up to 0.7 feet occurred at the upstream edge of the chevron dike field but propagated less than 0.4 miles upstream. Increase in water surface elevation can be caused by a number of compounding factors, including complex three-dimensional flow patterns not represented in a two-dimensional simulation. A comparison of two post-construction bed geometries indicates variability in water surface elevation up to 0.4 feet at the upstream edge of the chevron dike field, and variability up to 0.5 feet throughout the study domain due to natural changes in the Mississippi River's mobile bed. Differences between the pre- and post-construction water surface elevations are not consistently greater than differences resulting from natural variability in bed formations.

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# 1. Introduction

IIHR – Hydroscience & Engineering used fixed-bed, two-dimensional (2D) hydrodynamic simulations of a 10.5-mile reach of the Middle Mississippi River (MMR) adjacent to St. Louis, Missouri to characterize the effects of a newly constructed dike field and extension of a longitudinal training structure on flood stages. Simulations were conducted over a range of flow conditions using comprehensive bathymetric and topographic data. Simulation results were used to compare water surface elevations along the study reach before and after river training structure construction. Results of the analysis are specific to the study location and cannot not be generalized or applied to other river training structures or to other locations.

# 2. Numerical model development

Two-dimensional hydrodynamic simulations were performed using the United States Bureau of Reclamation Sedimentation and River Hydraulics Two-Dimensional (SRH-2D) modeling software. Bathymetric data describing pre- and post-construction MMR bed conditions were used in 2D simulations to predict water surface elevations at six different flow rates. Pre- and post-construction simulation results were compared to evaluate effects of the river training structures on water surface elevations. Two sets of post-construction simulation results were also compared to characterize natural variability of water surface elevation due to the mobile river bed.

## *2.1. Geometry*

Bathymetric and topographic data were provided by the United States Army Corps of Engineers (USACE). The model domain extended from USGS gage 07010000 upstream 10.5 miles (Figure 1). Multi-beam bathymetric data collected before river training structure construction were merged with single-beam hydrographic survey data in the main channel and Mosenthein Chute, and used to represent 2001 – 2007 pre-construction riverbed geometry (Figure 2). Multi-beam bathymetric data collected in 2009 were merged with main channel and Mosenthein Chute bathymetric data and used to represent post-construction riverbed geometry (Figure 2). Following model calibration and validation, a second bathymetric data set – collected in 2010 – became available (Figure 2). Light Detection and Ranging (LiDAR) data from City of

St. Louis and Metro East Sanitary District (MESD) flood protection projects were combined with Scientific Assessment Strategy Team (SAST) elevation data to create the overbank topography.

Riverbed geometry and overbank topography were used to create three numerical meshes:

(1) a mesh representing the 2001 – 2007 geometry without river training structure additions,

(2) a mesh representing the 2009 geometry with river training structure additions, and

(3) a mesh representing the 2010 geometry with river training structure additions.

Meshes were generated with SMS 10.1 mesh generation software and contained approximately 49,900 elements. Lower mesh resolution (100-200 m) was used in the overbank and in the main river channel where no river training structures existed. Higher mesh resolution (40 m) was used in the vicinity of river training structures (Figure 3). Triangular cells were used to represent the majority of the computational domain; quadrilateral cells were only used in areas of high mesh resolution to maintain a maximum change in area of 50 percent between adjacent elements. Bridge pier footprints were removed from the computational domain. Because SRH-2D cannot model pressurized flow, bridge deck submergence and overflow were not modeled.

