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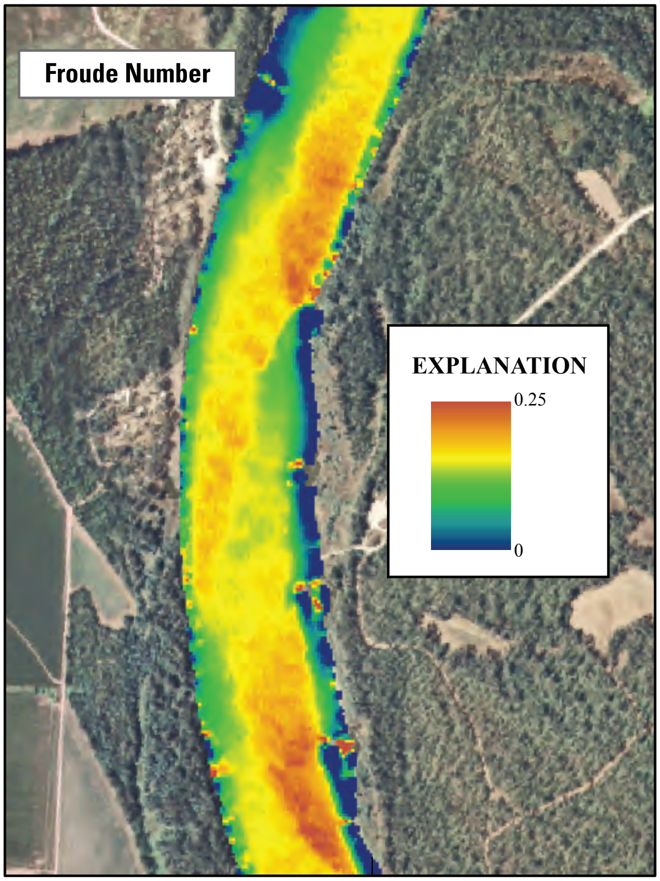
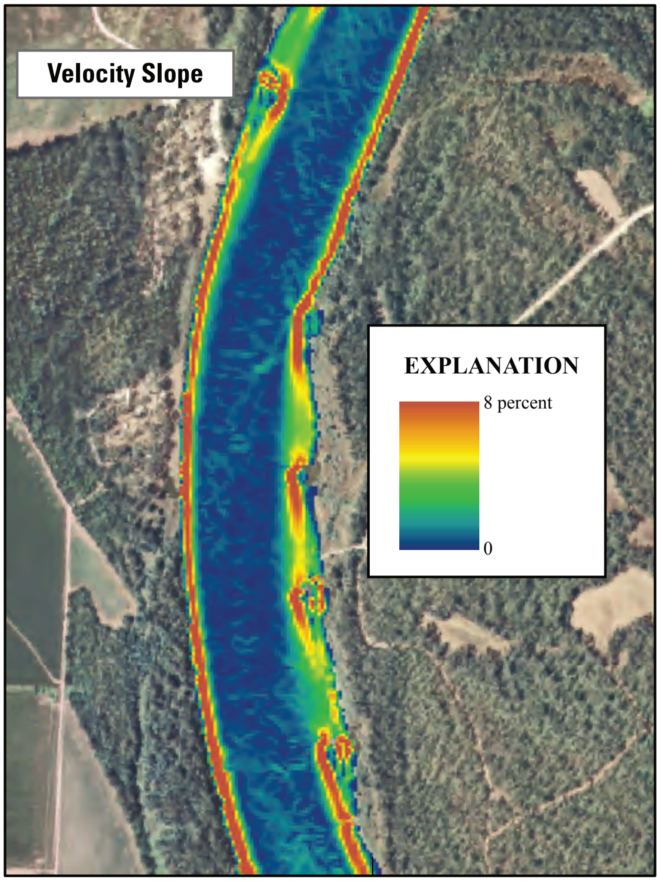
U.S. Army Corps of Engineers, Yankton, South Dakota

Hydrodynamic Simulations of Physical Aquatic Habitat Availability for Pallid Sturgeon in the Lower Missouri River, at Yankton, South Dakota, Kenslers Bend, Nebraska, Little Sioux, Iowa, and Miami, Missouri, 2006–07





Scientific Investigations Report 2009–5058

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Front cover: Examples of derivative hydraulic habitat metrics at Little Sioux reach: Froude number and velocity slope.

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
mile (mi)	1.609	kilometer (km)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

SI to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
meter (m)	1.094	yard (yd)
	Area	
hectare (ha)	2.471	acre
square kilometer (km^2)	247.1	acre
square meter (m^2)	10.76	square foot (ft^2)
hectare (ha)	0.003861	square mile (mi^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic meter (m^3)	264.2	gallon (gal)
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic meter (m^3)	1.308	cubic yard (yd^3)
cubic kilometer (km^3)	0.2399	cubic mile (mi^3)
	Flow rate	
meter per second (m/s)	3.281	Foot per second (ft/s)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
	Mass	
megagram, metric ton (Mg)	1.102	ton, short (2,000 lb)
Megagram, metric ton (Mg)	0.9842	ton, long (2,240 lb)

Distances along the Missouri River are given in river miles upstream from the junction with the Mississippi River at St. Louis, Missouri, as measured by the U.S. Army Corps of Engineers in 1960.

Horizontal coordinate information is referenced to the World Geodetic System of 1984 (WGS 84). Elevation data are referenced to the North American Vertical Datum of 1988 (NAVD88).

Hydrodynamic Simulations of Physical Aquatic Habitat Availability for Pallid Sturgeon in the Lower Missouri River, at Yankton, South Dakota, Kenslers Bend, Nebraska, Little Sioux, Iowa, and Miami, Missouri, 2006–07

By Robert B. Jacobson, Harold E. Johnson, III, and Benjamin J. Dietsch

Abstract

The objective of this study was to assess the sensitivity of habitat availability in the Lower Missouri River to discharge variation, with emphasis on habitats that might support spawning of the endangered pallid sturgeon. We constructed computational hydrodynamic models for four reaches that were selected because of evidence that sturgeon have spawned in them. The reaches are located at Miami, Missouri (river mile 259.6–263.5), Little Sioux, Iowa (river mile 669.6–673.5), Kenslers Bend, Nebraska (river mile 743.9–748.1), and Yankton, South Dakota reach (river mile 804.8–808.4). The models were calibrated for a range of measured flow conditions, and run for a range of discharges that might be affected by flow modifications from Gavins Point Dam. Model performance was assessed by comparing modeled and measured water velocities.

A selection of derived habitat units was assessed for sensitivity to hydraulic input parameters (drag coefficient and lateral eddy viscosity). Overall, model results were minimally sensitive to varying eddy viscosity; varying lateral eddy viscosity by 20 percent resulted in maximum change in habitat units of 5.4 percent. Shallow-water habitat units were most sensitive to variation in drag coefficient with 42 percent change in unit area resulting from 20 percent change in the parameter value; however, no habitat unit value changed more than 10 percent for a 10 percent variation in drag coefficient. Sensitivity analysis provides guidance for selecting habitat metrics that maximize information content while minimizing model uncertainties.

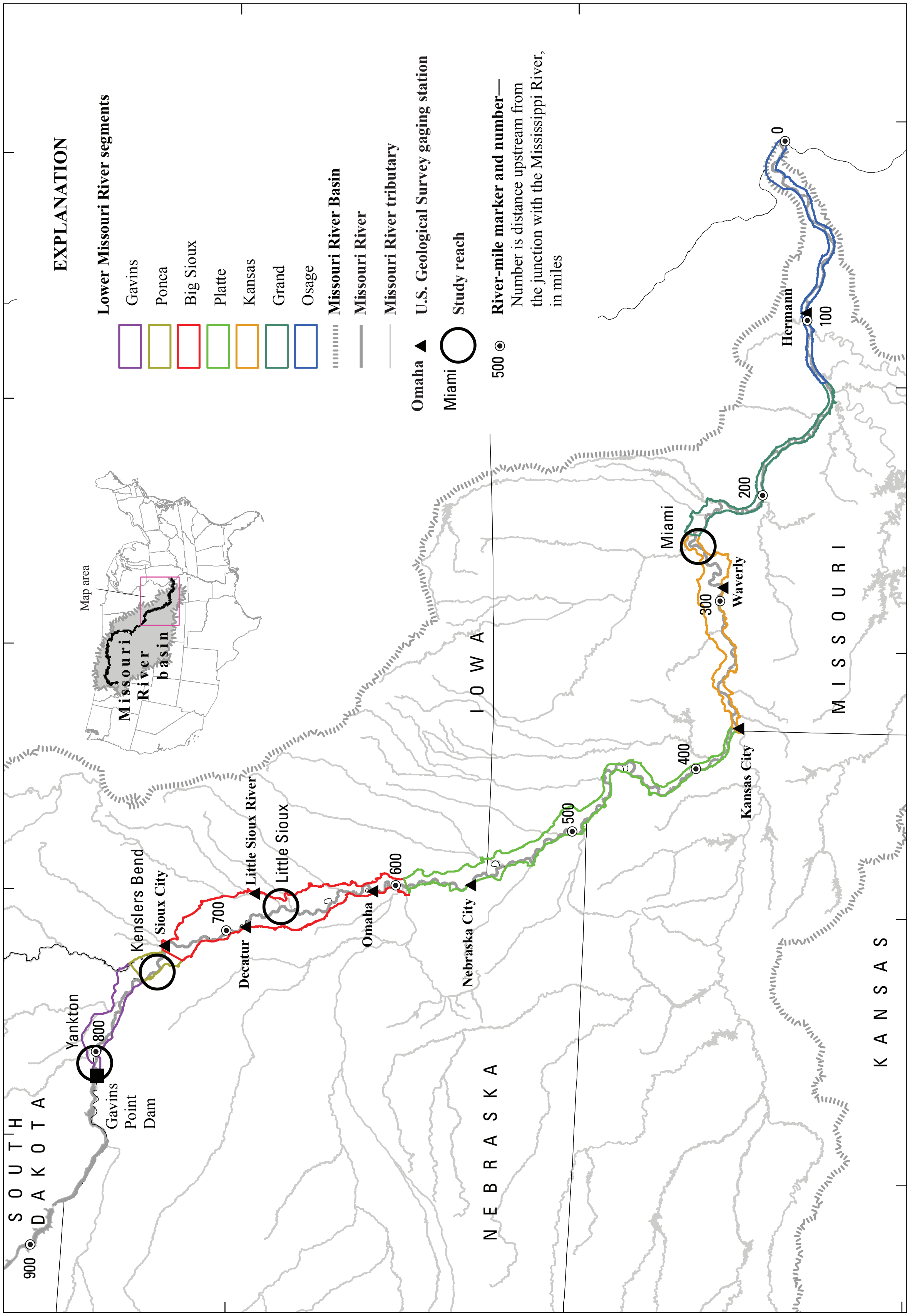
To assess model sensitivities arising from topographic variation from sediment transport on an annual time scale, we constructed separate models from two complete independent surveys in 2006 and 2007. The net topographic change was minimal at each site; the ratio of net topographic change to water volume in the reaches at 95 percent exceedance flow was less than 5 percent, indicating that on a reach-average basis, annual topographic change contributed little to habitat area variation. Net erosion occurred at Yankton (the upstream reach) and because erosion was distributed uniformly, there was little affect on many habitat metrics. Topographic change was spatially nonuniform at Little Sioux and Kenslers Bend reaches. Shallow water habitat units and some reach-scale patch statistics (edge density, patch density, and Simpson's Diversity Index) were affected by these changes. Erosion dominated at the downstream reach but habitat metrics did not vary substantially from 2006 to 2007.

Among habitat metrics that were explored, zones of convergent flow were identified as areas that most closely correspond to spawning habitats of other sturgeon species, as identified in the scientific literature, and that are consistent with sparse data on pallid sturgeon spawning locations in the Lower Missouri River. Areas of convergent zone habitat varied little with discharges that would be associated with spring pulsed flows, and relations with discharge changed negligibly between 2006 and 2007.

Other habitat measures show how physical habitat varies with discharge and among the four reaches. Wake habitats defined by velocity gradients seem to correspond with migration pathways of adult pallid sturgeon. Habitats with low Froude-number correspond to low energy areas that may accumulate passively transporting particles, organic matter, and larval fish. Among the modeled reaches, Yankton had substantially longer water residence time for equivalent flow exceedances than the other three modeled reaches. Longer residence times result from greater flow resistance in the relatively wide, shallow channel and may be associated with longer residence times of passively transported particulate materials.

Introduction

This report addresses sensitivity of physical aquatic habitat for pallid sturgeon (*Scaphirhynchus albus*) in the Lower Missouri River (fig. 1) using multidimensional hydrodynamic



Base data from the National Atlas, 2006
Universal Transverse Mercator projection
Zone 15

Waterbody data from the U.S. Geological Survey National Hydrography Dataset, 2006

Figure 1. Locations of hydrodynamic modeling reaches used in this study.

modeling. The modeling approach is used to quantify habitat availability as it changes with seasonal or annual variations in discharge and channel morphology. Emphasis is placed on assessing sensitivity for a range of discharges that might be amenable to pulsed flow modification, or a "spring rise." The modeling approach provides a systematic basis for defining physical habitat variables thought to be important for various life stages of pallid sturgeon (and other Missouri River fishes) and for exploring alternative definitions of important habitats.

Background

The Missouri River drains 1,371,000 square kilometers (km^2) of North America and hosts to the nation's largest reservoir system with 91 cubic kilometers (km^3) of storage (Galat and others, 2005b). The mainstem system of six reservoirs impounds 53 percent of the drainage basin upstream from the junction with the Mississippi River at St. Louis (fig. 1). Downstream from Gavins Point Dam the river is known as the Lower Missouri River (LMOR). Constructed between 1937 and 1963, the reservoir system has substantially altered the flow regime, including reductions in intra-annual flow variability, generally decreased spring pulses, and generally increased summer flows. The intensity of hydrologic alteration diminishes somewhat downstream from the dams as tributaries enter the Missouri River (fig. 2). The 590 km downstream from the Kansas River confluence (at Kansas City, Missouri) retains substantial intra-annual variability including spring-summer flow pulses (fig. 2).

The sediment regime of the river also has been substantially altered as a result of reservoir operations, decreasing from 326 million metric tons per year (Mg/y) to 55 million Mg/y as measured at Hermann, Missouri (Jacobson and others, U.S. Geological Survey, written commun., 2009). The decrease in sediment load also has been associated with decreases in turbidity that are thought to affect native fish fauna (Galat and others, 2005a; Blevins, 2006).

From St. Louis, Missouri to Sioux City, Iowa, the LMOR also has been engineered for bank stabilization and navigation. Engineering of the LMOR channel began in the 1830s with clearing of large woody debris and bank stabilization to improve conditions for steamboat navigation; channelization intensified considerably from 1930 to 1970 (Ferrell, 1996). Wing dikes and revetments now stabilize 1,200 km of riverbanks. Dikes and other navigation structures serve to focus the flow in the thalweg to maintain a narrow, swift, and self-dredging navigation channel in what was historically a shallow river characterized by interspersed braided, anabranched, and single-channel reaches. River engineering resulted in the loss of as much as 400 km^2 of river-corridor habitats (Funk and Robinson, 1974; Hesse and Sheets, 1993; National Research Council, 2002; U.S. Army Corps of Engineers, 2004; Galat and others, 2005b).

Changes to flow regime, sediment regime, and channel morphology on the LMOR have been associated with declines of native species (National Research Council, 2002; U.S. Fish and Wildlife Service, 2003). Biological information to support this inference includes the general decline of native fish species populations, commercial fish catches (Hesse, 1987; Pflieger and Grace, 1987; Hesse and others, 1989; Hesse and Sheets, 1993; Galat and others, 2005b), and sandbar nesting birds (U.S. Fish and Wildlife Service, 2000) in the LMOR since regulation and channelization. In 2000, the U.S. Fish and Wildlife Service issued a Biological Opinion, subsequently amended in 2003, that indicated management actions that threatened three listed species, the pallid sturgeon, interior least tern (*Sternula antillarum athalassos*), and the piping plover (*Charadrius melodus)* (U.S. Fish and Wildlife Service, 2000; 2003). Among other remedies, the amended Biological Opinion (U.S. Fish and Wildlife Service, 2003) prescribed reasonable and prudent alternatives related to management of flow regime and channel morphology to provide habitat for reproduction and survival of these species. Specifically, the Biological Opinion called for naturalization of the flow regime to:

- build sandbars in 95 km of the LMOR downstream from Gavins Point Dam to support nesting of the least tern and piping plover;
- connect the main channel to the flood plain seasonally, to augment nutrient and energy exchange, and to provide fish access to overbank habitats;
- maintain nursery habitat for larval and juvenile pallid sturgeon by achieving seasonal low flows in late summer;
- provide an environmental spawning cue for the pallid sturgeon through some combination of discharge and discharge-related variables like temperature, turbidity, and water velocity;
- provide access to spawning habitat or "conditioning" of spawning habitat for pallid sturgeon by flushing fine sediment from coarse substrate.

The amended Biological Opinion also called for restoration of a portion of the shallow-water aquatic habitat lost from river engineering. Shallow-water habitat (SWH) on the LMOR has been defined as 0–1.5 meters (m) depth and 0–0.6 meters per second (m/s) current velocity, and is thought to be important for rearing of larval and juvenile pallid sturgeon and for other native fishes (U.S. Fish and Wildlife Service, 2003; U.S. Army Corps of Engineers, 2004). The Amended Biological Opinion requires restoration of 4,800–7,900 hectares of lost aquatic habitat (assumed to be SWH) by the year 2020 and allows this habitat to substitute for achievement of SWH by flow manipulation (item 3, above). SWH is being created by a variety of mechanisms, including excavation of side-channel chutes, dike notching, bank notching, and construction of chevrons.

In addition to changes in channel morphology that result from purposeful re-engineering of channel, there are complex

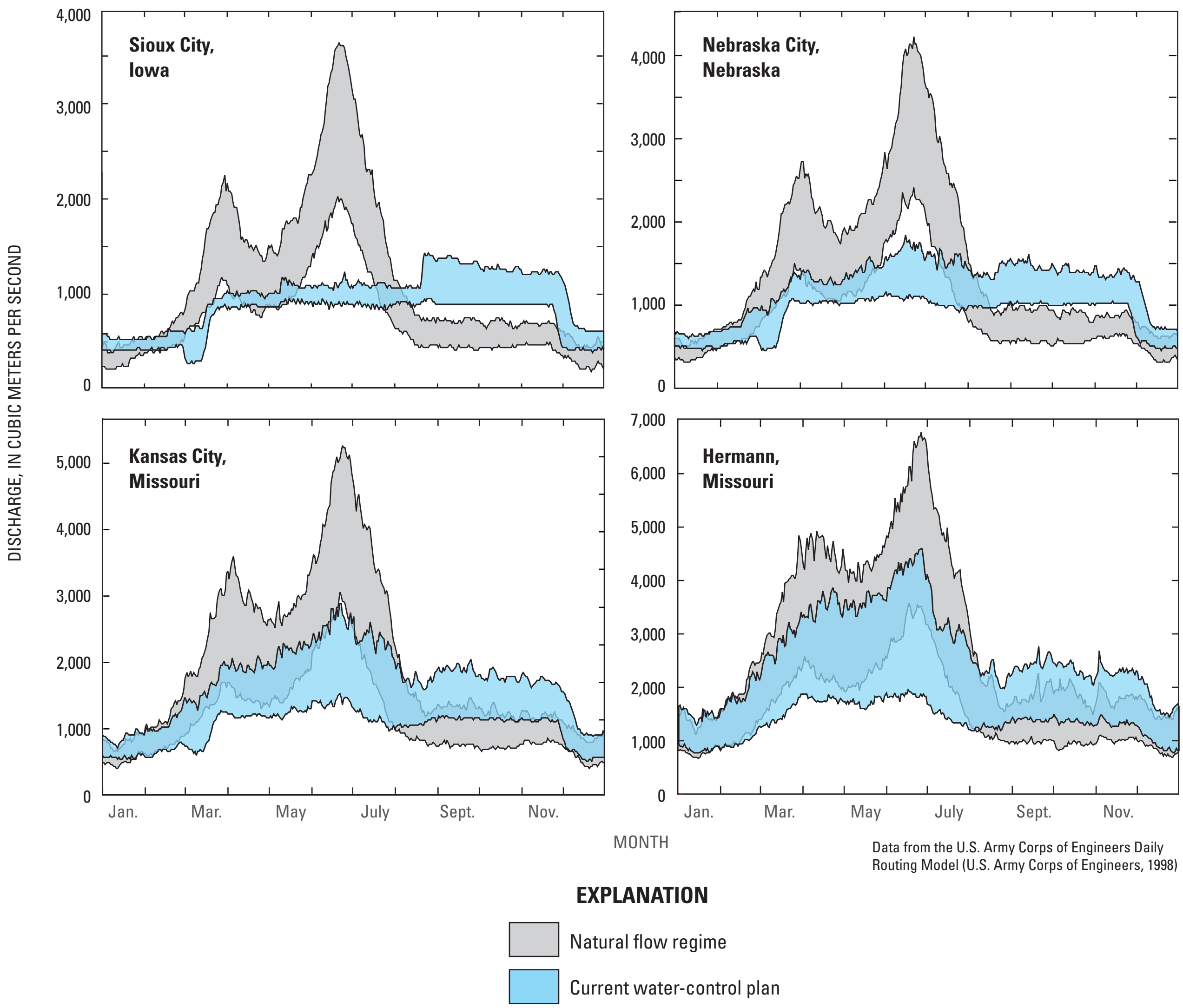


Figure 2. Duration hydrographs showing variation in 25–75 percent flow exceedances, current water control plan and natural flow regime (run of the river).

readjustments of channel morphology that take place as a result of influxes or effluxes of sediment related to seasonal patterns of sediment transport, tributary flows, and large flood events (Elliott and others, 2009) . These factors can result in background variability in the quality and quantity of habitat availability to river organisms.

Aquatic Habitat Assessment

There are three fundamental challenges in assessments of aquatic habitat availability. The first challenge is to account for variable discharge so rivers or reaches can be assessed on an equivalent-flow basis. The standard approach, adopted in this study, is to use hydraulic modeling to assess how discharge affects distributions of depths and velocities in the aquatic environment (Bovee, 1982; Bovee and others, 1998; Jacobson and Galat, 2006; Johnson and others, 2006). Hydrodynamic modeling is especially useful for understanding the spatial and temporal organization of habitat patches that may determine reproductive success at the reach scale (Coutant, 2004; Jacobson and Galat, 2006; Johnson and others, 2006). The use of two or three dimensional hydrodynamic models allows quantification of spatial attributes of habitat, including diversity (Reuter and others, 2003; Pasternack and others, 2004), gradients between habitat units (Crowder and Diplas, 2006; Johnson and others, 2006), patch dynamics (Bowen and others, 2003), and patch persistence (Bovee and others, 2004).

The second fundamental challenge is to incorporate dynamic geomorphic adjustments of the channel in hydraulic assessments of habitat. Habitat simulation studies generally have been limited in performance because they have assumed a fixed bed, and typical habitat models lack the ability to model sediment transport and channel evolution. For low-flow studies or studies on rivers with immobile beds this is a minor problem; however, for studies that consider the ecological effects of flows capable of transporting bed material, this has been a substantial limitation because the models do not account for changing channel boundary conditions (geometry and flow resistance) during individual flow events or over seasons. New understanding of sediment transport at scales relevant to habitat (Schmeeckle and Nelson, 2003) and hydrodynamic modeling code that can simulate bed evolution (McDonald and others, 2005) are contributing to progress toward relaxing the assumption of a fixed bed. For the purposes of this study, we evaluate effects of bed changes by evaluating habitat based on two bed geometries surveyed a year apart, and by reference to surveys of within-year bed changes (Elliott and others, 2009).

The third, and greatest, challenge is estimating habitat functions for aquatic biota. Fish habitat is conventionally defined as the place or a set of places where a fish, a fish population, or a fish assemblage finds suitable environmental features to survive and reproduce (Orth and White, 1999). Because Missouri River sturgeon migrate long distances during their lives (DeLonay and others, 2007), habitat assessments need to consider a broad suite of locations within the river system. A more restricted definition of physical habitat is the three-dimensional structure in which riverine organisms live; time (frequency, duration, sequence, rate of change) adds a critical fourth dimension (Gordon and others, 1992). Water depth, flow velocity, and substrate are the three main characteristics of physical habitat that are usually evaluated. Vegetation is also often measured to the extent that it operates to provide substrate or cover to aquatic organisms, or provides shading that alters water temperatures. Water temperature and turbidity typically are also strongly associated with depth and flow velocity, depending on the geomorphology and hydrology of the system. All of these factors can contribute to ecological functions of a habitat patch.

A primary uncertainty associated with habitat simulations, and a frequent source of criticisms, is the degree to which the assessed habitat availability relates to population processes, including the occurrence of limiting conditions or ecological bottlenecks (Gutreuter, 2004; Bergman and others, 2008). Data are rarely available to link population demographic processes, such as reproductive success, directly to hydraulic parameters. We address habitat requirements through the results of coordinated habitat-use studies for Missouri River sturgeon (Korschgen, 2007; Reuter and others, U.S. Geological Survey, written commun., 2009), from other literature on sturgeon habitat use (Bramblett and White, 2001; Braaten and others, 2008), and through inference from general understanding of sturgeon life histories (Wildhaber and others, 2007).

Study Areas

This study assesses habitat availability in four reaches of the LMOR: Miami, Missouri (river mile[1] 259.6–263.5), Little Sioux, Iowa (river mile 669.6–673.5), Kenslers Bend, Nebraska (river mile 743.9–748.1), and Yankton, South Dakota (river mile 804.8–808.4; fig. 1). Hydrologic and hydraulic statistics for these reaches are summarized in table 1. The reaches were selected based on two criteria: each reach (1) has patches of hard substrate with particle size ranging from gravel to boulder, thought to be preferred spawning substrate for sturgeon (Laustrup and others, 2007) or (2) was the upstream apex of movement of a female shovelnose sturgeon (*Scaphirhynchus platorynchus*) that completely spawned in 2005 (DeLonay and others, 2007), or both. Complete spawning indicates that the fish was verified to have dropped her eggs, but successful fertilization, hatch, or recruitment was not verified. For three of the four reaches, evidence is strong that spawning occurred somewhere within the reach. The Yankton reach lacked data confirming sturgeon spawning activity in 2005. However, the reach was selected for study because has the most extensive deposit of gravel-cobble substrate identified on the Lower Missouri River (Laustrup and others, 2007); spawning-like activity of sturgeon was confirmed in this reach during 2006 (Gerald Mestl, Nebraska Game and Parks Commission, oral commun., 2006). Each reach was delineated to be approximately 6 km in length to encompass two or more bend-crossover units to ensure that a representative range of habitat patches was present.

Purpose and Scope

Models of natural systems generally are classified into two categories: those used to predict and those used to increase understanding of the system (Kirkby, 1996). The focus of this report is the use of hydrodynamic models to increase understanding of what is suitable spawning and early-life-stage habitat for the Missouri River sturgeon and to address the sensitivity of habitat to flow variation. The modeling effort is exploratory and intended to elucidate relations between sturgeon and their environment. This work is a component of a suite of collaborative studies being carried out by the U.S. Geological Survey as part of the Comprehensive Sturgeon Research Program (Korschgen, 2007). The work is cooperatively funded through the U.S. Army Corps of Engineers Missouri River Recovery–Integrated Science Program and the U.S. Geological Survey.

The scope of the study was chosen to encompass a representative range of the hydrologic and geomorphic variability of the LMOR. The Miami reach is characterized by a navigation channel typical of the downstream 735 miles of the Missouri River and a flow regime that has recovered

[1]River miles are the customary units of longitudinal measurement on the Lower Missouri River and are measured upstream from St. Louis, Missouri. These river miles correspond to the channel position in 1960.

Table 1. Characteristics of modeling reaches.

[m, meters]

Reach	River miles	Nearest stream gage[1]	Length[2] (m)	Average bankfull width (m)	Reach slope (m/m)
Miami, Missouri	259.6 – 263.5	Waverly, Missouri	6,320	345	0.00015
Little Sioux, Iowa	669.6 – 673.5	Decatur, Nebraska	6,250	223	0.00021
Kenslers Bend, Nebraska	743.9 – 748.1	Sioux City, Iowa	6,450	243	0.00024
Yankton, South Dakota	804.8 – 808.4	Yankton and Gavins Point, South Dakota	5,580	436	0.00012

[1] Hydrologic record from this stream gage used to calculate flow statistics for the modeling reach.

[2] Length refers to the habitat-inventory portion of the reach, which is slightly shorter than the modeled length in order to avoid edge effects.

substantial amounts of inter- and intra-annual variability. The next upstream reach at Little Sioux has a typical navigation channel and a substantially altered flow regime. The Little Sioux and Miami reaches have been included in recent low-intensity restoration activities, including dike notching and unrooting dikes from the bank. Restoration activities in these two reaches varied minimally during the period of this study. The reach at Kenslers Bend reach has a simplified, engineered channel geometry and a highly altered flow regime. The most upstream reach at Yankton has a complex channel geometry and highly altered flow regime representative of the unchannelized segment of the LMOR river mile 753–811.

Methods

Our general approach was to use multi-dimensional hydrodynamic modeling to characterize and inventory hydraulic habitats over a range of discharges. Hydraulic models are useful in habitat studies because they can explicitly account for changing discharge conditions, and thereby allow for assessments of discharge effects or for comparisons among sites at a constant discharge or flow exceedance. Hydrodynamic models, however, generally are limited in their ability to capture dynamic conditions associated with sediment transport and geomorphic change, factors that can alter hydraulic roughness and how water is conveyed through a model reach. To assess how channel dynamics may contribute to modeling errors, we model each of the four reaches during each of two years, based on two complete, high-resolution topographic surveys. In addition, coordinated studies of geomorphic dynamics at the four reaches (Elliott and others, 2009) provide contextual understanding of how channel dynamics at bedform to reach scales may contribute to model errors and habitat dynamics.

Data Collection

Topographic data for the hydrodynamic models were obtained by combining existing elevation data sets (photogrammetrically derived digital elevation data and airborne Light Detection and Ranging [LIDAR] data) with new hydroacoustic surveys. LIDAR elevation data also were used to supplement topographic information in terrestrial locations that underwent minimal geomorphic change during 2006 and 2007. All elevation data were collected in or converted to the North American Vertical Datum 1988 (NAVD88) for consistency among datasets. Conversions used the VERTCON program (Mulcare, 2004).

Hydrographic and Topographic Surveying

Two general types of surveys were employed to develop topographic data for the hydrodynamic models. For each modeling reach in 2006 and 2007, complete compilation surveys were performed, including hydroacoustic surveys in the channel and real-time kinematic global positioning system (RTK-GPS) surveys of the banks and engineering structures. At Yankton and Kenslers Bend these data were supplemented with LIDAR data; at Little Sioux and Miami, they were supplemented with photogrammetric elevation data. Compilation surveys were completed during relatively high water periods when depths allowed efficient collection of hydroacoustic data by boat (fig. 3).

Each reach was surveyed an additional three to four times during 2006 and 2007 to develop data for model calibration and assessment (fig. 3, table 2). The calibration surveys included longitudinal profiles and approximately 30 transects that were randomly selected from the total set of cross-sectional transects. The randomly selected transects were used in a coordinated study to evaluate geomorphic changes on seasonal timeframes (Elliott and others, 2009), and they were used to provide water-surface elevation and velocity data for this study.

Hydrographic Surveying

Compilation hydrographic surveys consisted of 300 transects spaced at 20 m intervals, plus two or three long-profile surveys. Identical transect locations were used in 2006 and 2007. Transects were terminated laterally when the depth became too shallow for the boat to survey, at approximately 0.30 m. Depths were measured with a 200 kilohertz (kHz) single beam echo sounder with an 8^{o} transducer. The echo sounder was calibrated for draft and sound velocity using a bar check before each survey. Hypack® surveying software was used for navigation and to collect, process, and store sounding information. Depth readings were monitored in real time, and adjustments were made to equipment settings, such as gain and tracking gates, to minimize false bottom readings. The data were edited in the office to remove false bottom identifications, spikes, and other anomalies not addressed during surveying.

Longitudinal profiles of depths, bottom elevations, and water-surface elevations were collected in the channel using similar equipment and collection protocols. Water-surface elevation profiles along the thalweg were collected for use in model calibration

Hydrographic data were georeferenced using survey-grade 12-channel real-time kinematic global positioning systems (RTK-GPS). Local base stations were established using static GPS surveys for elevation control and were used throughout the study. A repeater radio was used in some cases to improve radio signal strength during the hydrographic surveys. The GPS data were collected at 200 millisecond (ms) intervals, resulting in positions approximately every 0.30 m along each transect at typical boat speeds of 2–4 knots (1–2 m/s) during data collection. The RTK-GPS gives x, y, and elevation positions to 0.05 m-scale accuracy. Pitch and heave were not compensated during hydroacoustic data collection; however, survey boats were not operated under conditions with significant waves. The precision of the echosounder data is 0.03 m. Bar check results indicate that, under favorable bottom conditions, the depth and elevation accuracy are approximately 0.07 m.