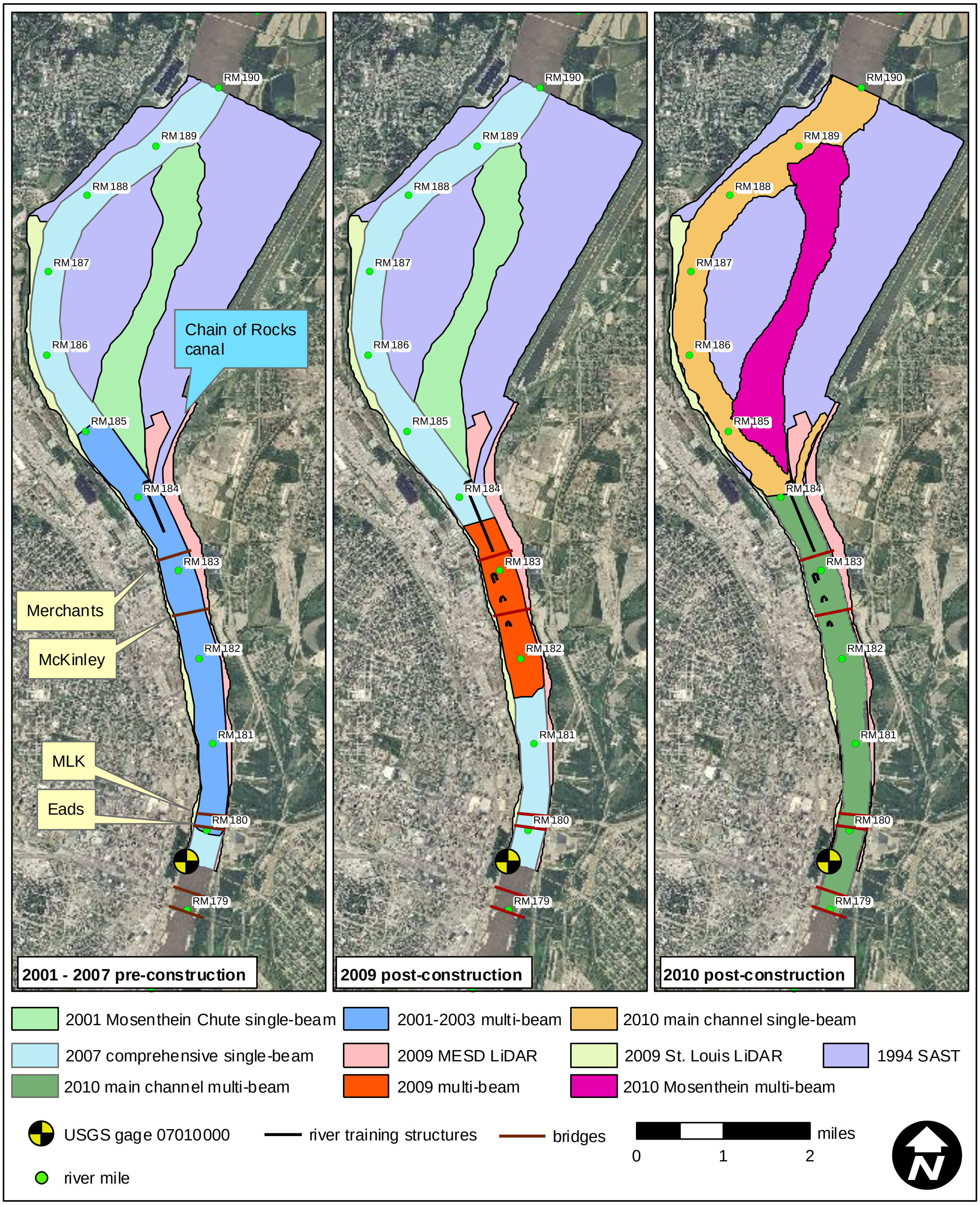


**Figure 1. Spatial extent of bathymetric and topographic data provided by USACE MVS.**

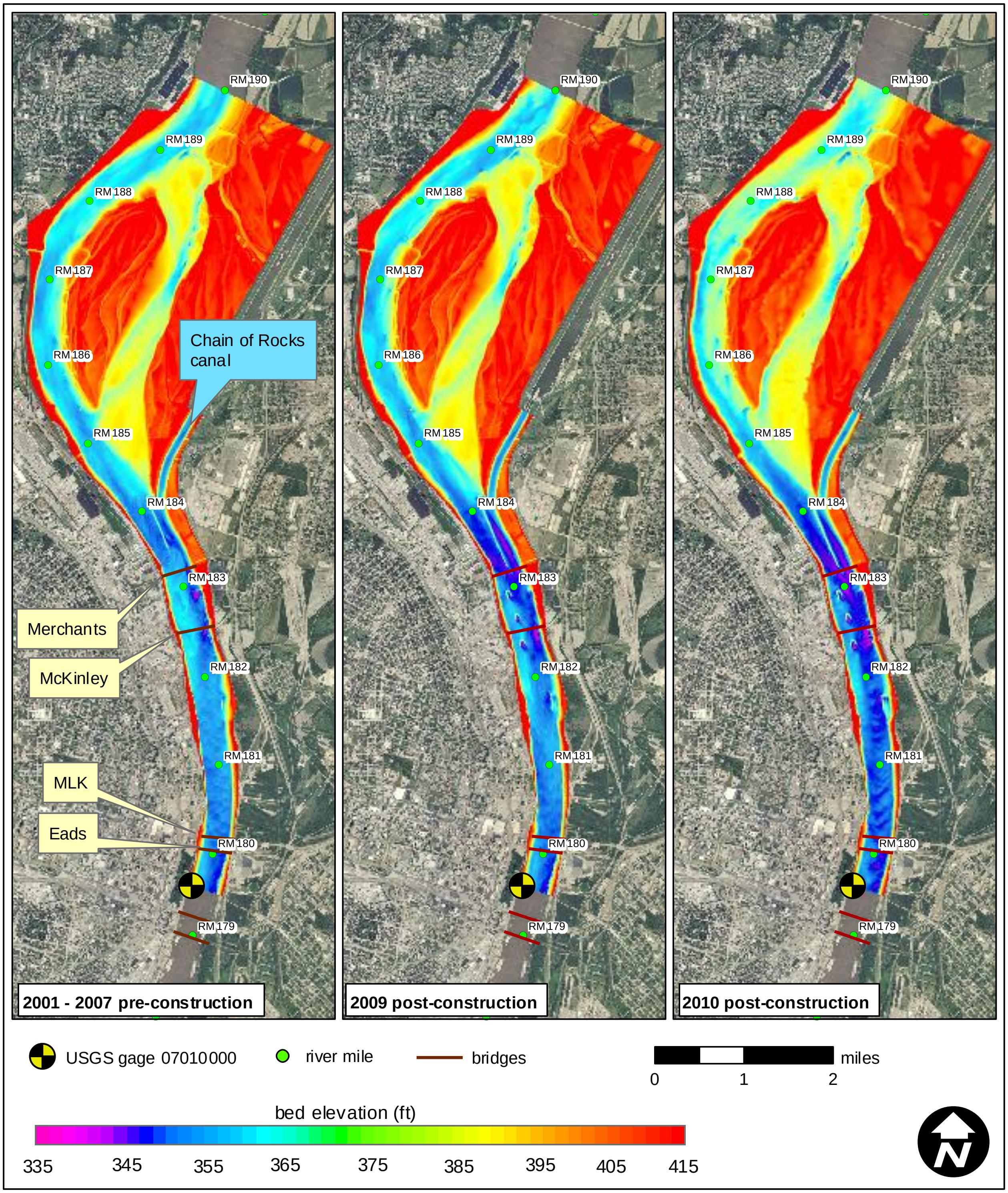


**Figure 2. River bed geometry created from bathymetric and topographic data provided by USACE MVS.**

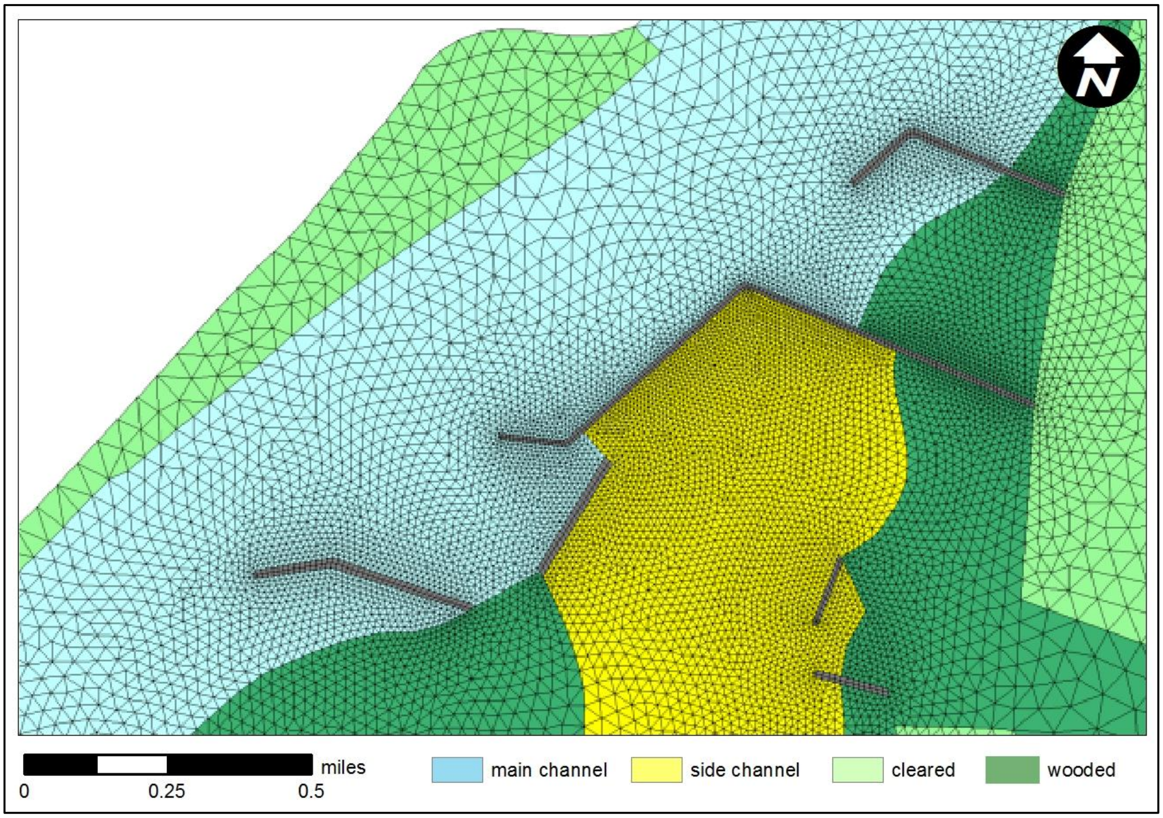


**Figure 3. Example of increased mesh resolution in the vicinity of river training structures at river mile 188.5.**

### *2.2. Boundary conditions*

No flow data were available for the Chain of Rocks Canal (Figure 1). However, USACE measurements and observations indicate flow in the canal is typically insignificant relative to total MMR discharge (Robert Davinroy, personal communication). In each simulation, all flow was assumed to enter the model domain from the MMR main channel, where a steady inflow boundary condition was imposed. A fixed water surface elevation at the downstream boundary was determined for each simulation using the stage-discharge rating curve for USGS gage 07010000 at St. Louis, MO (Figure 4).

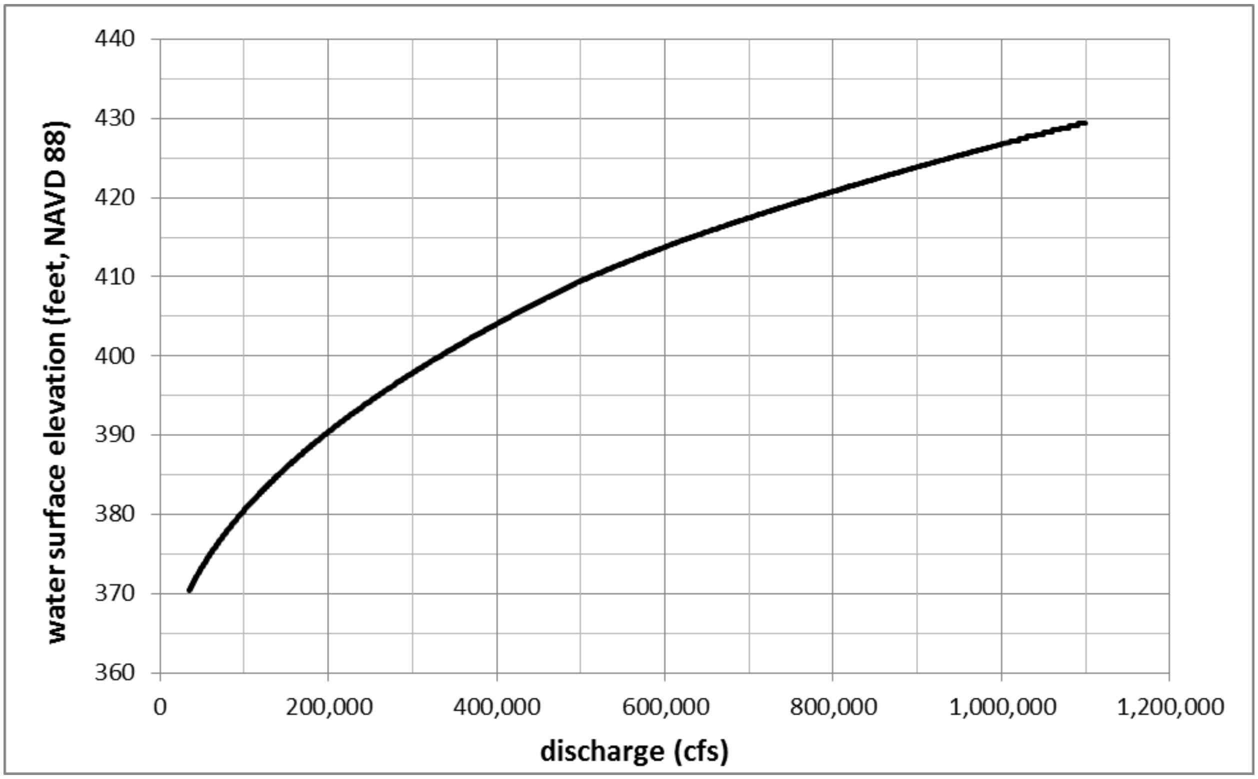


**Figure 4. Rating curve from USGS gage 07010000 used to establish water surface elevations for the downstream boundary condition. Data provided by USACE.**

### *2.3. Model calibration and validation*

Water surface elevation data collected by the USACE St. Louis District using real time kinematic satellite navigation on September 29, 2010 and June 29, 2011 were used to calibrate and validate the model, respectively (Figure 5). Measured stage and discharge at United States Geological Survey (USGS) gage 07010000 at St. Louis, MO were used to establish simulation boundary conditions. Discrete material types were spatially delineated based upon aerial photography and spatial data describing structure locations, and assigned to the pre- and 2009 post-dike construction meshes (Figure 6). Spatial distribution of material types was approved by USACE prior to model calibration. USACE recommended initial Manning's 'n' values (shown in Table 1) based upon previous model experience in an upstream study reach.

Because both water surface elevation surveys occurred after river training structure construction and the 2010 post-construction bathymetry was not available during calibration and validation, the 2009 post-construction mesh was used for both calibration and validation. IIHR varied initial Manning's 'n' values to evaluate model sensitivity to each material type. Twelve simulations were performed, with ‘n’ values for individual material types sequentially increased and decreased by 25 percent (Table 1). For each simulation, only the ‘n’ value being tested for sensitivity was modified. The model was relatively insensitive to all material types except stone dike and main channel (Figure 7). Water surface profiles associated with extreme discharges were not available, therefore influence of overbank ‘n’ values at extreme discharges was not considered in model calibration. All simulations over-predicted water surface elevation, indicating that initial main channel and stone dike ‘n’ values were too high.

Based upon initial sensitivity results, IIHR sequentially modified the stone dike and main channel ‘n’ values to determine a combination that fit the observed data well (Figure 8). Two combinations resulted in a low mean difference from measured water surface elevations:

(1) a main channel ‘n’ value of 0.020 and a stone dike value of 0.060 resulted in a mean under-prediction of 0.02 feet, and

(2) a main channel ‘n’ value of 0.021 and a stone dike value of 0.040 resulted in a mean over-prediction of 0.02 feet.