Discharges

A separate protocol was used for determining discharge during surveys. For each survey date, a transect or a set of closely-spaced transects, oriented perpendicular to flow, was selected in an area with relatively low turbulence and relatively consistent depth and velocity. Representative discharges were measured by collecting location information using RTK-GPS or differential global positioning system (DGPS) equipment, depth readings using a 200 kHz single-beam echo sounder, and velocity data using a Teledyne RDI Rio Grand 1200 kHz acoustic Doppler current profiler (ADCP) unit. The selected transect or set of transects was traversed four times, twice in each direction. WinRiver software (version 10.06) was used to integrate, display, and store measurement data, and to compute a total discharge for each of the four passes. An average of the four discharges was used as the representative discharge for the survey.

Terrestrial Topographic Surveying

Topographic surveys were conducted to provide accurate elevations along channel banks and engineered control structures, such as wing dikes and spur dikes, and in depths too shallow for bathymetric surveying. Pole-mounted RTK-GPS units were used to collect ground elevation points along survey transects and to define key topographic features that would not be adequately characterized by transect data or existing data sets. The combination of hydrographic survey, topographic survey, and supplementary data points produced a high-resolution topographic dataset for characterizing the modeled reaches (fig. 4*A*).

Acoustic Doppler Current Velocity Measurements

Acoustic Doppler velocity profiles were collected concurrently with hydrographic surveys. A 1200 kHz ADCP was used in conjunction with WinRiver software to collect, process, and store velocity profiles. These velocity data were processed to compute vertically-averaged velocity vectors for each vertical profile, or “ensemble.” A selection of vertically-averaged velocity vectors was used to assess modeled velocities.

Substrate and Sediment

Substrate data sets were collected with RoxAnn instrumentation (Sonavision, Aberdeen, Scotland) during compilation surveys. RoxAnn seabed classification instruments analyze the return signals from the echo sounder and generate two parameters, E1 and E2. E1 is based on the shape of the first return and E2 is based on the shape of the second return (Hamilton, 2001; Elliott and others, 2009). Statistical processing of RoxAnn data generally followed procedures established by other seabed classification studies (Cholwek and others, 2000; Brown and others, 2005), although methods had to be optimized for the turbid and high-velocity conditions of the LMOR. Specific methods are described by Reuter (Joanna Reuter, U.S. Geological Survey, written commun., 2008) Substrate classes were verified through qualitative sediment sampling, side-scan sonar surveys of selected areas, and repeat substrate mapping.

The substrate classification verified that the bed of the Missouri River is dominated by sand with localized areas of sandy mud and mud in slack-water areas associated with wing dikes and tributary mouths. Coarse substrate exists in patches in the Yankton reach and is associated with wing dikes and revetments in all reaches.

Hydrodynamic Modeling

We selected the Multi-Dimensional Surface Water Modeling System (MD_SWMS) as the hydrodynamic model for this study. MD_SWMS (McDonald and others, 2005) is a modular, public-domain two-dimensional hydraulic modeling code and graphic user interface (GUI) developed by the U.S. Geological Survey (McDonald and others, 2005). FaSTMECH is the computational model used within the MD_SWMS modeling system (Nelson and others, 2003). FaSTMECH is an implementation of the Reynolds equations of fluid motion using an eddy viscosity turbulence closure, depth averaging, and an assumption of hydrostatic pressure distribution

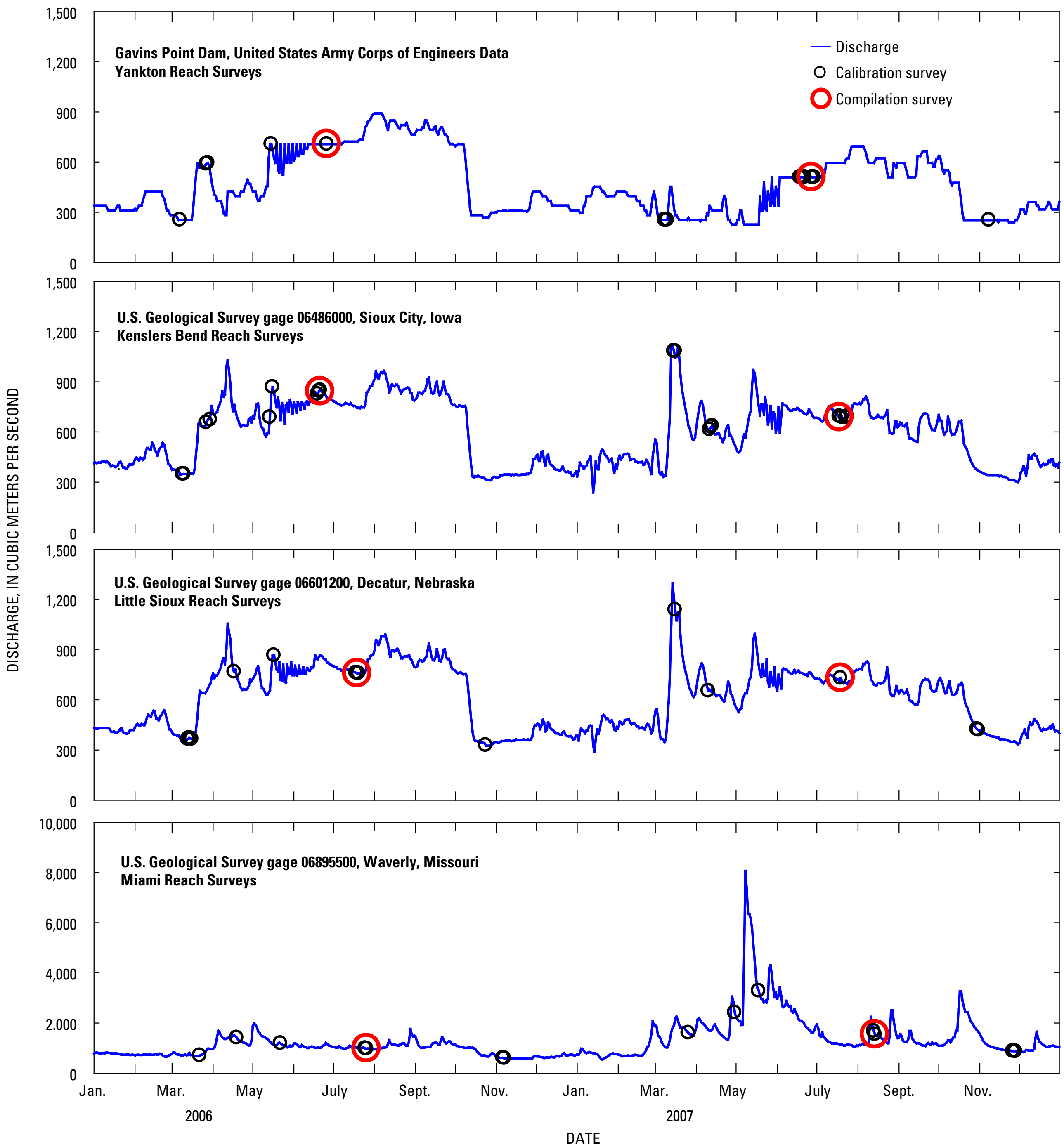
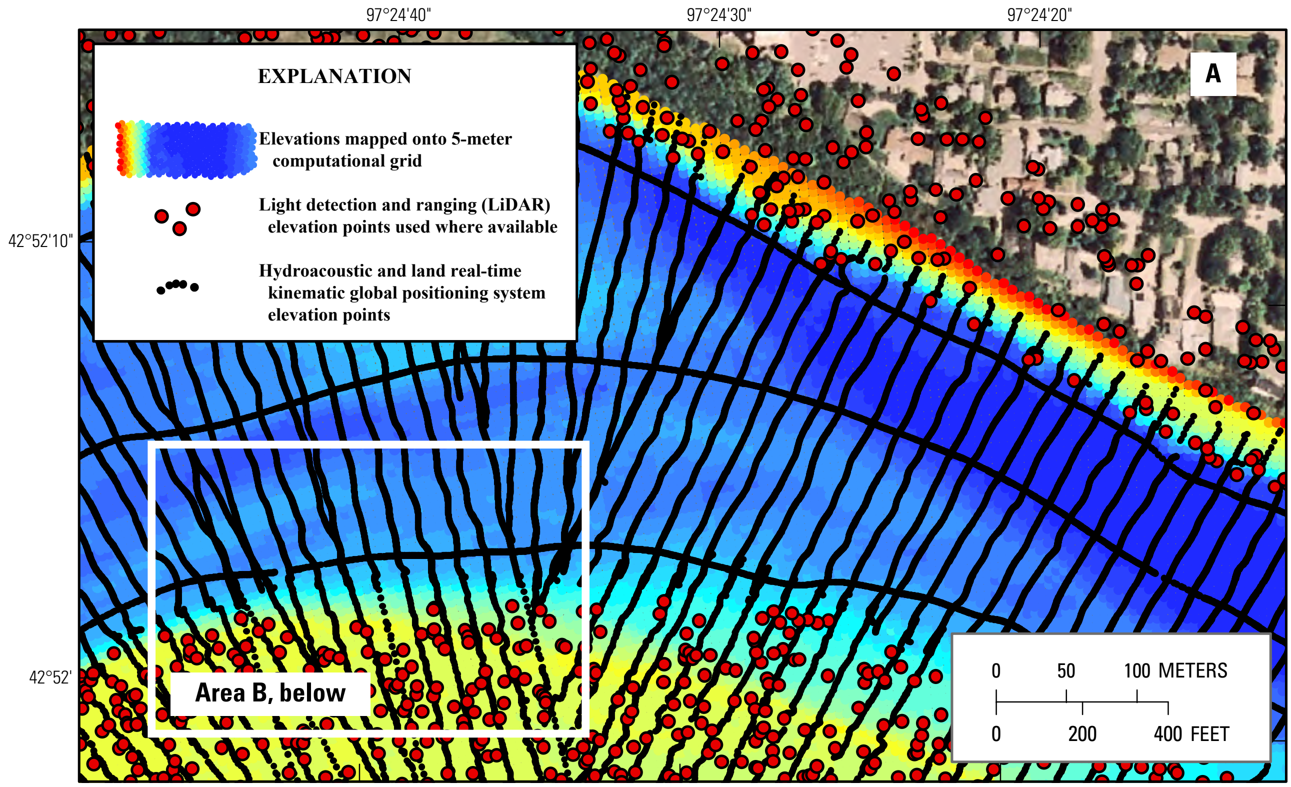


Figure 3. Discharge hydrographs for four hydrodynamic modeling reaches showing dates of compilation and calibration surveys.



Base from U.S. Department of Agriculture National Agriculture Imagery Program, digital data, 2006
Universal Transverse Mercator projection
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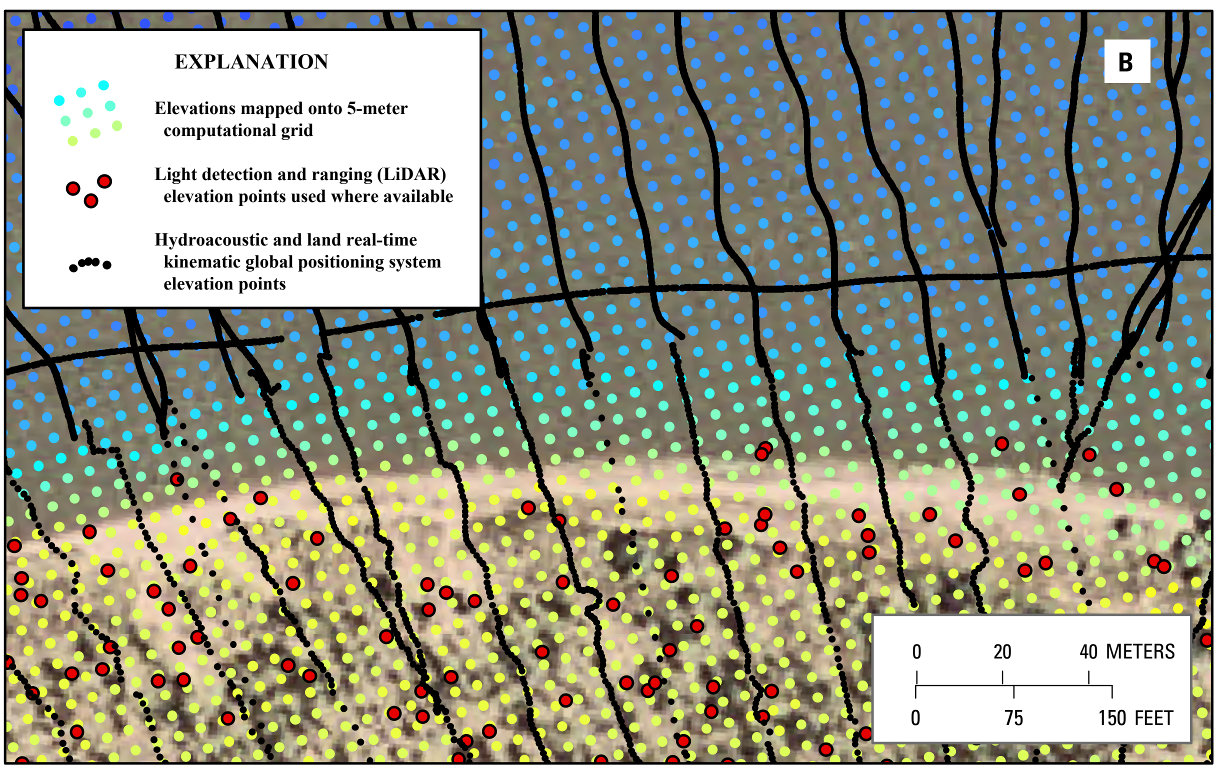

Base from U.S. Department of Agriculture National Agriculture Imagery Program, digital data, 2006
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Figure 4. Examples from Yankton, South Dakota modeling reach showing types and density of data: *(A)* Elevation points from three sources, *(B)* Close up showing elevation points and nodes of 5-m computational grid nodes.

in open-channel flow. The last assumption is key because it neglects vertical accelerations that may occur where there are rapid changes in bed elevation, such as those associated with wing dikes.

We implemented FaSTMECH as steady flow simulations on a streamwise computational coordinate system with 5-m node spacing (fig. 4*B*). Inputs to the model were reach topography, upstream discharge, downstream water-surface elevation, and estimates of drag coefficient and lateral eddy viscosity.

Model Development

Eight computational hydrodynamic model geometries were constructed using the MD_SWMS modeling system. For each of the four sites, one model was generated using discharge and elevation data collected in 2006, and a second model was created using discharge and elevation data collected in 2007. Parts of the channel and bank that did not experience erosion or deposition during 2006–08 were used in both models at each site. Each of the eight models was calibrated for several flow conditions: four flow conditions for 2006 models and three or four flow conditions for 2007 models.

Modeled Flows

The discharges observed during the hydrographic surveys were the basis for calibration conditions. At each site, hydrographic surveys were completed for four flow conditions in 2006 and three flow conditions in 2007. Each of these flow conditions was used in model calibration.

To capture habitat conditions for discharges likely to be encountered during spring pulsed flows, our objective was to simulate flows over a nominal range of 25–90 percent flow exceedance. Because of a lack of available flows and scheduling, we were unable to measure hydraulic conditions over the intended range of discharges at Kenslers Bend and Yankton. Calibration data were collected for 7–98 percent flow exceedance at Miami, 15–93 percent flow exceedance at Little Sioux, 64–99 percent flow exceedance at Kenslers Bend, and 56–94 percent flow exceedance at Yankton (table 2).

Water Stage

Water-surface elevations used in the calibrations were determined from hydrographic survey data. For each model and flow condition, an observed water-surface elevation nearest the downstream end of the modeling grid was used as the downstream water-surface elevation. Linear or power-law functions were fit to the values of water-surface elevation and discharge, and the statistical models were used to estimate water-surface elevations for nonmeasured conditions.

Terrain Models

We developed terrain models for each of the eight compilation surveys by computing a triangular irregular network for the hydrographic, terrestrial, and supporting elevation data. The model extended from the thalweg to the top of the bank for a corridor nominally 20 m outside the bank. The modeled corridor included some embayments where small tributaries entered the Missouri River (figs. 5–8).

Sediment Classification and Hydraulic Roughness

Hydraulic roughness in MD_SWMS is parameterized by the drag coefficient, a dimensionless number that integrates frictional resistance from the bed, including roughness arising from bed particles and bedforms. Because of uncertainties in how various factors integrate to produce frictional resistance, the standard practice in MD_SWMS modeling is to calibrate the model to measured water-surface elevations by varying the drag coefficient. Knowledge of bed sediment can provide useful guidance to setting and varying the drag coefficient but is not necessary for model calibration. Bed-sediment classification data from the modeling reaches were used to confirm general sediment types but were not used to set drag coefficient values.

Based on general uniformity of the sediment classes in the modeling reaches, we also elected to calibrate the models to a single drag coefficient value for each reach and discharge, rather than varying the coefficient spatially within the reach. Use of a spatially varied drag coefficient would add unnecessary complexity to the calibration process and was not supported by the sediment classification data (Reuter and others, U.S. Geological Survey, written commun., 2008), success in modeling velocity distributions (see section on model assessment following), or sensitivity analysis (see section on sensitivity analysis following).

Frictional resistance can arise from form roughness associated with sedimentary bedforms. Dynamic adjustments of bedforms to depth, velocity, and water temperature impose substantive challenges to calibrating hydrodynamic models in sandbed rivers. Typical dimensions of bedforms measured in long profiles (table 3, from Elliott and others, 2009) indicate that dune-size bedforms are prominent in these reaches. Because of the dynamic variation of these bedforms during the period of study (Elliott and others, 2009) we did not attempt to model bedform contributions to flow resistance explicitly. Bedform roughness is implicit in calibrated drag coefficients and dynamic changes in bedform roughness probably contribute substantially to overall modeling error. Drag coefficients for simulation runs were interpolated and (to a limited extent) extrapolated from the relations developed between drag coefficient and discharge for the calibration runs.

Computational Grid

Curvilinear, orthogonal computational grids were developed for each of the eight models (fig. 4*B*). Each grid was

Table 2. Discharges and hydraulic parameter values for calibration and solution runs for four hydrodynamic modeling reaches.

[m^3/s, cubic meters per second; m, meters; m^2/s, square meters per second; na, not applicable]

Reach	Run	Date	Discharge (m^3/s)	Approximate flow exceedance (percent)	Downstream stage (m)	Drag coefficient (dimensionless)	Lateral eddy viscosity coefficient (m^2/s)	Water surface prediction, root mean square error (m)
Miami, Missouri - 2006	Calibration	11/6/2006	588	98	189.46	0.0041	0.026	0.039
	Calibration	3/23/2006	633	96	189.68	0.0054	0.027	0.044
	Calibration	7/25/2006	944	83	190.60	0.0046	0.036	0.029
	Calibration	5/22/2006	1,166	68	191.10	0.0047	0.042	0.029
	Calibration	4/19/2006	1,376	53	191.55	0.0044	0.048	0.036
	Calibration	4/30/2007	2,472	14	193.36	0.0035	0.079	0.029
	Calibration	5/18/2007	3,136	7	194.92	0.0040	0.098	0.026
	Solution	2006	550	98	189.27	0.0048	0.025	na
	Solution	2006	600	97	189.52	0.0048	0.026	na
	Solution	2006	650	95	189.73	0.0047	0.027	na
	Solution	2006	700	93	189.88	0.0047	0.029	na
	Solution	2006	750	91	190.03	0.0047	0.030	na
	Solution	2006	800	89	190.17	0.0047	0.032	na
	Solution	2006	850	86	190.32	0.0047	0.033	na
	Solution	2006	900	85	190.47	0.0046	0.035	na
	Solution	2006	950	83	190.61	0.0046	0.036	na
	Solution	2006	1,000	80	190.73	0.0046	0.038	na
	Solution	2006	1,050	77	190.84	0.0046	0.039	na
	Solution	2006	1,100	74	190.95	0.0046	0.040	na
	Solution	2006	1,150	70	191.06	0.0045	0.042	na
	Solution	2006	1,200	65	191.18	0.0045	0.043	na
	Solution	2006	1,250	61	191.28	0.0045	0.044	na
	Solution	2006	1,300	58	191.39	0.0045	0.046	na
	Solution	2006	1,350	55	191.49	0.0045	0.047	na
	Solution	2006	1,400	52	191.59	0.0044	0.049	na
	Solution	2006	1,450	49	191.67	0.0044	0.050	na
	Solution	2006	1,500	46	191.75	0.0044	0.051	na
	Solution	2006	1,550	44	191.84	0.0044	0.053	na
	Solution	2006	1,600	41	191.92	0.0044	0.054	na
	Solution	2006	1,650	39	192.00	0.0043	0.056	na
	Solution	2006	1,700	36	192.08	0.0043	0.057	na

Table 2. Discharges and hydraulic parameter values for calibration and solution runs for four hydrodynamic modeling reaches.—Continued

[m^3/s, cubic meters per second; m, meters; m^2/s, square meters per second; na, not applicable]

Reach	Run	Date	Discharge (m^3/s)	Approximate flow exceedance (percent)	Downstream stage (m)	Drag coefficient (dimensionless)	Lateral eddy viscosity coefficient (m^2/s)	Water surface prediction, root mean square error (m)
Miami, Missouri - 2006	Solution	2006	1,750	34	192.17	0.0043	0.059	na
	Solution	2006	1,800	32	192.25	0.0043	0.060	na
	Solution	2006	1,850	30	192.33	0.0043	0.061	na
	Solution	2006	1,900	28	192.41	0.0042	0.063	na
	Solution	2006	1,950	27	192.50	0.0042	0.064	na
	Solution	2006	2,000	25	192.58	0.0042	0.066	na
	Solution	2006	2,050	23	192.66	0.0042	0.067	na
	Solution	2006	2,100	22	192.74	0.0042	0.068	na
	Solution	2006	2,150	21	192.83	0.0041	0.070	na
	Solution	2006	2,200	19	192.91	0.0041	0.071	na
	Solution	2006	2,250	18	192.99	0.0041	0.073	na
	Solution	2006	2,300	17	193.08	0.0041	0.074	na
	Solution	2006	2,350	16	193.16	0.0041	0.076	na
	Solution	2006	2,400	15	193.24	0.0040	0.077	na
	Solution	2006	2,450	15	193.32	0.0040	0.078	na
	Solution	2006	2,500	14	193.41	0.0040	0.080	na
	Solution	2006	2,550	13	193.54	0.0040	0.081	na
	Solution	2006	2,600	12	193.66	0.0040	0.083	na
	Solution	2006	2,650	12	193.78	0.0039	0.084	na
	Solution	2006	2,700	11	193.89	0.0039	0.086	na
	Solution	2006	2,750	11	194.01	0.0039	0.087	na
	Solution	2006	2,800	10	194.13	0.0039	0.088	na
	Solution	2006	2,850	10	194.25	0.0039	0.090	na
	Solution	2006	2,900	9	194.36	0.0038	0.091	na
	Solution	2006	2,950	9	194.48	0.0038	0.093	na
	Solution	2006	3,000	8	194.60	0.0038	0.094	na
	Solution	2006	3,050	8	194.72	0.0038	0.096	na
	Solution	2006	3,100	8	194.83	0.0038	0.097	na
	Solution	2006	3,150	7	194.95	0.0037	0.098	na

Table 2. Discharges and hydraulic parameter values for calibration and solution runs for four hydrodynamic modeling reaches.—Continued

[m³/s, cubic meters per second; m, meters; m²/s, square meters per second; na, not applicable]

Reach	Run	Date	Discharge (m^3/s)	Approximate flow exceedance (percent)	Downstream stage (m)	Drag coefficient (dimensionless)	Lateral eddy viscosity coefficient (m^2/s)	Water surface prediction, root mean square error (m)
Miami, Missouri - 2007	Calibration	11/27/2007	743	91	190.18	0.0052	0.030	0.0362
	Calibration	8/15/2007	1,384	53	191.70	0.0049	0.048	0.0388
	Calibration	3/26/2007	1,473	47	191.95	0.0053	0.051	0.0194
	Calibration	4/30/2007	2,472	14	193.36	0.0035	0.079	0.0281
	Calibration	5/18/2007	3,136	7	194.92	0.0041	0.098	0.0073
	Solution	2007	550	98	189.72	0.0054	0.025	na
	Solution	2007	600	97	189.84	0.0054	0.026	na
	Solution	2007	650	95	189.96	0.0053	0.027	na
	Solution	2007	700	93	190.08	0.0053	0.029	na
	Solution	2007	750	91	190.20	0.0053	0.030	na
	Solution	2007	800	89	190.32	0.0052	0.032	na
	Solution	2007	850	86	190.43	0.0052	0.033	na
	Solution	2007	900	85	190.55	0.0052	0.034	na
	Solution	2007	950	83	190.67	0.0051	0.036	na
	Solution	2007	1,000	80	190.79	0.0051	0.037	na
	Solution	2007	1,050	77	190.91	0.0051	0.039	na
	Solution	2007	1,100	74	191.03	0.0050	0.040	na
	Solution	2007	1,150	70	191.14	0.0050	0.041	na
	Solution	2007	1,200	65	191.26	0.0050	0.043	na
	Solution	2007	1,250	61	191.38	0.0049	0.044	na
	Solution	2007	1,300	58	191.50	0.0049	0.046	na
	Solution	2007	1,350	55	191.62	0.0049	0.047	na
	Solution	2007	1,400	52	191.74	0.0048	0.049	na
	Solution	2007	1,450	49	191.88	0.0048	0.050	na
	Solution	2007	1,500	46	191.99	0.0048	0.052	na
	Solution	2007	1,550	44	192.06	0.0047	0.053	na
	Solution	2007	1,600	41	192.13	0.0047	0.055	na
	Solution	2007	1,650	39	192.20	0.0046	0.056	na
	Solution	2007	1,700	36	192.27	0.0046	0.057	na
	Solution	2007	1,750	34	192.34	0.0046	0.059	na

Table 2. Discharges and hydraulic parameter values for calibration and solution runs for four hydrodynamic modeling reaches.—Continued

[m^3/s, cubic meters per second; m, meters; m^2/s, square meters per second; na, not applicable]

Reach	Run	Date	Discharge (m^3/s)	Approximate flow exceedance (percent)	Downstream stage (m)	Drag coefficient (dimensionless)	Lateral eddy viscosity coefficient (m^2/s)	Water surface prediction, root mean square error (m)
Miami, Missouri - 2007	Solution	2007	1,800	32	192.41	0.0045	0.060	na
	Solution	2007	1,850	30	192.48	0.0045	0.062	na
	Solution	2007	1,900	28	192.55	0.0045	0.063	na
	Solution	2007	1,950	27	192.62	0.0044	0.064	na
	Solution	2007	2,000	25	192.69	0.0044	0.066	na
	Solution	2007	2,050	23	192.76	0.0044	0.067	na
	Solution	2007	2,100	22	192.83	0.0043	0.069	na
	Solution	2007	2,150	21	192.91	0.0043	0.070	na
	Solution	2007	2,200	19	192.98	0.0043	0.071	na
	Solution	2007	2,250	18	193.05	0.0042	0.073	na
	Solution	2007	2,300	17	193.12	0.0042	0.074	na
	Solution	2007	2,350	16	193.19	0.0042	0.076	na
	Solution	2007	2,400	15	193.26	0.0041	0.077	na
	Solution	2007	2,450	15	193.33	0.0041	0.078	na
	Solution	2007	2,500	14	193.40	0.0041	0.080	na
	Solution	2007	2,550	13	193.54	0.0040	0.081	na
	Solution	2007	2,600	12	193.66	0.0040	0.083	na
	Solution	2007	2,650	12	193.78	0.0039	0.084	na
	Solution	2007	2,700	11	193.89	0.0039	0.086	na
	Solution	2007	2,750	11	194.01	0.0039	0.087	na
	Solution	2007	2,800	10	194.13	0.0038	0.088	na
	Solution	2007	2,850	10	194.25	0.0038	0.090	na
	Solution	2007	2,900	9	194.36	0.0038	0.091	na
	Solution	2007	2,950	9	194.48	0.0037	0.093	na
	Solution	2007	3,000	8	194.60	0.0037	0.094	na
	Solution	2007	3,050	8	194.72	0.0037	0.096	na
	Solution	2007	3,100	8	194.83	0.0036	0.097	na
	Solution	2007	3,150	7	194.95	0.0036	0.098	na

Table 2. Discharges and hydraulic parameter values for calibration and solution runs for four hydrodynamic modeling reaches.—Continued

[m³/s, cubic meters per second; m, meters; m²/s, square meters per second; na, not applicable]

Reach	Run	Date	Discharge (m^3/s)	Approximate flow exceedance (percent)	Downstream stage (m)	Drag coefficient (dimensionless)	Lateral eddy viscosity coefficient (m^2/s)	Water surface prediction, root mean square error (m)
Little Sioux, Iowa - 2006	Calibration	10/24/2006	350	93	306.28	0.0048	0.023	0.0479
	Calibration	3/14/2006	383	90	306.39	0.0055	0.022	0.0575
	Calibration	7/18/2006	768	55	307.81	0.0067	0.040	0.0476
	Calibration	5/16/2006	884	37	308.51	0.0063	0.044	0.0299
	Calibration	3/16/2007	1,150	15	309.42	0.0060	0.056	0.0368
	Solution	2006	250	98	305.95	0.0052	0.017	na
	Solution	2006	300	97	306.12	0.0053	0.020	na
	Solution	2006	350	93	306.28	0.0053	0.022	na
	Solution	2006	400	88	306.45	0.0054	0.024	na
	Solution	2006	450	80	306.64	0.0055	0.026	na
	Solution	2006	500	76	306.82	0.0056	0.028	na
	Solution	2006	550	74	307.01	0.0056	0.030	na
	Solution	2006	600	71	307.19	0.0057	0.032	na
	Solution	2006	650	69	307.37	0.0058	0.034	na
	Solution	2006	700	67	307.56	0.0059	0.036	na
	Solution	2006	750	60	307.74	0.0059	0.038	na
	Solution	2006	800	51	308.00	0.0060	0.041	na
	Solution	2006	850	42	308.31	0.0061	0.043	na
	Solution	2006	900	34	308.57	0.0062	0.045	na
	Solution	2006	950	25	308.74	0.0062	0.047	na
	Solution	2006	1,000	21	308.91	0.0063	0.049	na
	Solution	2006	1,050	18	309.08	0.0064	0.051	na
	Solution	2006	1,100	16	309.25	0.0065	0.053	na
	Solution	2006	1,150	15	309.42	0.0065	0.055	na
Little Sioux, Iowa - 2007	Calibration	10/31/2007	435	83	306.96	0.0072	0.025	0.0288
	Calibration	4/10/2007	673	68	307.82	0.0080	0.035	0.0671
	Calibration	7/20/2007	700	67	307.80	0.0078	0.037	0.0594
	Calibration	3/16/2007	1,150	15	309.42	0.0071	0.056	0.0352
	Solution	2007	250	98	306.29	0.0078	0.017	na

Table 2. Discharges and hydraulic parameter values for calibration and solution runs for four hydrodynamic modeling reaches.—Continued

[m^3/s, cubic meters per second; m, meters; m^2/s, square meters per second; na, not applicable]

Reach	Run	Date	Discharge (m^3/s)	Approximate flow exceedance (percent)	Downstream stage (m)	Drag coefficient (dimensionless)	Lateral eddy viscosity coefficient (m^2/s)	Water surface prediction, root mean square error (m)
Little Sioux, Iowa - 2007	Solution	2007	300	97	306.47	0.0078	0.019	na
	Solution	2007	350	93	306.65	0.0077	0.021	na
	Solution	2007	400	88	306.83	0.0077	0.024	na
	Solution	2007	450	80	307.01	0.0077	0.026	na
	Solution	2007	500	76	307.19	0.0077	0.028	na
	Solution	2007	550	74	307.38	0.0076	0.030	na
	Solution	2007	600	71	307.56	0.0076	0.032	na
	Solution	2007	650	69	307.74	0.0076	0.034	na
	Solution	2007	700	67	307.80	0.0076	0.037	na
	Solution	2007	750	60	307.98	0.0075	0.039	na
	Solution	2007	800	51	308.16	0.0075	0.041	na
	Solution	2007	850	42	308.34	0.0075	0.043	na
	Solution	2007	900	34	308.52	0.0075	0.045	na
	Solution	2007	950	25	308.70	0.0074	0.048	na
	Solution	2007	1,000	21	308.88	0.0074	0.050	na
	Solution	2007	1,050	18	309.06	0.0074	0.052	na
	Solution	2007	1,100	16	309.24	0.0074	0.054	na
	Solution	2007	1,150	15	309.42	0.0073	0.056	na
Kenslers Bend, Nebraska - 2006	Calibration	3/10/2006	295	99	320.15	0.0042	0.017	0.072
	Calibration	3/30/2006	592	76	330.35	0.0072	0.028	0.031
	Calibration	5/16/2006	754	64	330.65	0.0062	0.034	0.045
	Solution	2006	250	100	328.91	0.0040	0.016	na
	Solution	2006	300	98	329.22	0.0042	0.017	na
	Solution	2006	350	96	329.49	0.0048	0.019	na
	Solution	2006	400	92	329.71	0.0053	0.021	na
	Solution	2006	450	88	329.92	0.0059	0.023	na
	Solution	2006	500	84	330.10	0.0064	0.025	na
	Solution	2006	550	79	330.26	0.0070	0.026	na
	Solution	2006	600	76	330.41	0.0073	0.028	na
	Solution	2006	650	74	330.55	0.0071	0.030	na
	Solution	2006	700	69	330.67	0.0069	0.032	na