IIHR selected a main channel ‘n’ value of 0.021 and a stone dike value of 0.040. A lower ‘n’ value for stone dike structures was chosen due to high mesh resolution in the vicinity of river training structures (Figure 3). Energy loss due to flow obstruction is captured by the mesh geometry and only surface roughness is accounted for by the Manning’s ‘n’ value.

Reducing side channel ‘n’ was considered due to the significant difference between the calibrated main channel ‘n’ and USACE-recommended side channel ‘n’. USACE noted that bed material in the side and main channels is likely similar, and a significantly different ‘n’ value may not be an accurate physical representation. To investigate the potential impacts of reducing the side channel roughness, a simulation was performed with the side channel ‘n’ decreased to 0.024, while maintaining original calibrated roughness values for other material types. Figure 9 displays a comparison of simulated water surface elevation profiles for side channel ‘n’ of 0.030 and 0.024. Modifying the side channel ‘n’ did not significantly change simulated water surface elevation, reinforcing previously demonstrated model insensitivity to side channel ‘n’ for September 9, 2010 boundary conditions. While the model was insensitive to side channel roughness, due to the arguments described above, USACE and IIHR agreed that a side channel ‘n’ of 0.024 was appropriate.

All other ‘n’ values were set to values recommended by USACE. Final calibrated roughness coefficients are shown in Table 2. Figure 10 compares measured and simulated water surface elevation profiles for September 29, 2010, using the calibrated Manning’s ‘n’ values. Water surface elevations are displayed on the left axis and over-prediction of simulated water surface elevation is displayed on the right axis. The calibrated Manning’s ‘n’ values resulted in a mean over-prediction of 0.02 feet.

Figure 11 displays September 9, 2010 simulated and measured water surface elevations in the immediate vicinity of the chevron dike field. While the numerical simulation reasonably predicts the reach-scale water surface profile, small-scale disagreements between measured and simulated water surface elevations occur. Small-scale differences can be attributed to variability in river bed geometry and limitations of the two-dimensional, depth-averaged simulation. Because water surface elevations were not measured at the same time as bathymetry, small-scale differences in the water surface elevation can be expected due to natural changes in the Mississippi River’s mobile bed. Local differences in water surface elevation can also be expected due to the two-dimensional model’s inability to simulate three-dimensional flow features.

Flow and stage data from June 29, 2011 were simulated with the calibrated Manning’s ‘n’ values to validate the numerical model. On average, the numerical model under-predicted water surface elevation by 0.1 feet. Figure 12 displays measured and simulated water surface elevation profiles for June 29, 2011. Water surface elevations are displayed on the left axis and over-prediction of simulated water surface elevation is displayed on the right axis.

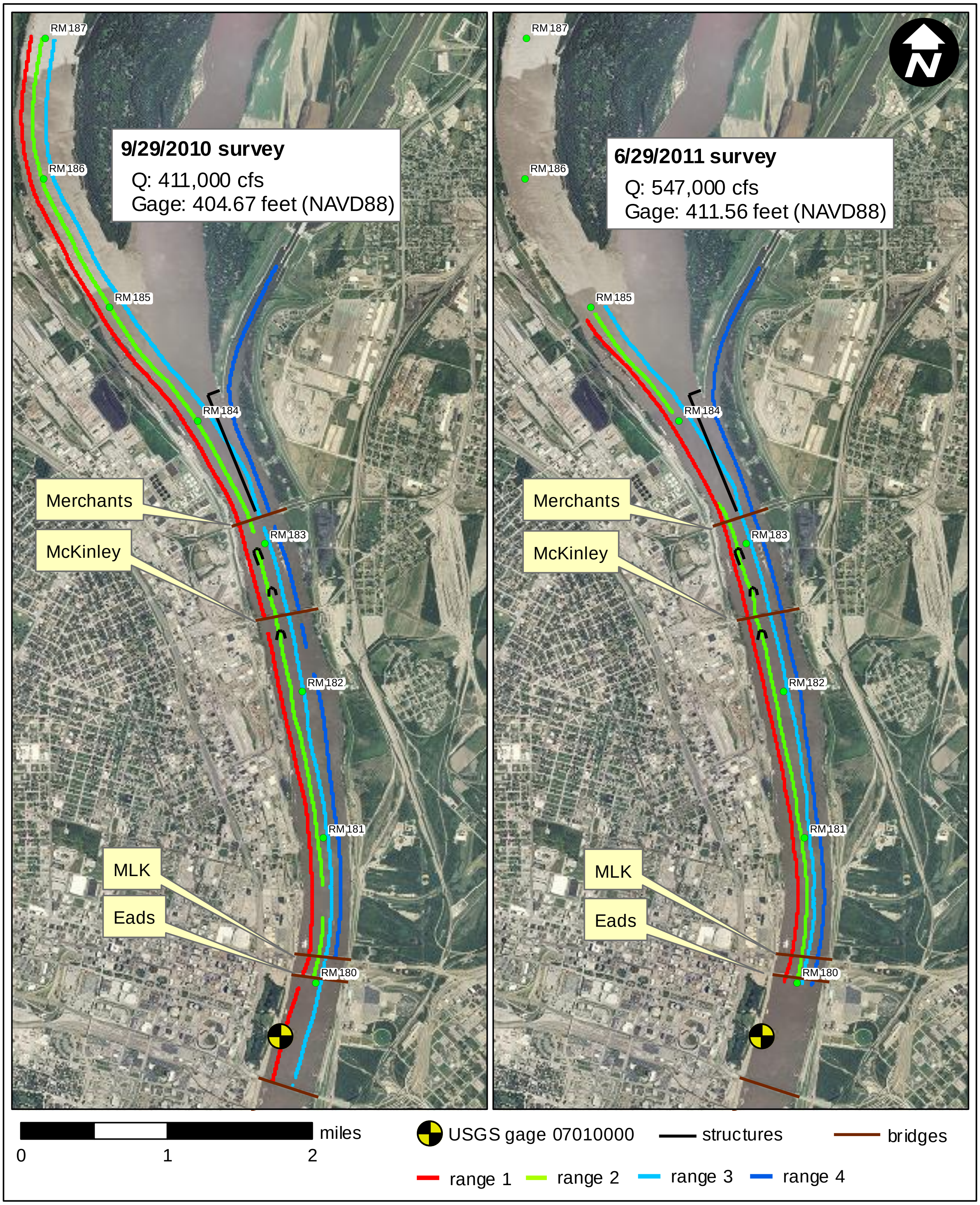


**Figure 5. Locations of longitudinal water surface elevation profiles measured by USACE on September 29, 2010 (left) and June 29, 2011 (right). Profiles were used for model calibration and validation, respectively.**

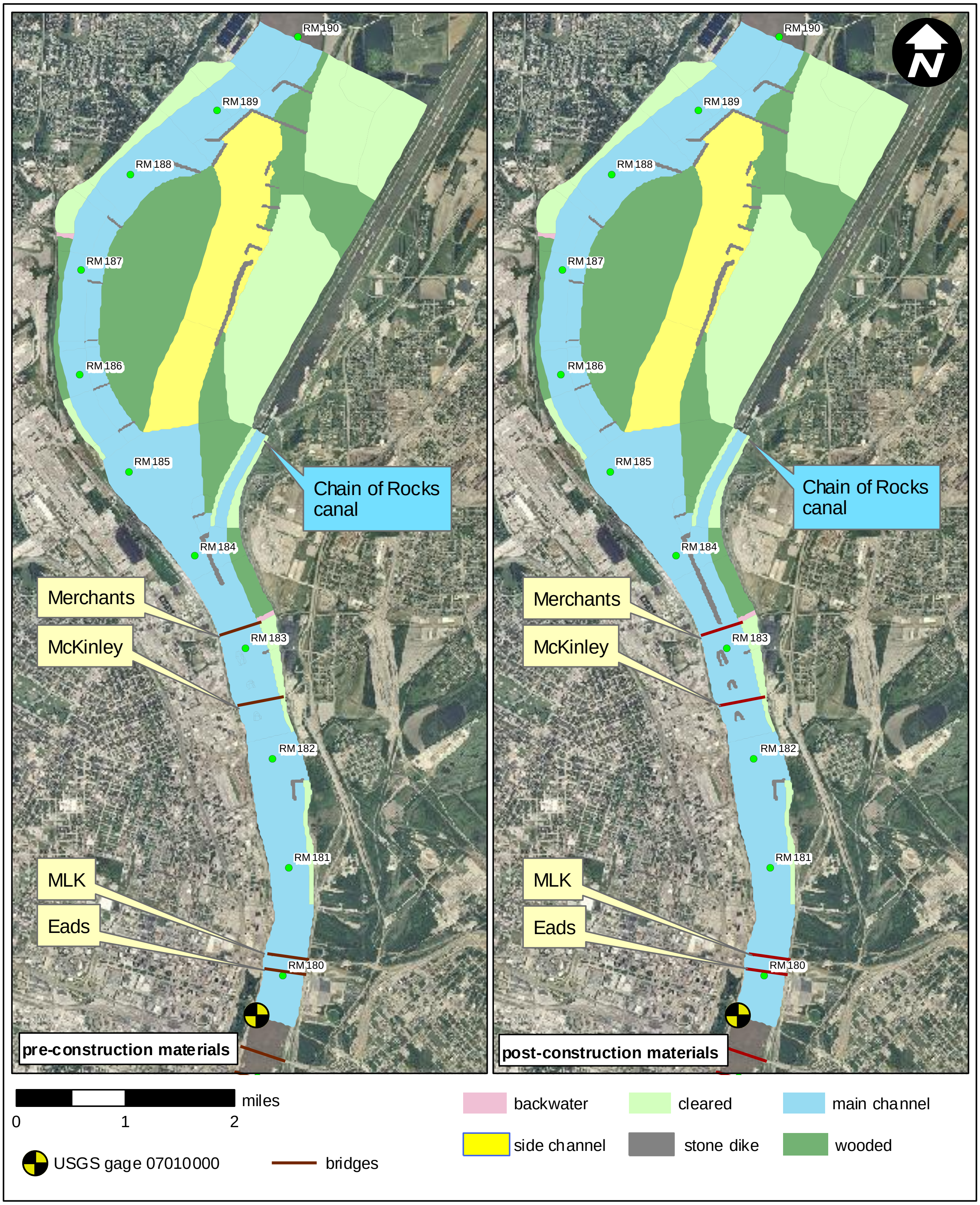


**Figure 6. Spatial distribution of material types in the pre- and post-dike construction meshes. Because both water surface elevation surveys occurred after dike construction, the 2009 post-construction mesh was used for all calibration and validation simulations.**