Table 2. Discharges and hydraulic parameter values for calibration and solution runs for four hydrodynamic modeling reaches.—Continued

[m^3/s, cubic meters per second; m, meters; m^2/s, square meters per second; na, not applicable]

Reach	Run	Date	Discharge (m^3/s)	Approximate flow exceedance (percent)	Downstream stage (m)	Drag coefficient (dimensionless)	Lateral eddy viscosity coefficient (m^2/s)	Water surface prediction, root mean square error (m)
Kenslers Bend, Nebraska - 2006	Solution	2006	750	64	330.79	0.0067	0.034	na
	Solution	2006	800	59	330.90	0.0065	0.035	na
	Solution	2006	850	54	331.01	0.0063	0.037	na
	Solution	2006	900	43	331.11	0.0061	0.039	na
	Solution	2006	950	34	331.20	0.0060	0.041	na
Kenslers Bend, Nebraska - 2007	Calibration	4/12/2007	469	86	329.90	0.0064	0.023	0.0540
	Calibration	3/15/2007	624	75	330.39	0.0060	0.029	0.0360
	Calibration	7/25/2007	629	75	330.57	0.0070	0.029	0.0322
	Solution	2007	250	100	328.91	0.0040	0.016	na
	Solution	2007	300	98	329.22	0.0042	0.017	na
	Solution	2007	350	96	329.49	0.0048	0.019	na
	Solution	2007	400	92	329.71	0.0053	0.021	na
	Solution	2007	450	88	329.92	0.0059	0.023	na
	Solution	2007	500	84	330.10	0.0064	0.025	na
	Solution	2007	550	79	330.26	0.0070	0.026	na
	Solution	2007	600	76	330.41	0.0073	0.028	na
	Solution	2007	650	74	330.55	0.0071	0.030	na
	Solution	2007	700	69	330.67	0.0069	0.032	na
	Solution	2007	750	64	330.79	0.0067	0.034	na
	Solution	2007	800	59	330.90	0.0065	0.035	na
	Solution	2007	850	54	331.01	0.0063	0.037	na
	Solution	2007	900	43	331.11	0.0061	0.039	na
	Solution	2007	950	34	331.20	0.0060	0.041	na
Yankton, South Dakota - 2006	Calibration	3/7/2006	292	90	350.46	0.0045	0.012	0.029
	Calibration	3/30/2006	577	66	351.07	0.0041	0.020	0.023
	Calibration	5/15/2006	680	56	351.19	0.0047	0.023	0.026
	Solution	2006	200	99	350.27	0.0046	0.010	na
	Solution	2006	250	94	350.37	0.0046	0.011	na
	Solution	2006	300	90	350.46	0.0045	0.013	na
	Solution	2006	350	87	350.56	0.0044	0.014	na

Table 2. Discharges and hydraulic parameter values for calibration and solution runs for four hydrodynamic modeling reaches.—Continued

[m³/s, cubic meters per second; m, meters; m²/s, square meters per second; na, not applicable]

Reach	Run	Date	Discharge (m³/s)	Approximate flow exceedance (percent)	Downstream stage (m)	Drag coefficient (dimensionless)	Lateral eddy viscosity coefficient (m²/s)	Water surface prediction, root mean square error (m)
Yankton, South Dakota - 2006	Solution	2006	400	83	350.65	0.0043	0.016	na
	Solution	2006	450	79	350.75	0.0043	0.017	na
	Solution	2006	500	73	350.84	0.0042	0.018	na
	Solution	2006	550	69	350.94	0.0041	0.020	na
	Solution	2006	600	64	351.03	0.0042	0.021	na
	Solution	2006	650	61	351.13	0.0044	0.023	na
	Solution	2006	700	54	351.22	0.0047	0.024	na
	Solution	2006	750	48	351.32	0.0047	0.025	na
	Solution	2006	800	42	351.41	0.0047	0.027	na
	Solution	2006	850	32	351.51	0.0047	0.028	na
	Solution	2006	900	27	351.60	0.0047	0.030	na
	Solution	2009	950	20	351.70	0.0047	0.031	na
Yankton, South Dakota - 2007	Calibration	3/9/2007	255	94	350.40	0.0055	0.011	0.029
	Calibration	3/13/2007	459	77	350.72	0.0048	0.017	0.022
	Calibration	6/28/2007	497	73	350.84	0.0042	0.018	0.023
	Solution	2007	200	99	350.27	0.0057	0.010	na
	Solution	2007	250	94	350.37	0.0055	0.011	na
	Solution	2007	300	90	350.46	0.0054	0.013	na
	Solution	2007	350	87	350.56	0.0052	0.014	na
	Solution	2007	400	83	350.65	0.0050	0.016	na
	Solution	2007	450	79	350.75	0.0048	0.017	na
	Solution	2007	500	73	350.84	0.0042	0.018	na
	Solution	2007	550	69	350.94	0.0043	0.020	na
	Solution	2007	600	64	351.03	0.0043	0.021	na
	Solution	2007	650	61	351.13	0.0044	0.023	na
	Solution	2007	700	54	351.22	0.0045	0.024	na
	Solution	2007	750	48	351.32	0.0045	0.025	na
	Solution	2007	800	42	351.41	0.0046	0.027	na
	Solution	2007	850	32	351.51	0.0047	0.028	na
	Solution	2007	900	27	351.60	0.0047	0.030	na
	Solution	2007	950	20	351.70	0.0048	0.031	na

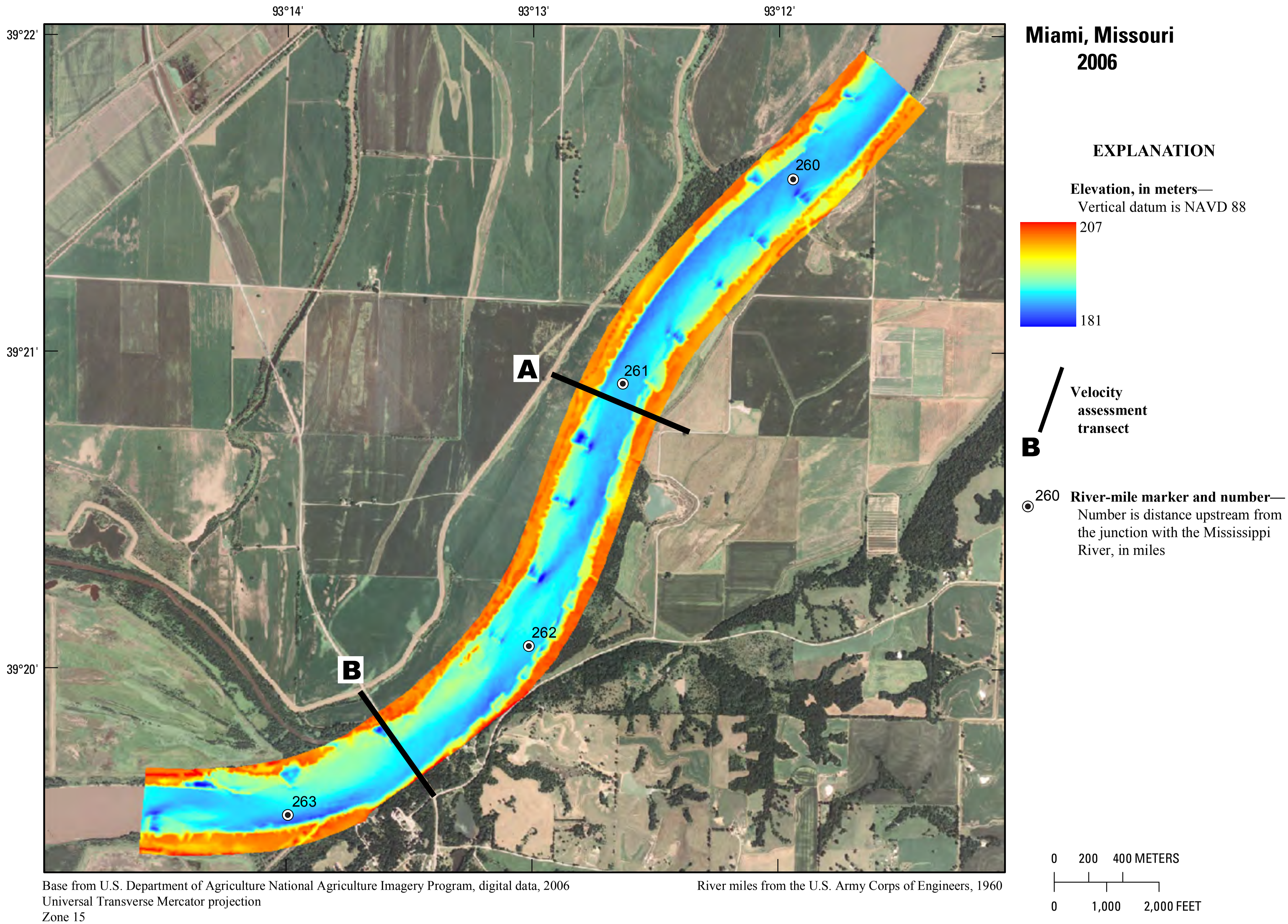
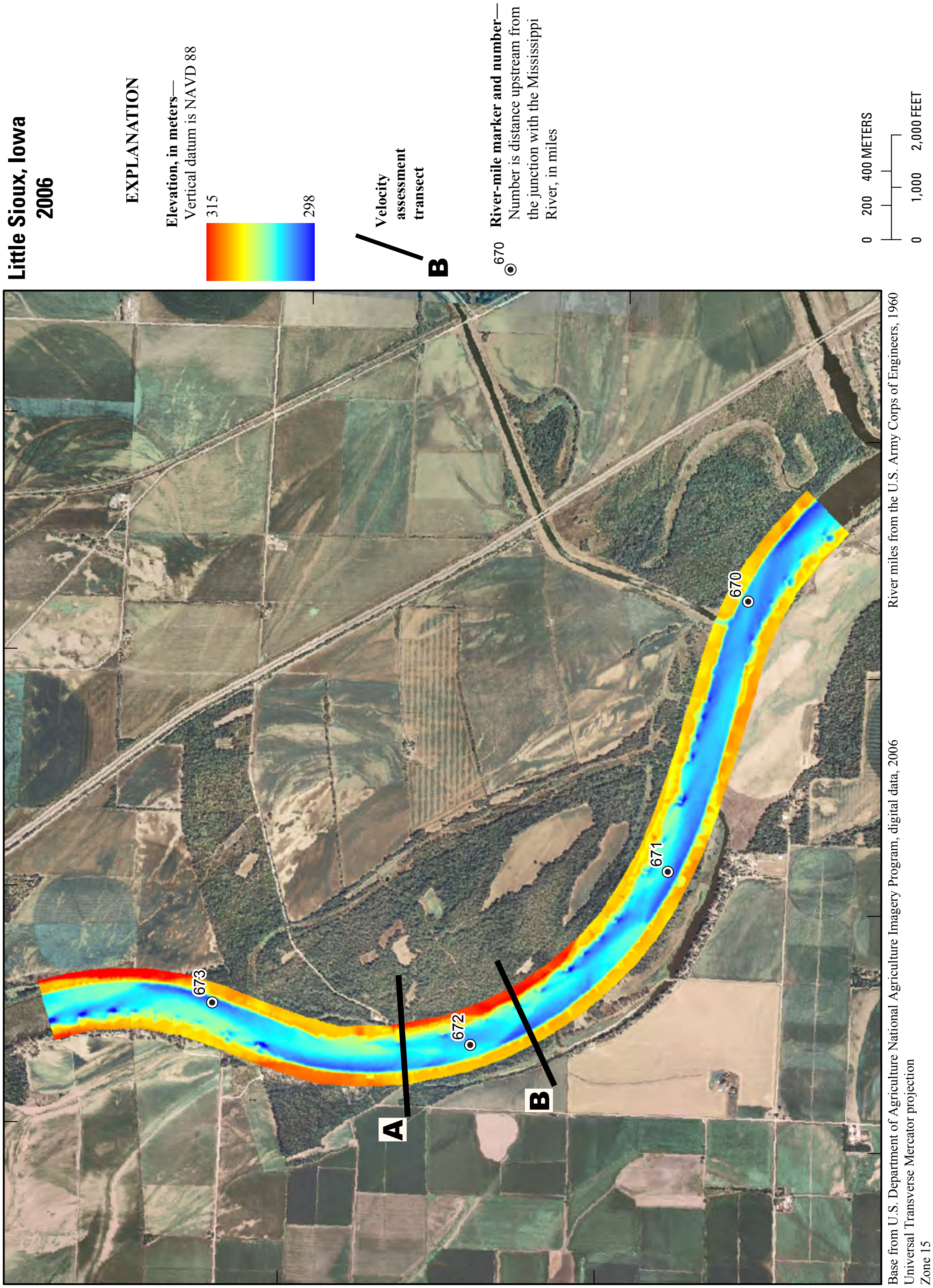


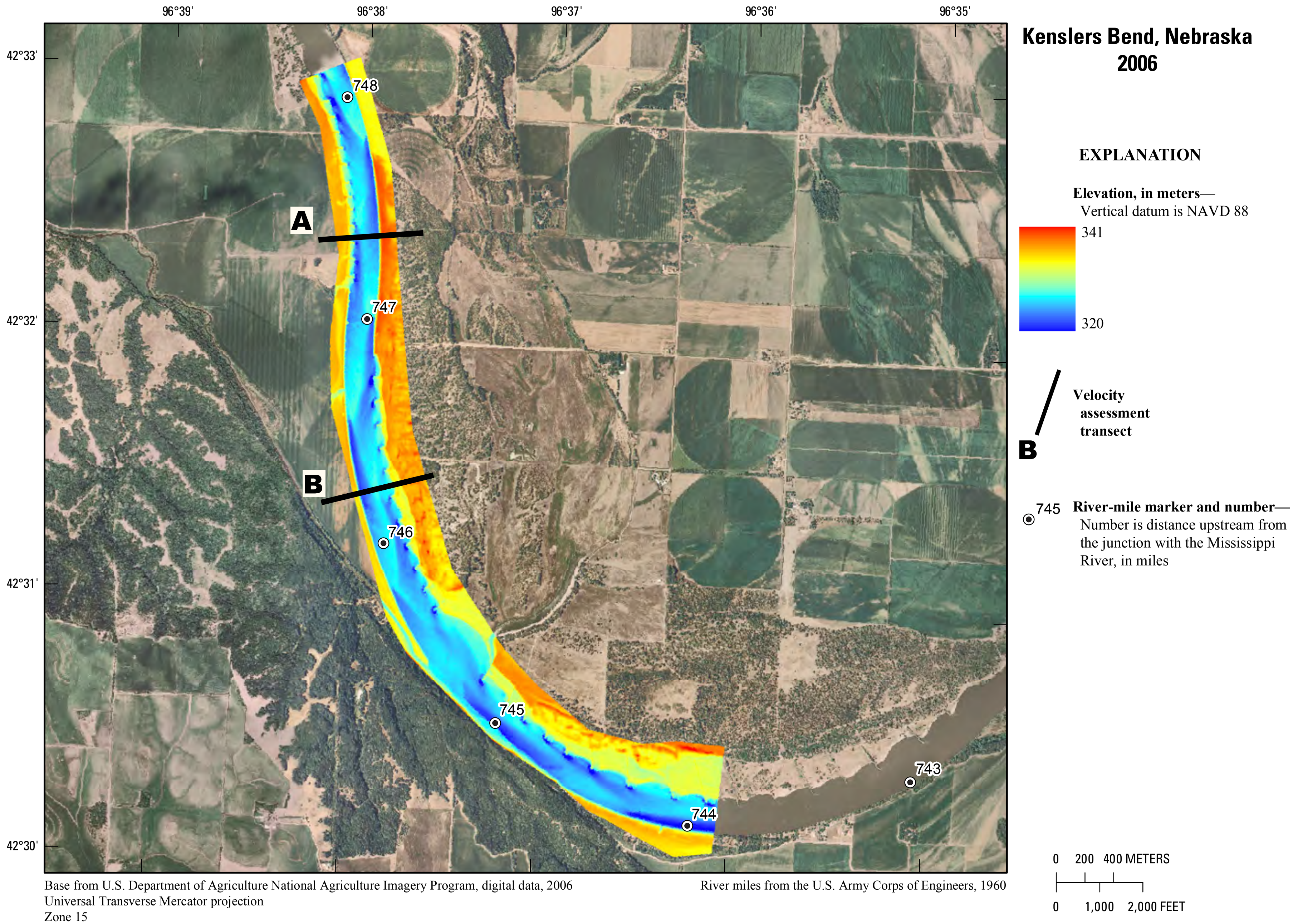
Figure 5. Elevation of the hydrodynamic modeling reach at Miami, Missouri, 2006 bathymetry.