**Table 1. Manning's 'n' values used in initial sensitivity analysis. Values for individual material types were sequentially increased and decreased by 25 percent.**

| material type | 'n' value recommended by USACE | 25% decrease in 'n' value recommended by USACE | 25% increase in 'n' value recommended by USACE |
|---|---|---|---|
| wooded | 0.120 | 0.090 | 0.150 |
| cleared | 0.070 | 0.053 | 0.088 |
| stone dikes | 0.070 | 0.053 | 0.088 |
| backwater | 0.040 | 0.030 | 0.050 |
| main channel | 0.028 | 0.021 | 0.035 |
| side channel | 0.030 | 0.023 | 0.038 |

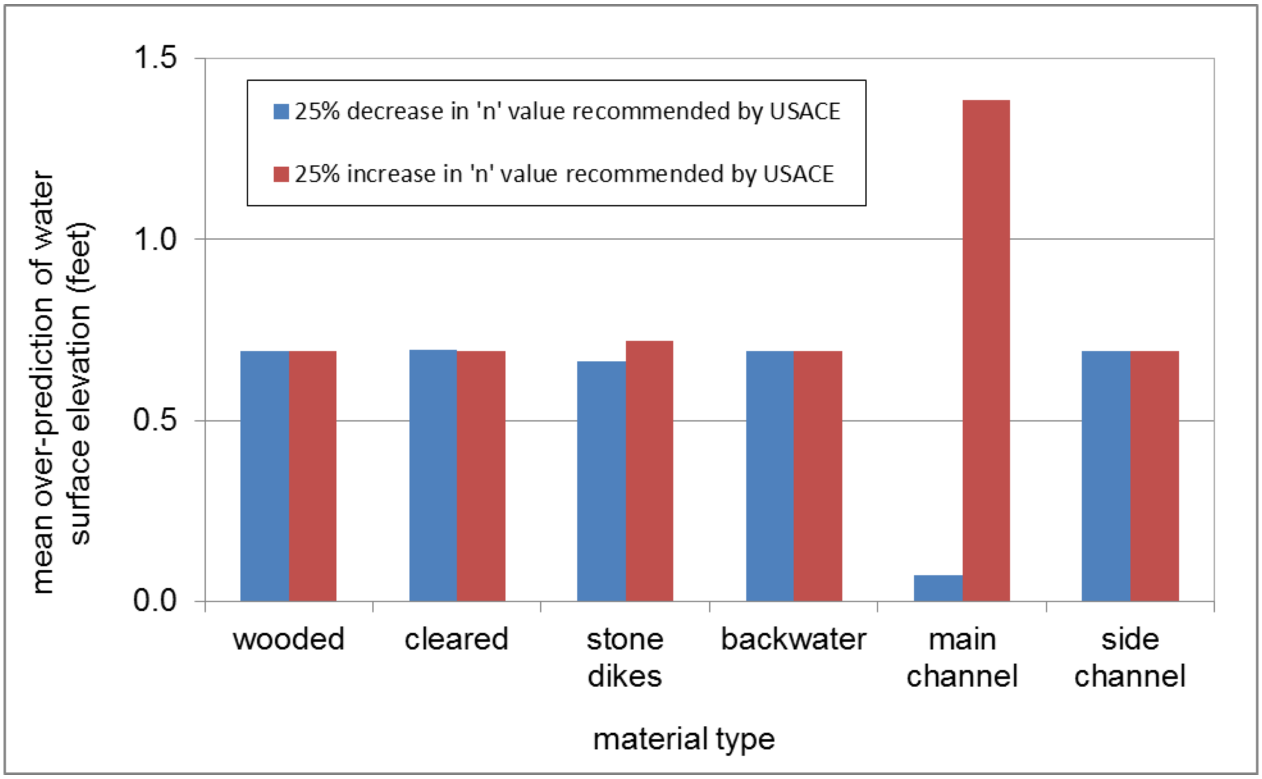


**Figure 7. Numerical model sensitivity to Manning's 'n' values. The model was relatively insensitive to all material types except stone dike and main channel. All simulations over-predicted water surface elevation, indicating that initial 'n' values for the main channel and stone dikes were too high.**

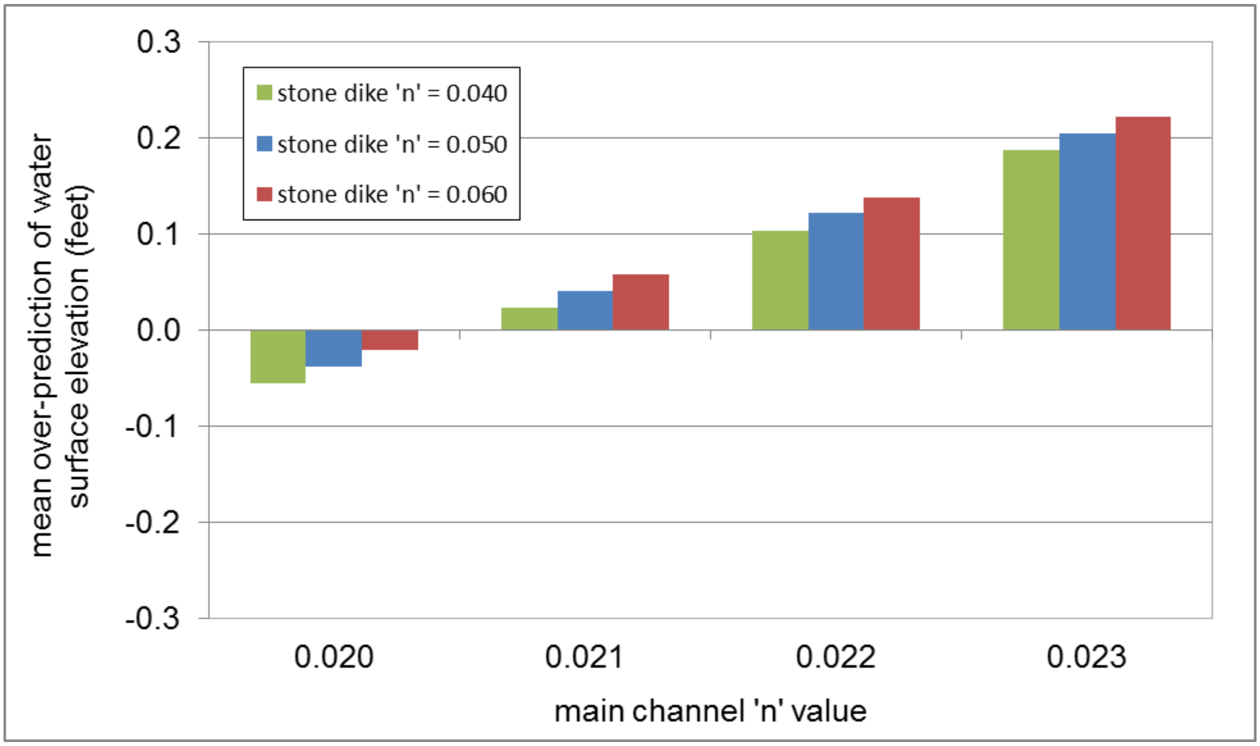


**Figure 8. Simulated over-prediction of water surface elevation for various adjustments to stone dike and main channel 'n' values.**

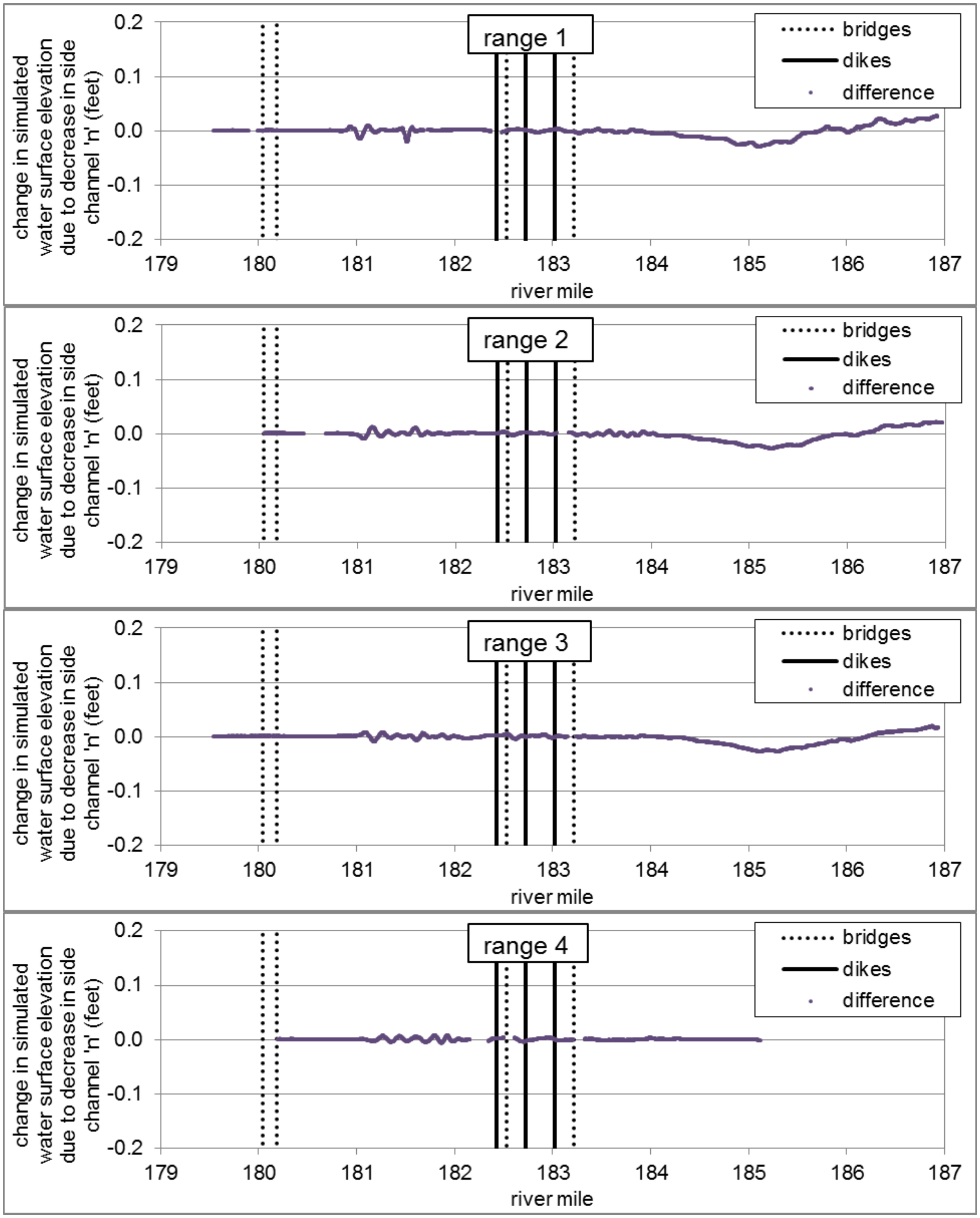


**Figure 9. Difference in simulated water surface elevation profiles using September 29, 2010 boundary conditions. Simulation results with side channel 'n' of 0.024 were subtracted from results with side channel 'n' of 0.030. Differences were typically less than 0.05 feet.**

**Table 2. Selected Manning's 'n' values. Only main channel, side channel and stone dike values were modified from USACE-recommended values.**

| material type | calibrated 'n' value |
|---|---|
| wooded | 0.120 |
| cleared | 0.070 |
| stone dikes | 0.040 |
| backwater | 0.040 |
| main channel | 0.021 |
| side channel | 0.024 |

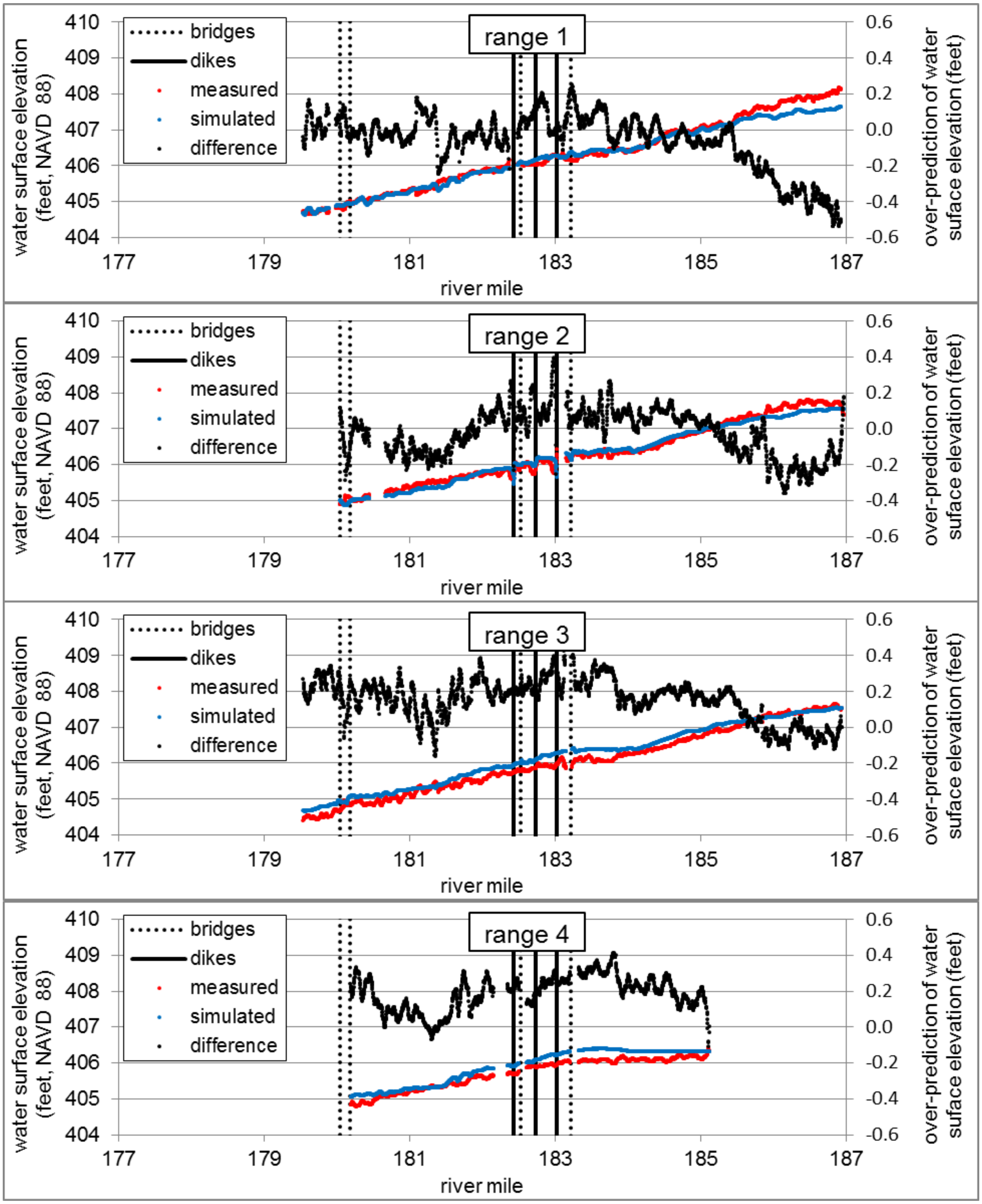


**Figure 10. Comparison of simulated and measured water surface elevation profiles for September 29, 2010. Range locations are shown in Figure 5 (left). Mesh representing 2009 post-construction bathymetry was used for calibration.**

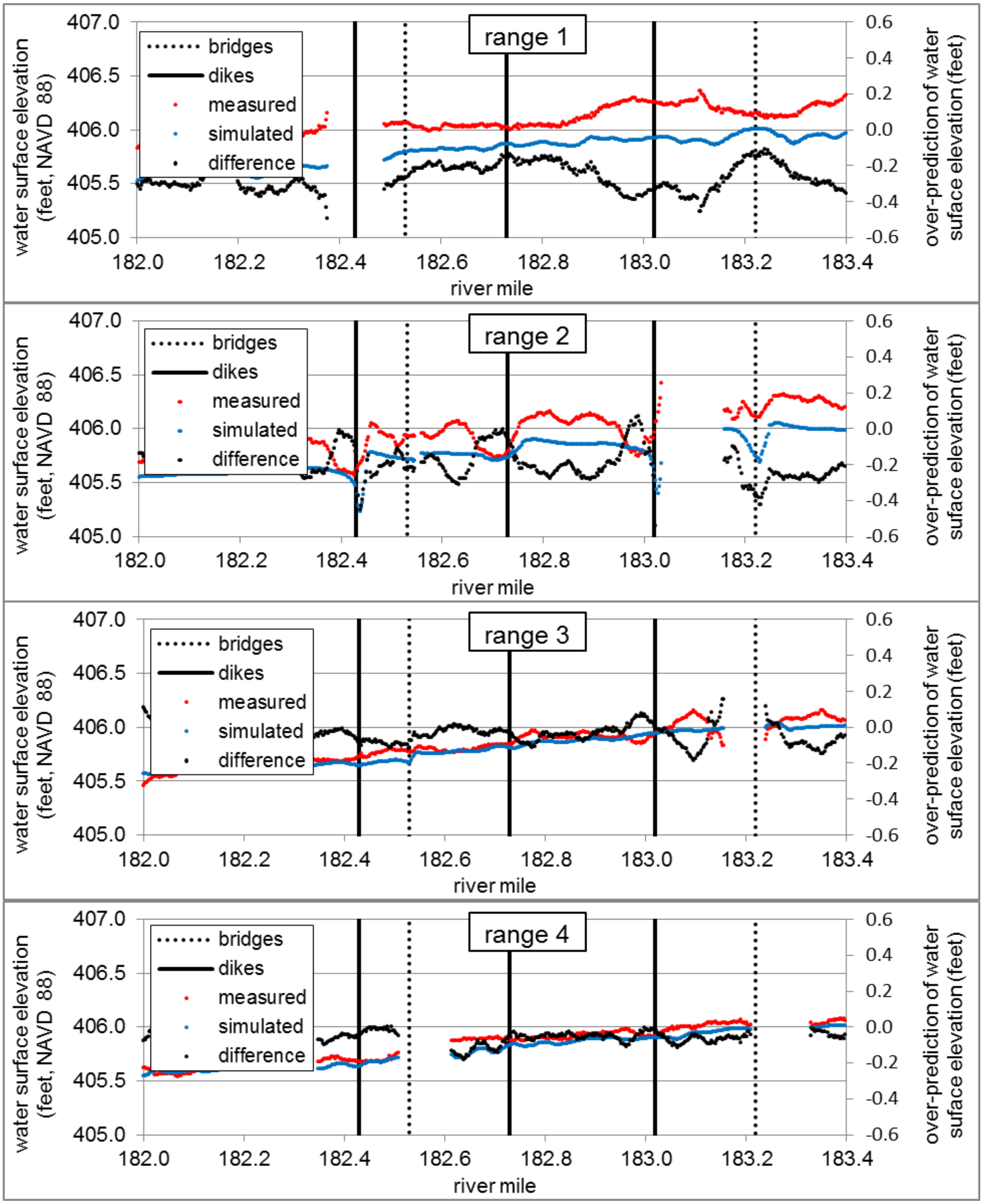


**Figure 11. Comparison of simulated and measured water surface elevation profiles for September 29, 2010 in the immediate vicinity of the chevron dikes. The numerical model predicts the general water surface profile but does not predict small-scale changes in water surface elevation.**