Base from U.S. Department of Agriculture National Agriculture Imagery Program, digital data, 2006
Universal Transverse Mercator projection
Zone 15

River miles from the U.S. Army Corps of Engineers, 1960

Figure 6. Elevation of the hydrodynamic modeling reach at Little Sioux, Iowa, 2006 bathymetry.



Base from U.S. Department of Agriculture National Agriculture Imagery Program, digital data, 2006
Universal Transverse Mercator projection
Zone 15

River miles from the U.S. Army Corps of Engineers, 1960

Figure 7. Elevation of the hydrodynamic modeling reach at Kenslers Bend, Nebraska. 2006 bathymetry.

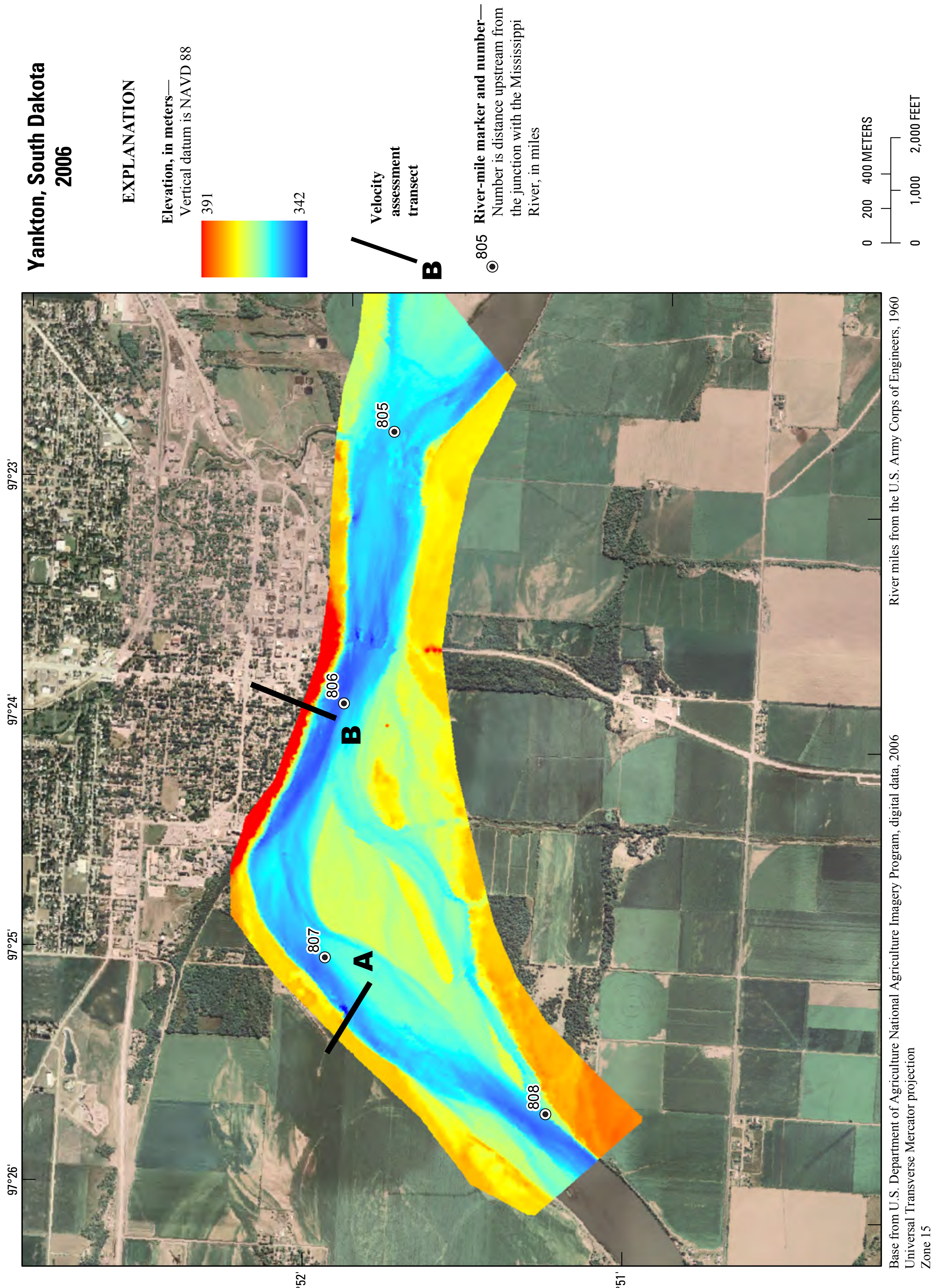


Figure 8. Elevation of the hydrodynamic modeling reach at Yankton, South Dakota, 2006 bathymetry.

created by drawing a centerline from the upstream end of the modeling reach to the downstream end. Around the centerline, the computation grid was expanded in the cross-stream direction to extend to elevations higher than the highest expected water-surface elevations in each model. Grid incrementing was adjusted in the streamwise and cross-stream directions such that a 5 m by 5 m grid was produced. Elevations then were assigned to grid nodes from the underlying terrain model (fig. 4*B*).

Boundary Conditions

MD_SWMS uses discharge and downstream water-surface elevation as boundary conditions for each hydrodynamic simulation (table 2). The discharge was maintained constant for each model run and downstream stage was assumed to be constant in the cross-stream direction. For selected models, simplified channel extensions were added to the upstream or downstream ends of the reach to allow for stabilization of flow. Models were run through sufficient number of iterations to converge with discharge errors of less than 2 percent in all cases.

Calibration

Each model was calibrated for a given flow by iteratively changing the drag coefficient to match the modeled and observed water-surface elevation profiles (U.S. Army Corps of Engineers, 1993). A measure of calibration performance was computed by taking the root-mean squared error (RMSE) value of the differences of the modeled and observed water-surface elevations. The roughness coefficient with the lowest RMSE value of water-surface elevation differences and least difference in overall water-surface slope was chosen for that discharge model run (table 2, fig. 9). Multiple calibrations over a range of discharges produced a functional relation between discharge and drag coefficient for each reach, each year. Drag coefficients for non-calibration solutions were interpolated, and to a limited extent, extrapolated from these relations. Calibration to water-surface elevation assumes that if a model replicates energy loss (water-surface slope as an approximation of energy slope) it will accurately represent depths and velocities. Use of interpolated drag coefficients to model non-calibration flows assumes that the relation between discharge and drag coefficient does not change significantly over time from variation in parameters other than discharge. The first assumption can be evaluated by assessing how well modeled and measured velocities correspond, as discussed in the next section. Variation in boundary roughness because of effects of water temperature, sediment transport, and bedform changes are examples of factors not captured in the calibrated models that might change the relation between discharge and drag coefficient, and contribute to model error (Fenwick, 1969; U.S. Army Corps of Engineers, 1993).

The lateral eddy viscosity (LEV) coefficient is also an adjustable parameter in MD_SWMS. LEV parameterizes turbulent momentum transfer and has a strong effect on modeled velocities. In our model implementation, we did not adjust LEV by calibrating modeled velocity distributions to match measured data; instead, we computed LEV for each simulation using the relation:

$$LEV = 0.01 * v_{avg} * d_{avg} \quad (1)$$

where

LEV is lateral eddy viscosity coefficient, in square meters per second

v_{avg} is reach-average velocity, in meters per second

d_{avvg} is reach-average depth, in meters

Average velocity and average depth were calculated from discharge measurement data collected during surveys and modeled from nearby streamflow gaging stations. Because we did not use LEV in calibration, predicted velocity distributions provide an internal test of model performance.

Model Assessment

Assessment of the adequacy of model performance ultimately depends on how the model results will be used (U.S. Army Corps of Engineers, 1993; Bates and Anderson, 2001; Lane and Richards, 2001). We present two approaches to model assessment, an internal evaluation of velocity distributions and an analysis of the sensitivity of predicted habitat to variation in the model parameters. The second of these relates directly to performance of the model for its intended use—assessment of habitat variation with changes in discharge—and is discussed in a later section of this report on sensitivity analysis. Evaluation of velocity distributions is presented in this section.

In the velocity assessment, we evaluated how well the calibrated model predicts velocity distributions in typical cross sections. This is an internal test of how well the model predicts depth-average velocities in a cross section without adjusting LEV, a parameter that strongly affects the cross sectional velocity distribution. The cross sections were selected to represent a broad range of velocity conditions within each reach

Table 3. Average bedform dimensions at modeling reaches over period of study. From Elliott and others (2009).

[m^3/s, cubic meters per second; m, meters]

Reach	Discharge range (m^3/s)	Average bedform amplitude (m)	Average bedform wavelength (m)
Miami, Missouri	700–3,300	0.84	14.2
Little Sioux, Iowa	330–1,140	0.38	3.8
Kenslers Bend, Nebraska	350–830	0.35	4.0
Yankton, South Dakota	250–710	0.40	15.1

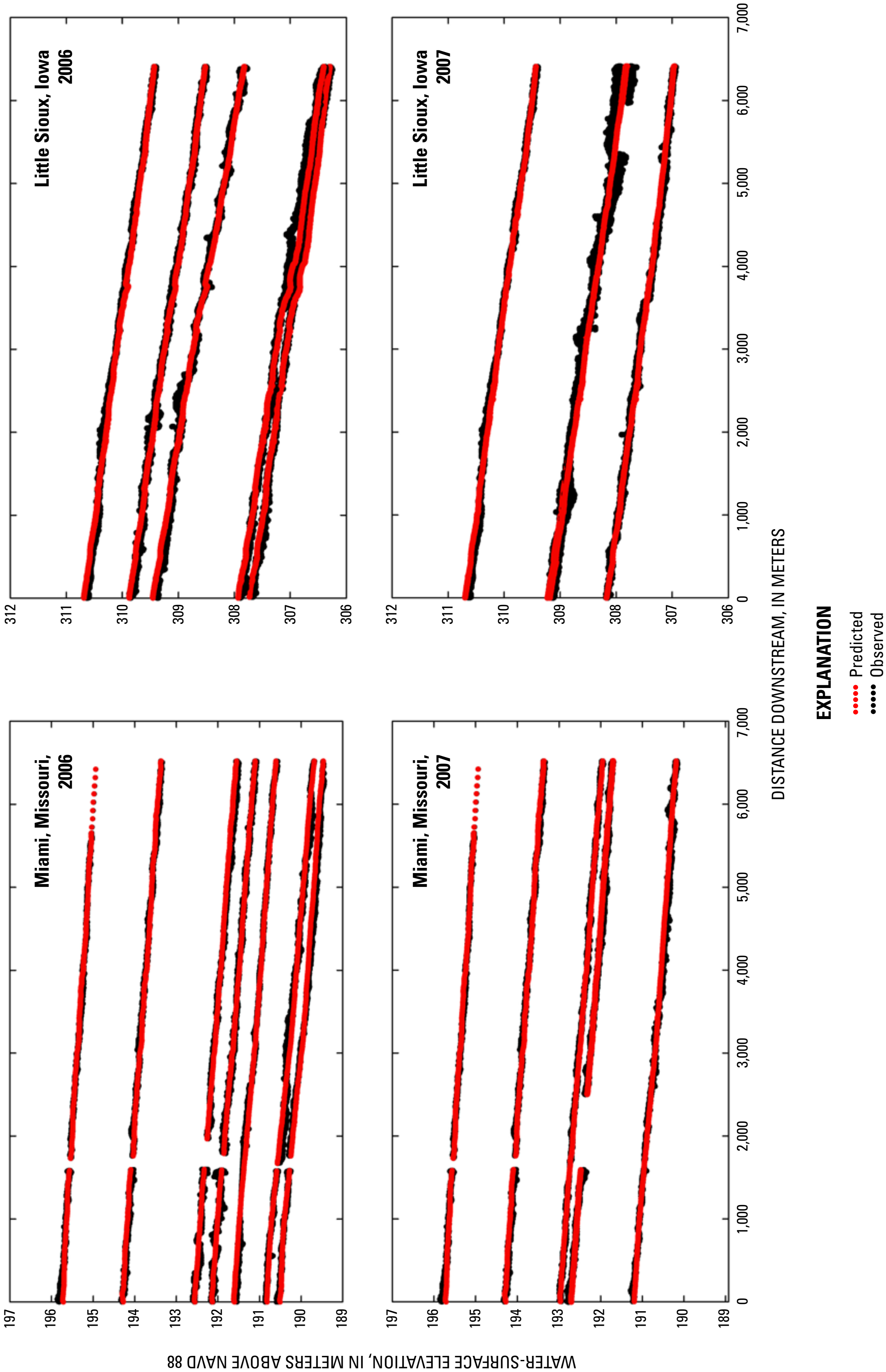


Figure 9. Predicted and observed water-surface elevations.

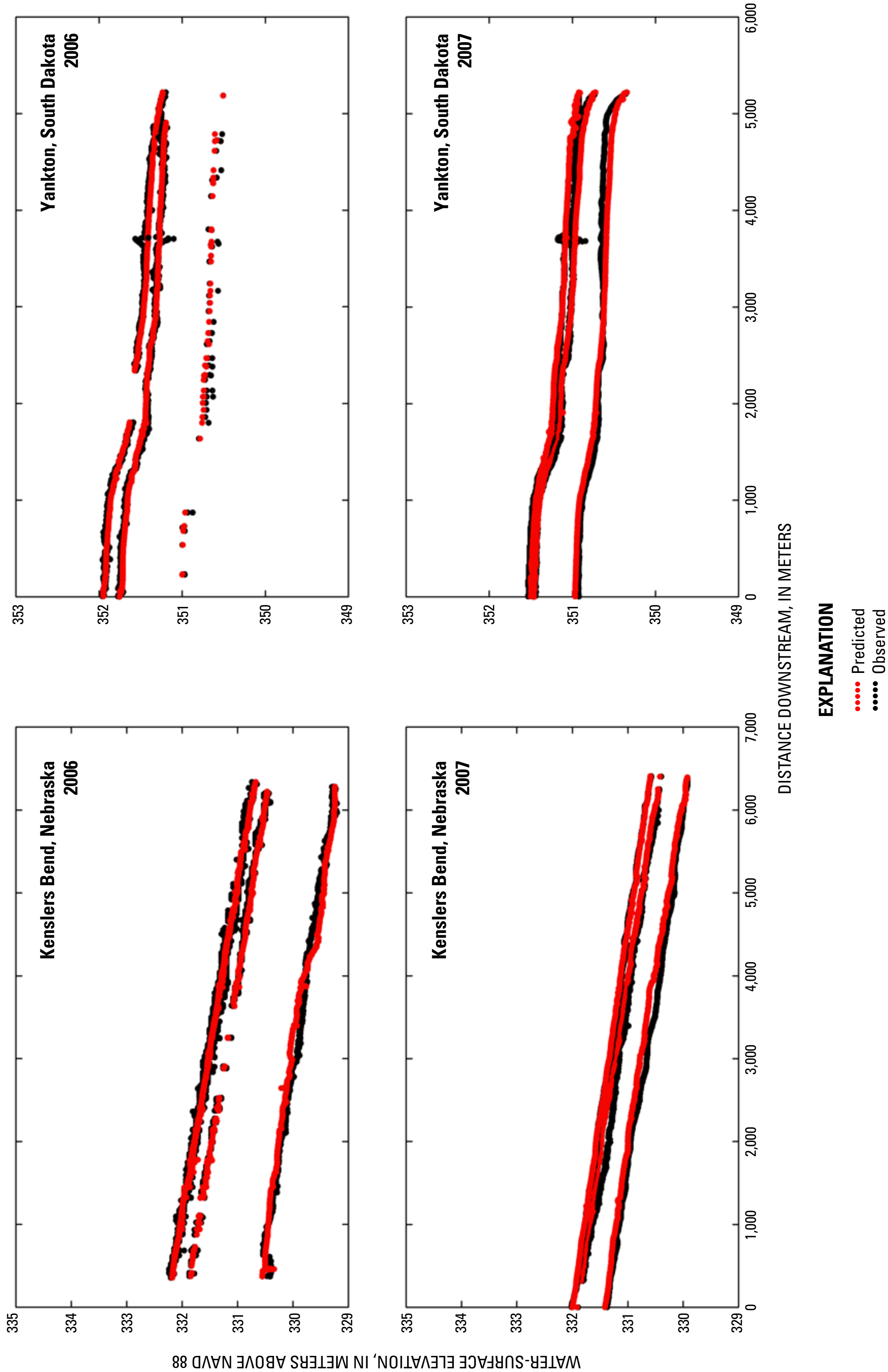


Figure 9. Predicted and observed water-surface elevations.—Continued

(figs. 5–8, 10). In the downstream three reaches, this included cross sections that extended from the main channel into low-velocity areas downstream from wing dikes. Modeled velocities were extracted from grids of the velocity field at locations where current velocities were measured with ADCP during surveys. Depth-averaged velocity magnitudes were computed from the ADCP data by vector averaging velocities in depth increments (bins) within the ADCP ensemble.