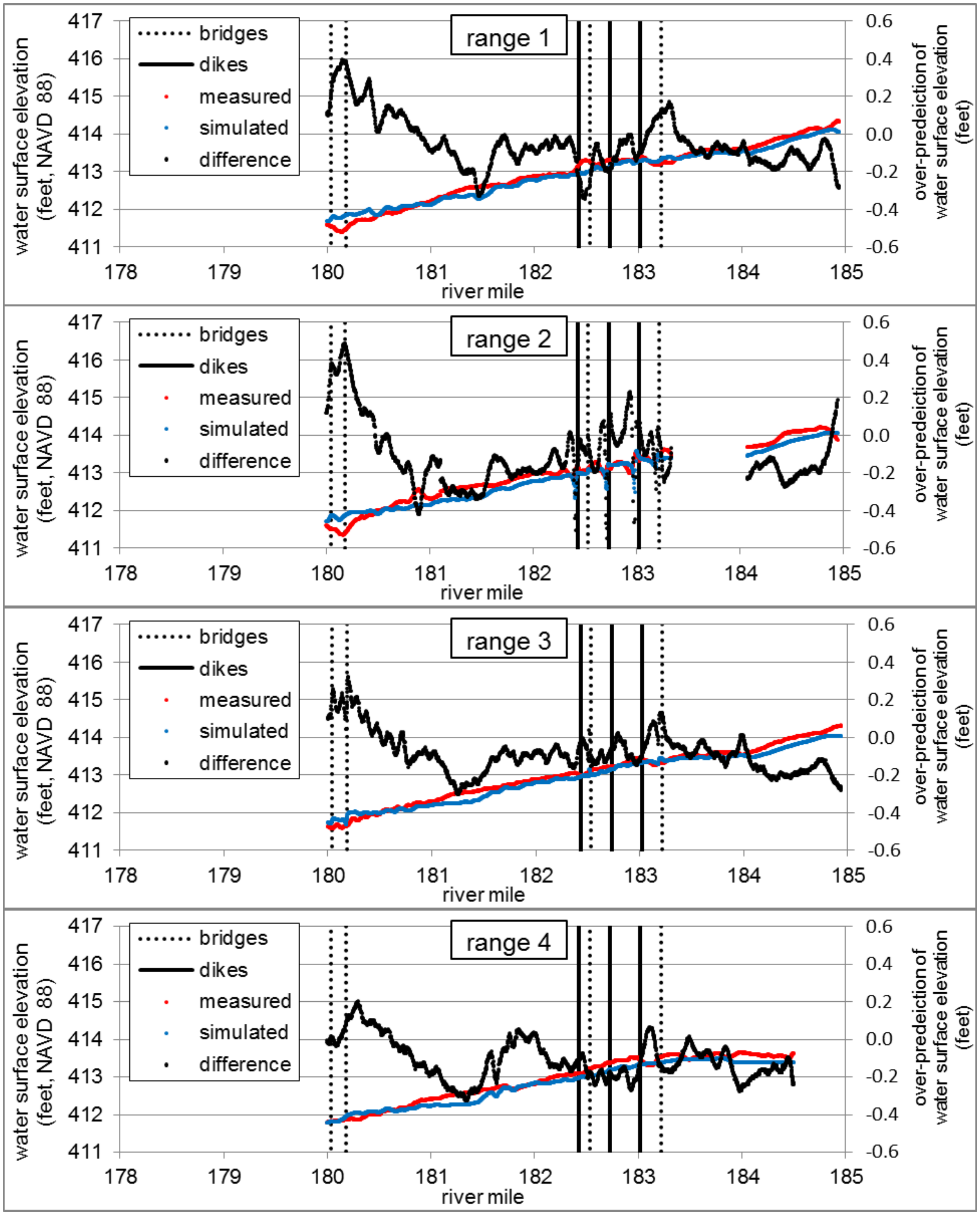


**Figure 12. Comparison of simulated and measured water surface elevation profiles for June 29, 2011. Range locations are shown in Figure 5 (right). Mesh representing 2009 post-construction bathymetry was used for validation.**

## 3. Pre-dike and 2010 post-dike comparison

During the investigation, a second post-dike bathymetric condition – based on comprehensive single- and multi-beam bathymetry collected by USACE in 2010 – was made available to IIHR. Figure 1 displays spatial extent of the 2010 bathymetry and Figure 2 displays river bed elevations. The 2010 bathymetry is a better representation of post-dike construction river bed conditions because the 2010 survey extent covered the entire model domain, while the 2009 survey only covered areas where new river training structure construction occurred. The 2010 bathymetry may also better represent a post-dike construction equilibrium state because the 2009 data were collected shortly after dike construction and the river may have not yet adjusted to a new dynamic equilibrium. Manning's 'n' values established in model calibration and validation were used in the 2010 bathymetry mesh.

Simulated water surface elevations from the 2010 post-dike bathymetry were compared to pre-dike water surface elevations for discharges of 250, 390, 540, 720, 910 and 1300 kcfs. Water surface elevations were extracted along ranges (Figure 13) to quantify differences between the pre-dike and 2010 post-dike water surface profiles. Figure 14 displays the profiles. Downstream of the chevron dike field, both positive and negative differences exist. Upstream of the dike field, 2010 post-dike water elevations were higher than pre-dike elevations for in-bank flow conditions (250 and 390 kcfs). For out-of-bank flow conditions (540 to 1300 kcfs), 2010 post-dike elevations were lower than pre-dike elevations. Figure 15 (left) displays increase in 2010 post-dike bathymetric elevations as compared to pre-dike bathymetry. Aggregation is evident from river mile 185 to 190, where increases of 10 to 20 feet exist in the main channel. Increases in bed elevation are likely causing the increase in water surface elevations for in-bank flow conditions upstream of river mile 185.

For all flows, difference in predicted water surface elevation was positive in the chevron dike field. Increases in water surface elevation up to 0.7 feet occurred at the upstream edge of the chevron dike centerline. Increased water surface elevation can be caused by a number of compounding factors, including the following:

(1) Simulated velocity vectors and discharges are depth-averaged in each computational element and cannot predict complex three-dimensional flow patterns in the dikes' vicinity.

(2) Cumulative effects of aggregation/scour (Figure 15) can cause changes in water surface elevations throughout the study reach.

(3) Manning's 'n' value was not modified for various flow scenarios. A single Manning's 'n' value cannot represent the anticipated decrease in energy loss due to surface roughness as discharge, depth, and the relative submergence of the dikes increase.

These factors limit the numerical model's ability to simulate small-scale, localized changes in water surface elevation, as demonstrated in Figure 11. Simulated differences in maximum water surface elevation cannot be directly attributed to the chevron dikes.

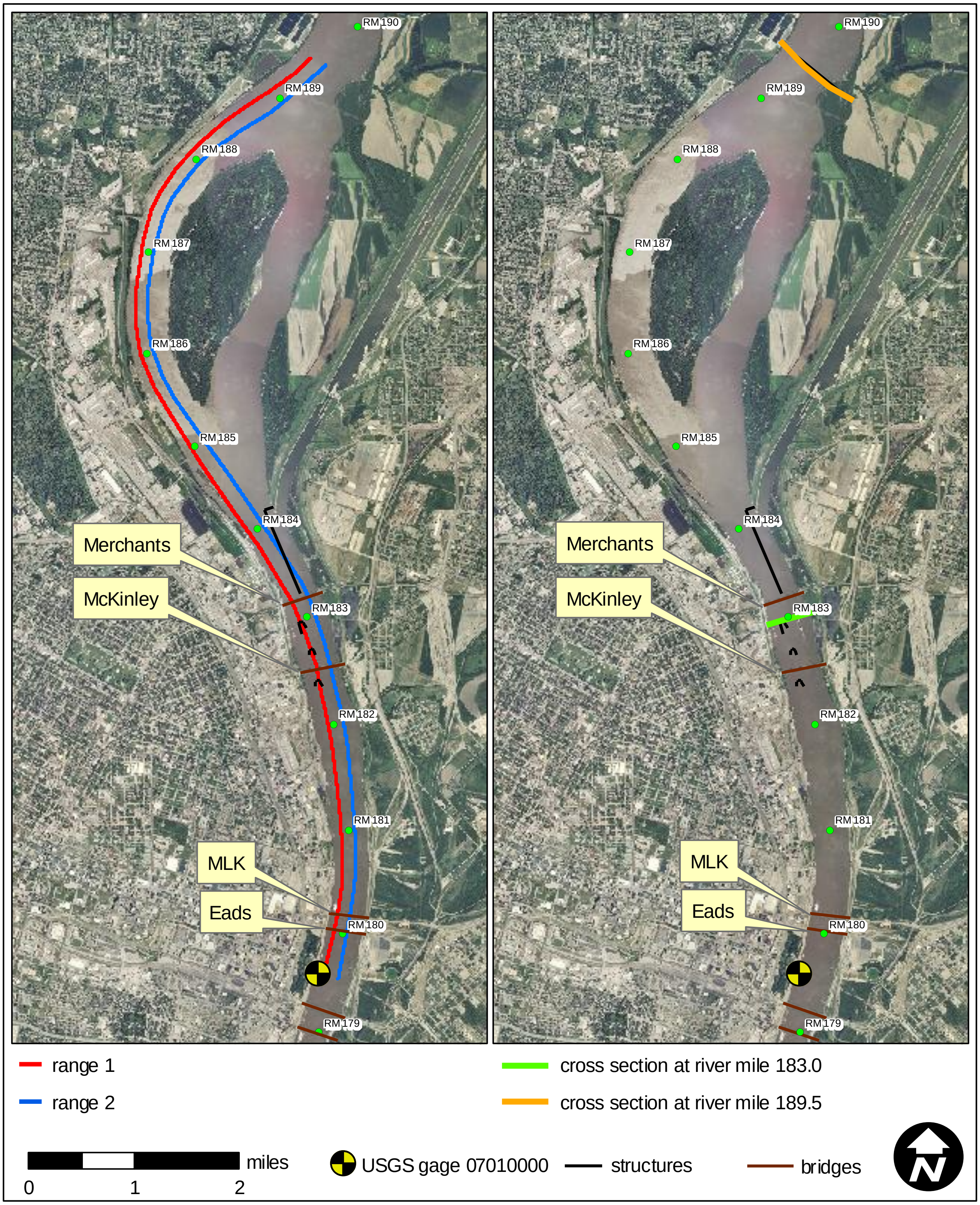


**Figure 13. Location of longitudinal ranges (left) and cross sections (right) used to extract water surface elevations from simulation results. Range 1 passes directly through the chevron dike field and range 2 is in the navigation channel. The cross sections are located immediately upstream of the dike field and at the upstream boundary of the study area.**