Comparison plots were examined for bias and accuracy (fig. 10). We considered general conformity of the modeled cross sectional velocity distribution to measured values to support model performance. No broad departures from measured data were noticed in the representative sample selected for velocity assessment, although small departures were common. In particular, the model captures the cross-channel velocity gradients that figure prominently in habitat definitions. Comparisons of modeled velocities to ADCP-measured velocities are capable of indicating gross model errors, but are inherently limited because ADCP data capture relatively high-frequency turbulent variation in the flow field and the model presents steady flow at a 5-m grid scale (Lane and Richards, 2001). The agreement between measured and modeled velocities indicates that calibration to a spatially uniform drag coefficient captures the salient features of velocity distributions in this river.

Hydraulic Definitions of Habitat

The concept of habitat can be treated as an extremely complex entity, encompassing all physical, chemical, and biological factors that interact to support occupancy of an organism (Hall and others, 1997; Bergman and others, 2008). For the purposes of this report, however, we define aquatic habitat more narrowly as the joint spatial and temporal distribution of depth, velocity, substrate, turbidity, temperature, and other related variables. At the reach scale, physical habitat typically is described even more narrowly as measures of depth, velocity, and substrate (Gordon and others, 1992; Reuter and others, 2003). This definition of habitat encompasses all spaces and is not organism specific, thereby allowing consideration of spaces for which the biological importance is unknown or only suspected.

Aquatic habitat can be considered a static volume of water with particular characteristics, or as a temporally and spatially varying entity. The seasonal occurrence, sequence, and durations of habitat availability may be critical for survival of some aquatic organisms because of life-stage-specific habitat requirements (Maddock, 1999; Doyle and others, 2005). Using two- or three-dimensional hydrodynamic models allows quantification of spatial attributes of habitat, including diversity (Reuter and others, 2003; Pasternack and others, 2004), gradients between habitat units (Crowder and Diplas, 2000; 2002; 2006; Johnson and others, 2006; Nestler and others, 2008), patch dynamics (Bowen and others, 2003), and patch persistence (Bovee and others, 2004). Advances also are being made in statistical methods for quantifying and analyzing habitat (Legleiter and Goodchild, 2005; Ahmadi-Nedushan and others, 2006), which may improve understanding of habitat-biota links.

Selection of Habitat Metrics

In order to explore functions and sensitivities of a wide range of potential habitat types, we use selected habitat metrics in three broad categories: simple depth/velocity combinations, complex hydraulic metrics, and reach-scale integrative metrics. Ultimately, habitat metrics used to help manage a particular species should be based on identification of specific habitat functions or limitations. We present and explore a wide range of habitat metrics in this report in order to characterize multiple, potential indicators of ecological function. Although direct links to pallid sturgeon reproduction or survival may be poorly defined at this time, the metrics are all fundamental descriptors of the hydrodynamics of the river in which the fish resides. The intent is to provide some new approaches to habitat characterization that may motivate testing of new hypotheses about ecological functions of habitats, whether those habitats relate directly to pallid sturgeon reproduction and survival or indirectly through food sources, competition, or predation (Wildhaber and others, 2007).

For the purposes of this study, we standardized on a minimum resolution of 5x5 m cells as a reasonable compromise between detail and cost. Many fundamental hydrodynamic and ecological processes are realized at a finer scale, including a range of turbulent flow features that may determine energy refugia and food distributions. Because of the resolution of the hydrodynamic model and the simplification of three-dimensional hydraulics into two dimensions, our habitat metrics should not be considered explicit descriptors of the processes. Rather, the habitat metrics are intended to be used as indicators of the variety of scales and processes occurring within the 5x5 m resolution.

Depth-Velocity Fields

Results from the hydrodynamic models were gridded into maps with 5-m square cells. The continuous velocity and depth grids then were used to place each cell into a depth-velocity category (table 4). The categories span the range of depth and velocity computed in the hydrodynamic models. The boundaries between categories are defined to provide sufficient resolution of depth and velocity bins without creating so many categories that trends are obscured. These depth-velocity fields provide potential habitat definitions with minimal functional interpretation. They are amenable to general exploration of trends in the modeled datasets and for calculation of measures of diversity (discussed below).

Available information in the scientific literature supports the notion that adult pallid sturgeon do not select strongly for depth. For example, Mississippi River pallid sturgeon were found in a wide range of depths, 1.8–19.1 m (Hurley, 1999) and Upper Missouri and Yellowstone River pallid sturgeon

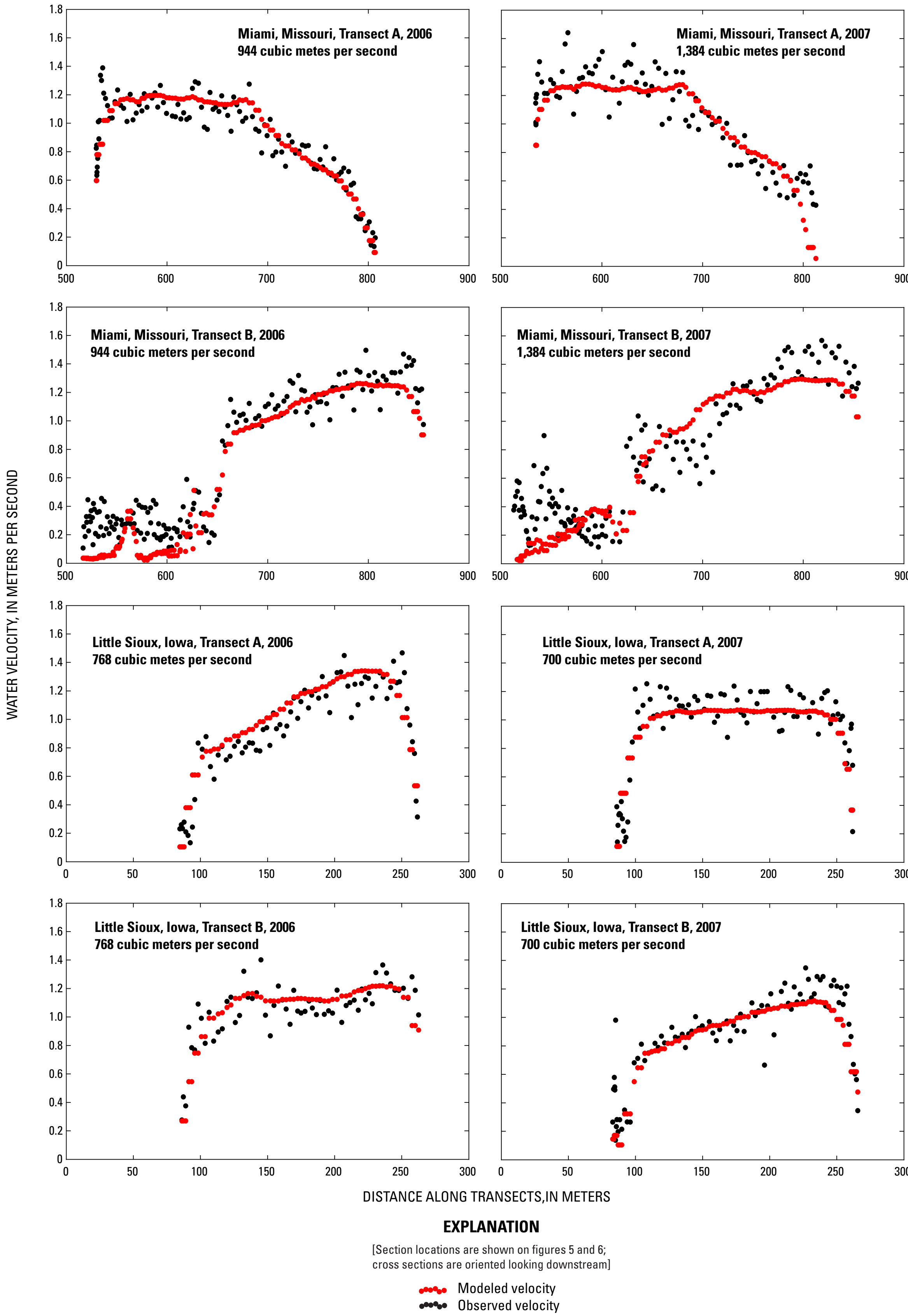


Figure 10. Comparisons between modeled and measured water velocities at selected transects, Miami, Missouri and Little Sioux, Iowa, Kenslers Bend, Nebraska and Yankton, South Dakota reaches, 2006 and 2007.

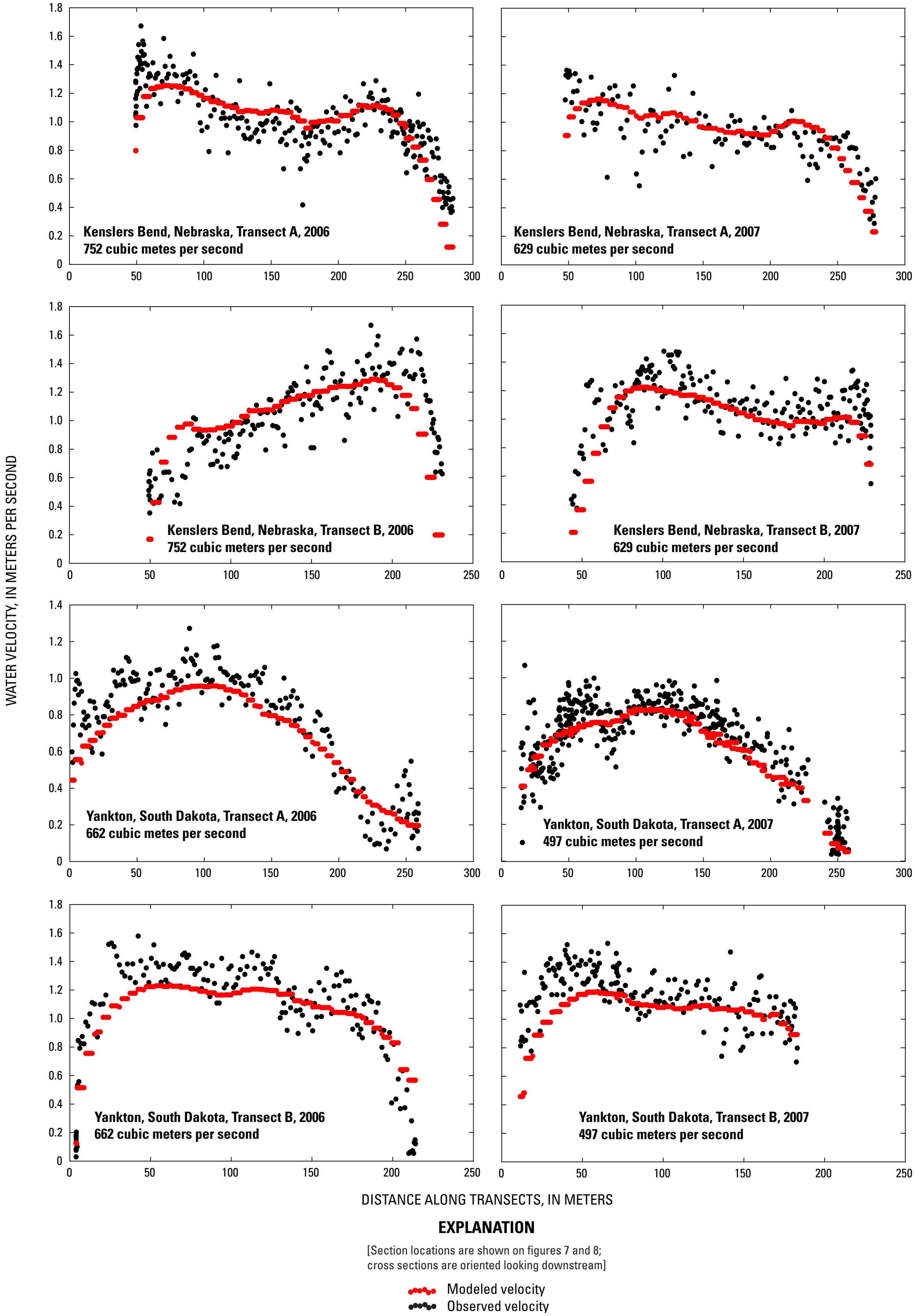


Figure 10. Comparisons between modeled and measured water velocities at selected transects, Miami, Missouri and Little Sioux, Iowa, Kenslers Bend, Nebraska and Yankton, South Dakota reaches, 2006 and 2007.—Continued

have been captured at 0.6–14.5 m depth (Bramblett and White, 2001). Lack of strong depth selection has also been supported by telemetry studies in the LMOR, in which adult sturgeon were located at depths symmetrically distributed around the mean depth available in many reaches (Jacobson and others, 2007). Depth selection of other fishes is often thought to relate strongly to provision of cover for predator avoidance (Rabeni and Jacobson, 1999), a factor that would be minimized in the turbid LMOR. Accordingly, for the purposes of this study, depths were arbitrarily divided into four classes: 0-1.5 m, 1.5–3.0 m, 3.0–4.5 m, and greater than 4.5 m. (table 4).

Pallid sturgeon selection for velocity appears stronger than for depth. Adult pallid sturgeon have been found at velocities 0–1.37 m/s in the Upper Missouri and Yellowstone Rivers (Bramblett and White, 2001) and 0.17–0.97 m/s in the Platte River (Snook and others, 2002). Selection of smaller than reach-average current velocity by adult pallid sturgeon has been documented in telemetry studies on the LMOR (Jacobson and others, 2007). Because of the key role of current velocity in energetics of many fishes, however, we included additional potential velocity classes in this analysis. As several small-bodied fishes (for example, sicklefin chub [*Macrhybopsis meeki*] and sturgeon chub [*Macrhybopsis gelida*]) are thought to be preferred food items for pallid sturgeon (Gerrity and others, 2006), and because swimming speed generally decreases with decreasing body size (Bainbridge, 1958; Weihs, 1973), we divided velocities into five classes, including a very slow current velocity 0–0.3 m/s (table 4). The remaining velocity classes were 0.3–0.6 m/s, 0.6–1.2 m/s, 1.2–1.8 m/s, and greater than 1.8 m/s.

Table 4. Depth and velocity combination fields and class codes used in habitat patch analysis.

[m, meters; m/s, meters per second]

Velocity class (m/s)	Depth class (m)			
	0-1.5	1.5-3.0	3.0-4.5	4.5+
0–0.03	11	21	31	41
0.3–0.6	12	22	32	42
0.6–1.2	13	23	33	43
1.2–1.8	14	24	34	44
1.8+	15	25	35	45

Hydraulic Parameters and Spatial Variation

Several habitat metrics were explored based on derivative hydraulic metrics or spatial variation (rate of change) of depth and velocity. Depth and velocity grids can be used to compute Froude number, a common dimensionless number relating inertial forces to gravity forces:

$$F = \frac{V}{\sqrt{gD}} \qquad (2)$$

where, V is current velocity, D is depth, and g is the gravitational constant. The Froude number has been investigated by other researchers for its usefulness in describing the combined effect of velocity and depth on habitat suitability (Jowett, 1993; Quinn and Hickey, 1994; Yu and Peters, 1997; Reuter and others, 2003). The range of Froude number that might be designated good or bad sturgeon habitat is unknown, although deep, slow areas around wing dikes have been identified as potential overwintering habitat for pallid sturgeon (Grady and others, 2001). In addition, low Froude numbers have been associated with deep, slow areas of the LMOR that are inhabited by invasive Asian carp (Kolar and others, 2005). For the purposes of this report, we selected low values of the Froude number to delineate deep, slow habitat areas, typically downstream from wing dikes, that could be accumulation areas for drifting larval fish or particulate organic matter. These areas coincide generally with Froude numbers less than 0.05.