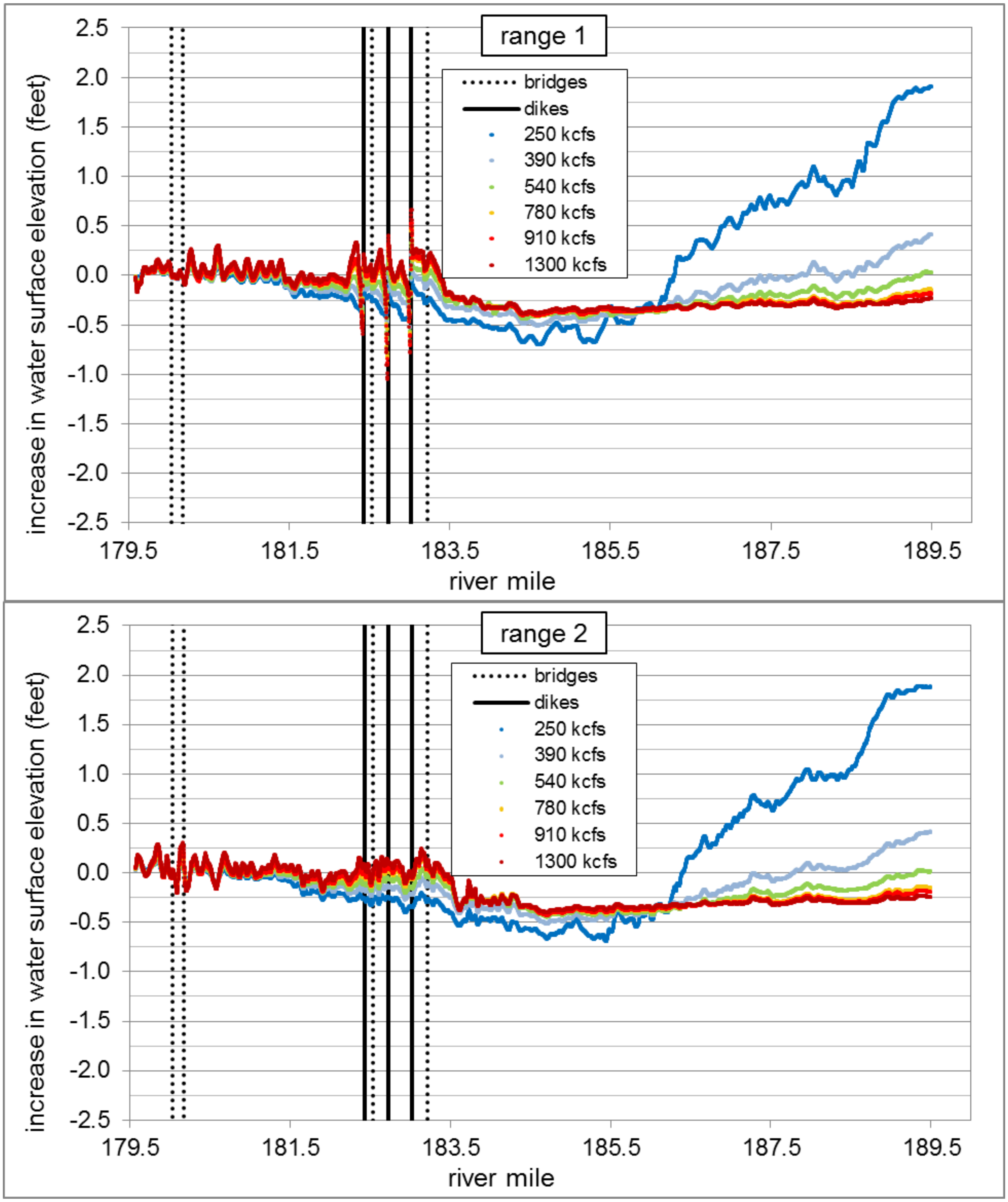


**Figure 14. Increase in predicted water surface elevations along profiles of the study reach. Simulated water surface elevations using pre-construction bathymetry were subtracted from elevations using 2010 post-construction bathymetry. Ranges used to extract data are displayed in Figure 13.**

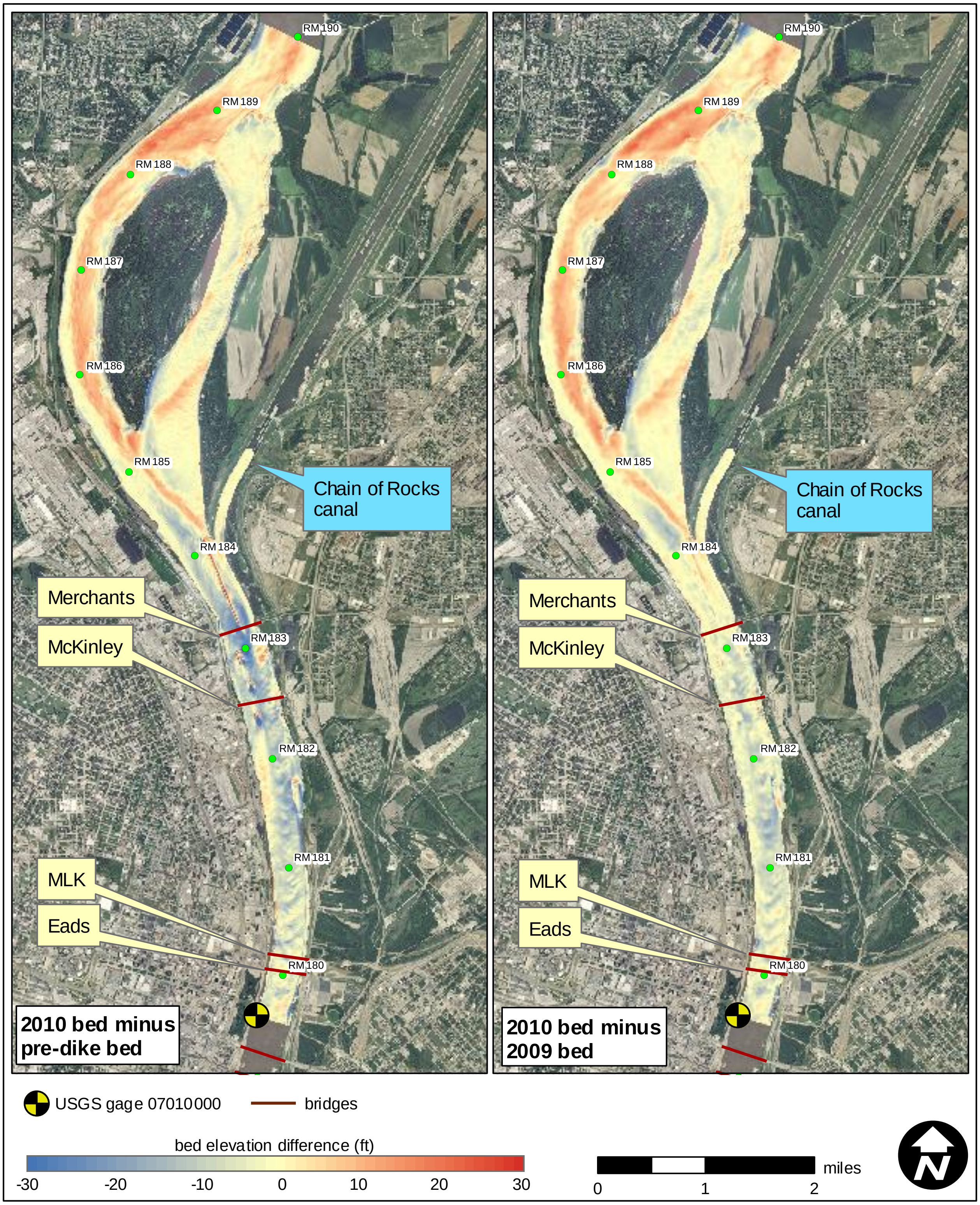


**Figure 15. Increase in 2010 post-dike bathymetry as compared to pre-dike bathymetry (left) and increase in 2010 post-dike bathymetry as compared to 2009 post-dike bathymetry (right).**

## 4. Natural variability in water surface due to mobile river bed

Because surveys representing the pre- and post-dike construction bathymetry were performed under different flow conditions, differences in water surface elevation cannot be directly attributed to the chevron dike field; differences could also be caused by changes in bathymetry resulting from scour or aggregation of the river bed and dynamic migration of bed material.

The 2009 post-dike bathymetry was used to simulate 250, 390, 540, 780, 910 and 1300 kcfs flow conditions. Simulated water surface elevations from the 2010 post-dike bathymetry were compared to 2009 post-dike water surface elevations to quantify variability in water surface elevation due to changes in bed geometry. Water surface elevations from 2010 post-construction results and 2009 post-construction results were extracted along ranges (Figure 13) and compared. Figure 16 displays difference in predicted water surface elevation between the 2010 and 2009 post-construction bed geometries. Differences in water surface elevation vary by river mile and discharge. At river mile 183.0 – immediately upstream of the chevron dike field – predicted differences in water surface elevation are up to 0.4 feet. At river mile 189.5 – near the upstream boundary of the study area – predicted differences in water surface elevation vary significantly with discharge. Larger differences are predicted for lower discharges.

Water surface elevation statistics for the pre/post-dike comparison, representing the combined influence of the dike field and natural bathymetric variability, and the 2009/2010 post-dike comparison, representing the influence of natural bathymetric variability alone, were contrasted to evaluate the dikes' relative effect. Figure 17 displays mean difference between simulated water surface elevations. Mean difference was determined by calculating the difference in water surface elevation at each cell of a three-meter-resolution grid covering the wetted portion of the model domain. Comparing mean differences in water surface elevation, 2010-to-pre-construction is similar to 2010-to-2009. Statistics indicate the combined impacts of the river training structures and bed variability on water surface elevation is similar to the impact of bed variability alone.

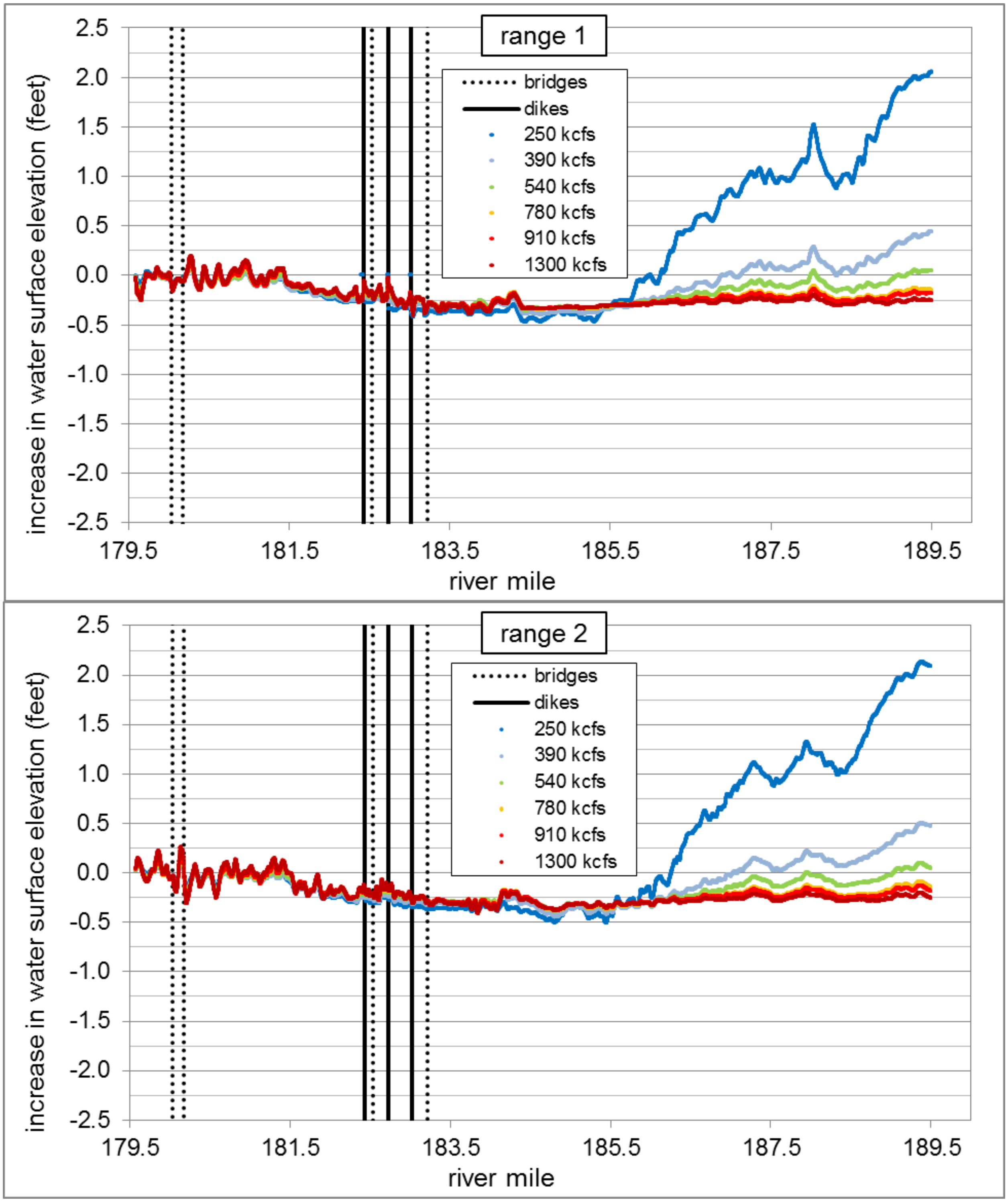


**Figure 16. Increase in predicted water surface elevations along profiles of the study reach. Simulated water surface elevations using 2009 post-construction bathymetry were subtracted from elevations using 2010 post-construction bathymetry. Ranges used to extract data are displayed in Figure 13.**

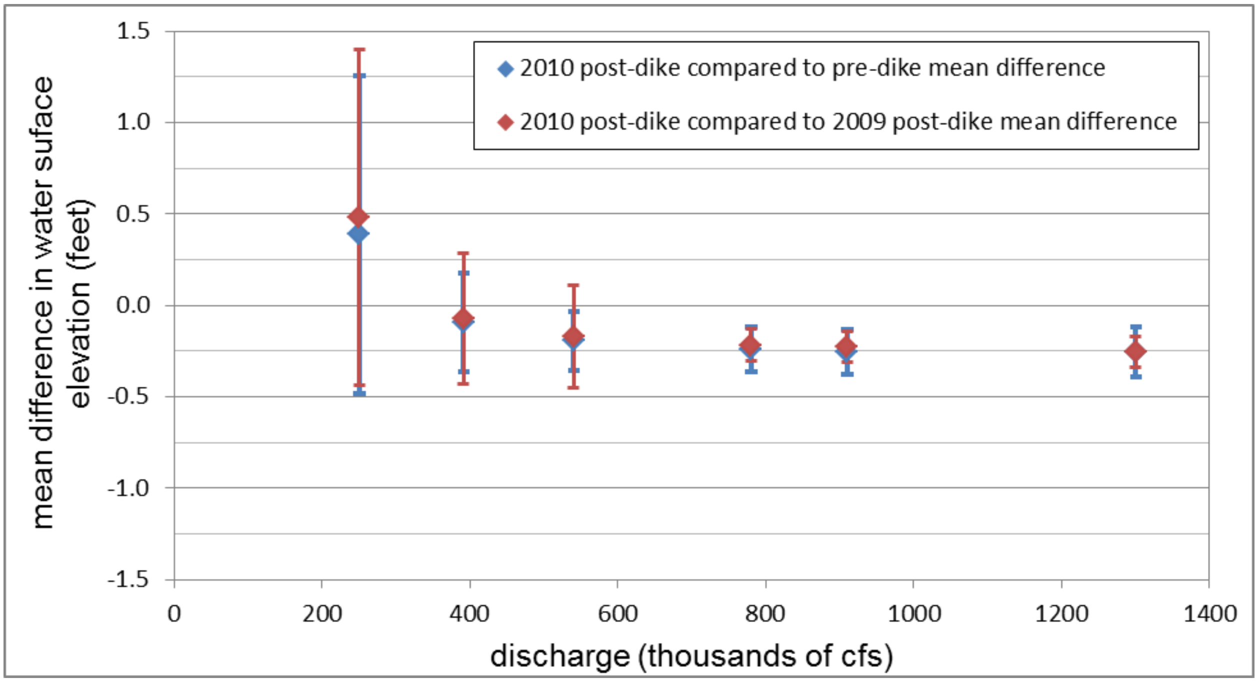


**Figure 17. Mean difference between simulated water surface elevations. Vertical bars represent one standard deviation. The 2010-to-pre-construction difference in mean is similar to the 2010-to-2009 difference in mean, indicating the combined impact of the river training structures and the Mississippi River's naturally variable river bed is comparable to that of the river bed alone.**

## 5. Conclusions

Simulations indicate river training structures do not cause significant differences in reach-scale water surface elevations for out of bank (flood) flow conditions. Comparison of pre- and post-dike construction simulations indicate small differences in water surface elevations for out of bank flow rates. Significant local increases in water surface elevation occurred at the upstream edge of the chevron dike field but did not propagate upstream for out of bank flow conditions.

A comparison of two post-construction bed geometries indicates variability in water surface elevation up to 0.4 feet at the upstream edge of the chevron dike field, and variability up to 0.5 feet throughout the study domain due to natural changes in the Mississippi River's mobile bed. Water surface elevation statistics for the 2010/pre-construction comparison and the 2010/2009 post-dike comparison indicate the combined impact of the river training structures and the Mississippi River's naturally variable river bed is comparable to that of river bed variability alone.

Possible future investigations should further explore the influence of model roughness parameterization and mesh construction on simulated water surface elevations, including the following analyses:

(1) a sensitivity analysis of overbank Manning's 'n' values using extreme flow conditions,
(2) a sensitivity analysis of chevron dike Manning's 'n' for multiple flow conditions, and
(3) a mesh sensitivity analysis to determine if mesh element size in the dikes' vicinity affects water surface elevations.

## 6. References

United States Bureau of Reclamation. 2010. Sedimentation and River Hydraulics - Two Dimensional River Flow Modeling.

United States Army Corps of Engineers Applied River Engineering Center. 2009 - 2010. Mississippi River bathymetric and flow data.