Identifying and quantifying pallid sturgeon spawning habitat is of particular interest to pallid sturgeon researchers (Quist and others, 2004; Bergman and others, 2008). Currently (February, 2009), spawning of pallid sturgeon in the wild has not been documented directly by observation. Telemetry studies have tracked migrating, gravid female pallid and shovelnose sturgeon to discrete reaches (including three of the four reaches in this study) and, in some cases, recaptures of the fish have confirmed that eggs had been released (DeLonay and others, 2007; U.S. Geological Survey, 2007). These studies and unpublished data from telemetry tracking during 2008 (A. DeLonay, oral commun., U.S. Geological Survey, January, 2009) trace spawning to reaches (100's of meters length) and in some cases patches (10's of meters length), but have not identified consistent spawning locations or characteristics of locations. Spawning potential within the modeling reaches, therefore, is explored largely through reference to known characteristics of spawning locations used by other sturgeon species.

Observations of white sturgeon (*Acipenser transmontanus*) egg deposition indicate that areas of convergent flow downstream from rapids or riffles generally are selected for spawning (Paragamian and others, 2001; Paragamian and others, 2002; McDonald and others, 2006). This tendency has been supported by observations of Chinese sturgeon spawning (Fu and others, 2007). Descriptions of spawning habitats of shortnose sturgeon emphasize areas of coarse substrate and well-developed turbulence (Kynard, 1997). Presumably, high turbulence acts to keep the coarse substrate free of fine sediment and may act as a physiological cue for conditions that will disperse eggs (Coutant, 2004). Based on these descriptions, we explored several measures of flow complexity that relate to convergence/divergence and turbulence.

We used variation in unit discharge as an indicator of flow convergence. Unit discharge is the discharge in a cell expressed per unit width, thereby indicating how much of a cross-sectional discharge passes through a particular cell. Areas of high flow convergence, Cn, were identified as those with unit discharges (discharge per unit channel width) greater than the mean plus one standard deviation at a given discharge. Areas of high *Cn* are consistent with three pallid sturgeon spawning patches identified by high-intensity telemetry tracking efforts during 2008; these three patches were all on outside revetted bends between river mile 230 and 370 (A. DeLonay, oral commun., U.S. Geological Survey, January, 2009).

The emerging data on catch and telemetry locations of migrating adult shovelnose and pallid sturgeon indicate selection for areas of high velocity gradients (Johnson and others, 2006; DeLonay and others, 2007; Jacobson and others, 2007; Reuter and others, U.S. Geological Survey, written commun., 2009). In smaller rivers, areas of recirculation and flow deformation have been associated with energy refugia for fishes and benthic invertebrates (Crowder and Diplas, 2002). This information has led us to explore additional hydraulic metrics related to spatial variability of velocity and flow deformation with the intent of defining metrics that combine ecological function and simplicity. Johnson and others (2006) defined a wake metric, Wk, that was intended to be indicative of flow separation and eddy shedding zones that occur downstream from flow obstructions and along sandbars. The turbulent vortices that exist in these zones are three-dimensional features ranging in size from millimeter scale to 10's of meters; such features are not captured at the scale or complexity of our two-dimensional models. Nevertheless, the velocity gradients that are coincident with the wake zones can be extracted from the hydrodynamic models. Wk habitats were defined as those with velocity standard deviations in a 50-m radius around a cell greater than 0.16 m/s and depth standard deviations between 0.5 and 1.5 m (Johnson and others, 2006). Pending additional information on sturgeon habitat selection, we simplified the definition of Wk to areas with greater than 2 percent variation in velocity per meter, calculated along the steepest velocity slope among eight neighboring cells. This equates to a threshold of 10 percent variation over the 5-m cell resolution of the models.

We also explored three derivative hydraulic metrics proposed by Crowder and Diplas (2002) and one proposed by Nestler and others (2008) for their information content in defining habitat functionality. Although the biological significance of these metrics is not known, we included them to illustrate approaches to measuring hydraulic complexity in the system that might be correlated with emerging biological datasets. The four derivative metrics were: kinetic energy gradient, vorticity, circulation in the total reach, and total distortion. Kinetic energy gradient (KEG) was originally proposed as the gradient of kinetic energy (proportional to $v^2/2$) between two points, requiring a predetermination of the direction of the gradient:

$$KEG = \frac{\frac{\partial}{\partial x}\frac{v^2}{2}}{\frac{v^2}{2}} \tag{3}$$

where, v = velocity magnitude. In our implementation of this concept we calculated kinetic energy at each cell as the velocity magnitude squared, divided by two times the gravitational constant, and assessed the spatial standard deviation of kinetic energy over a 3x3 cell (225 m^2) window. Using spatial standard deviation avoids the requirement to stipulate a direction of gradient and provides a more general assessment of where kinetic energy is being expended at the reach scale.

Vorticity, ξ, in a two-dimensional flow is twice the rate at which a fluid element rotates about a vertical axis, and is expressed as:

$$\xi = \left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right)\mathrm{k} \tag{4}$$

where, v is depth averaged velocity in the x direction, u is depth averaged velocity in the y direction, and k is the unit vector in the vertical dimension (Crowder and Diplas, 2006). We calculated ξ on the cell-based model output using orthogonal streamwise and stream-normal velocities, calculated between four points around the computational point. The average then was used as a measure of vorticity at the center point. Measures of vorticity at this scale are intended to assess rotation of water parcels on the order of 15 m diameter and, therefore, do not attempt to resolve rotation at smaller scales of turbulence.

Vorticity can be scaled to broader areas using the concept of circulation (Crowder and Diplas, 2002) by integrating ξ, over an area of interest. In discrete form, circulation is:

$$\Gamma = \sum \xi \Delta A \tag{5}$$

where ΔA is a unit area. In summing through an area of arbitrary size, positive and negative values of xi may cancel one another. Hence, another metric proposed to measure total strength of circulation in an area (absolute circulation) by summing the absolute value of vorticity (Crowder and Diplas, 2002):

$$\Gamma_{abs} = \sum |\xi| \Delta A \tag{6}$$

The spatial density or strength of circulation in an area can be calculated by dividing the Γ_{abs} by the total defined area. The area under consideration could be the entire reach or subsections within the reach.

A metric measuring total distortion of the flow field, S_l, originally was calculated as total hydraulic strain for high-resolution, three-dimensional velocity fields (Nestler and others, 2008). S_l was calculated as the sum of absolute values of all spatial velocity gradients and therefore included measures of linear deformation, rotation, and angular deformation. We simplified S_l for the two-dimensional case as:

$$S_l = \left|\frac{\partial u}{\partial x}\right| + \left|\frac{\partial u}{\partial y}\right| + \left|\frac{\partial v}{\partial x}\right| + \left|\frac{\partial v}{\partial y}\right| \quad (7)$$

S_l was calculated from each of the four corners of a 3x3 cell window relative to the center cell and the average value was assigned to the center cell.

Reach-Scale Integrative Metrics

Habitat metrics at the reach scale serve to illustrate integrated responses of habitat to discharge variation. We use benthic terrain mapping (BTM) to integrate habitat into landforms based on depth classification (Weiss, 2001; Lundblad and others, 2006; Jacobson and others, 2007). This calculation uses local concavity/convexity and slope of channel topography to map out landforms units that correspond roughly to bar complexes, the thalweg, and crossovers.

We assessed habitat patch complexity using spatial statistical tools available in Fragstats (McGarigal and Marks, 1995). For selected habitat classes based on depth and velocity fields (table 4), we calculated patch characteristic statistics including:

- Total patch area (hectares);
- Patch density (number per hectare);
- Edge density (meters of edges between patches per hectare);
- Simpsons Diversity Index (the probability that any two patches selected at random in the reach will be of different types, ranging 0-1);
- Reach-scale nearest neighbor (edge-to-edge distance from a patch to its nearest neighbor of the same class, in meters); and
- Interspersion and Juxtaposition Index (an index that measures adjacency of patches, such that maximum adjacency measures 100 percent).

At the reach scale, we also calculated mean residence time of water in the reach as the total volume of water divided by discharge, and total hydraulic strain by summing hydraulic strain through the reach. Mean residence time gives an integrated measure of ability of the reach to retain water or passively transporting particles (for example: invertebrate drift, particulate organic matter, or larval fish). Water residence time in rivers has been linked to diverse measures of habitat function including temperature (Webb, 1996), water quality (Roos and Pieterse, 1994; Kelly, 1997; James and others, 2008), and larvae retention (Mion and others, 1998). Mean residence time is inversely related to mean current velocity.

Habitat measures were computed within a georeferenced framework. Processing steps that did not require human judgment were automated with Python scripts (Python Software Foundation, Hampton, New Hampshire) and Perl scripts (Practical Extraction and Report Language, ActiveState Corporation, Vancouver, British Columbia), utilizing ArcGIS processing tools (version 9.2, Environmental Systems Research Institute, Inc., Redlands, California). All derivative maps were generated with 5-m grid cells and are stored in the Environmental Systems Research Institute (ESRI) grid format. Maps for the Miami reach were projected to UTM Zone 15N, NAD83 datum. Maps for Little Sioux, Kenslers Bend, and Yankton reaches were projected to UTM Zone 14N, NAD83.

Sensitivity Analysis

Systematic errors in the underlying hydrodynamic model can arise from incomplete specification of the hydraulic parameters (drag coefficient and lateral eddy viscosity coefficient), or from unmeasured variation in channel morphology. In turn, these errors may limit the ultimate value of information derived from the modeling process. A sensitivity analysis addresses how model outputs may vary for a range of potential errors in inputs and serves as an assessment of model performance.

Sensitivity to Drag Coefficient and Lateral Eddy Viscosity

We addressed sensitivity of modeled habitat variables to the drag coefficient and the lateral eddy viscosity coefficient by systematically varying values for one model from -20 to +20 percent of the calibrated or computed value (table 5). We evaluated variation in the RMSE of water surface elevation as a standard hydraulic modeling metric. We also calculated all the derivative habitat variables in order to understand propagated sensitivity of habitat variables to variation in drag coefficient and lateral eddy viscosity. Sensitivity is shown as reach-scale sums of selected variables and as percentage of the calibrated value.

Water-surface elevation RMSE is relatively sensitive to variation of the drag coefficient. A 20 percent variation of drag coefficient can result in as much as 0.08 m of increase in RMSE. This sensitivity propagates through to relatively high sensitivity of shallow, slow current velocity classes (classes 11 plus 12), because the shallow-water areas are inherently sensitive to variation in water-surface elevation. A 20 percent decrease in drag coefficient, for example, resulted in a 42 percent decrease in estimated area of the shallow water habitat class. Residence time and total wetted area were relatively insensitive to drag coefficient variation, as was area of convergent zones. Wake zones and low-Froude number zones were moderately sensitive, changing as much as 10 percent in area with a 20 percent variation in drag coefficient. Benthic terrain map classes and reach-scale patch statistics were relatively insensitive to drag coefficient variation. Mean nearest neighbor and patch density varied as much as 5 percent with variation of drag coefficient by 20 percent.

Most metrics were insensitive to 20 percent variation in lateral eddy viscosity. The largest change associated with 20 percent variation of lateral eddy viscosity was a 5.4 percent change in area of slow, deep water (class 41). Although sensitive to changes in lateral eddy viscosity, this habitat class did not change systematically as eddy viscosity was increased and decreased.

Sensitivity to Changes in Channel Morphology

Some of the LMOR bed is in motion almost all the time (Gaeuman and Jacobson, 2006; 2007b; 2007a). Changes in channel morphology at the reach and bedform scale can alter flow resistance, hydraulic connections, and consequently, habitat quality and availability. We assessed how morphologic changes at the reach scale may affect hydrodynamic modeling results by constructing individual models for 2006 and 2007 bed morphologies. Analysis of within-year and year-to-year morphologic variation in the modeling reaches is presented in a companion report (Elliott and others, 2009). Comparisons of channel morphology surveyed in 2006 and 2007 are shown in figures 11–14 and sensitivity of habitats on a year-to-year basis is discussed in the results section.

Year-to-year variability in channel morphology among the four sites relates to the flows experienced during the time period and the background sediment transport dynamics. The average annual suspended-sediment flux varies considerably from upstream to downstream on the LMOR. At Yankton, modern annual suspended-sediment flux is 0.24 x10^6 Mg/y (millions of megagrams per year) and it increases to 7.3 at Sioux City, 18.6 at Omaha, and 41.9 x10^6 Mg/y at Kansas City (Jacobson and others, U.S. Geological Survey, written commun., 2009). Hence, much more sediment is available for redistribution at the downstream reaches.

The Miami reach experienced the highest relative discharges among the four reaches, and the complete topographic survey used to evaluate change took place after the highest flows in 2007 (figs. 3, 11). The net effect of the high discharge was to accentuate existing topography, eroding sediment from the thalweg and depositing sediment on marginal bars. During this period Miami experienced net erosion of 48,000 m^3 (cubic meters; Elliott and others, 2009). Little Sioux and Kenslers Bend experienced relatively high peak flows during March 2006 (fig. 3) and both reaches experienced considerable redistribution of sediment (figs. 12, 13). In both, morphologic change included substantial deposition in the thalweg and erosion of bars. Net change at Little Sioux was 134,000 m^3 of erosion and Kenslers experienced 36,000 m^3 of deposition. Yankton experienced much diminished flows over the time period and had the least amount of morphologic change. Nonetheless, Yankton had a net 87,000 m^3 of erosion.

Modeling Results

The hydrodynamic modeling results for the four reaches for 2006 and 2007 provide insight into how physical habitat varies by segment of the LMOR, how it varies with discharge, and how it varies between years as a result of channel dynamics. The following sections address habitat variations principally through graphical analysis of habitat functions, that is, plots of habitat metrics by discharge. The plots are arranged to show variation by reach, variation with discharge, and variation during 2006 and 2007. Discharge is normalized by median daily discharge at the nearest streamflow gaging station in order to provide a basis for comparison among the reaches.

Depth and Velocity Fields

Depth-velocity fields form a mosaic of physical habitat patches. Generally, habitat patches are relatively small and highly interspersed at low discharges. As discharges increase in the channelized river, deep, swift water in the navigation channel increasingly dominates the patch structure (fig. 15). Patches in the unchannelized river (Yankton, not shown) generally are larger and less interspersed.

Depth-velocity classes exhibit characteristic responses to increasing discharge (habitat functions) in the channelized river (fig. 16). Slow and shallow water classes (classes 11, 12, and 22) are maximized at lowest discharges, whereas other classes that are intermediate depth and velocity (for example, class 33) increase in area from small to intermediate discharges and then decrease. Deep and swift classes (class 44) increase at a high rate as discharge increases (fig. 16*A*). The relation of classes to discharge in the unchannelized river is different, reflecting the smaller size of the river and the wider, shallower channel morphology (fig. 16*B*). Shallow-water classes at Yankton are proportionately larger and, although variable, do not decrease monotonically with increasing discharge. The deepest and fastest classes are relatively poorly represented at Yankton over all discharges.

Shallow, slow-current-velocity habitats are substantially diminished in the LMOR relative to historical conditions (Funk and Robinson, 1974; Jacobson and Galat, 2006). Although the functional relation of shallow, slow-current-velocity habitat to reproduction and survival of pallid sturgeon has not been documented, these habitats are thought to be important for rearing of larval and juvenile sturgeon and for supporting populations of prey fish for sturgeon and shorebirds (U.S. Fish and Wildlife Service, 2000; 2003). Two shallow, slow-water classes (11 and 12; table 4, fig. 17) characteristically decrease in area with increasing discharge in the channelized river. These habitat functions reflect drowning out of marginal, shallow water habitat as discharge increases within the banks (Jacobson and Galat, 2006; Johnson and others, 2006). The sum of classes 11 and 12 is equivalent to the shallow-water habitat unit defined in the Missouri River

Table 5. Sensitivity analysis results from varying drag coefficient and lateral eddy viscosity coefficient at Little Sioux reach, 2006 topography, 768 cubic meters per second.

[m²/s, square meters per second; m, meters; h, hour; km, kilometer; ha, hectare]

		Reach-scale metrics				Habitat patch areas					
Drag coefficient (dimensionless)	Eddy viscosity (m^2/s)	Water-surface elevation root mean square error (m)	Rotation (m^2/s)	Total strain (m^2/s)	Residence time (h/km)	Total area (ha)	Habitat classes 11 and 12 (ha)	Habitat class 41 (ha)	Convergent zones (ha)	Wake zones (ha)	Low-Froude number zones (ha)
0.0054	0.40	0.12	1,180.2	3,896.3	0.26	132.4	13.1	0.3	19.8	25.9	8.1
0.0060	0.40	0.07	1,107.4	3,611.6	0.26	132.6	21.3	0.3	19.8	25.3	7.8
0.0067	0.40	0.05	1,113.5	3,653.4	0.26	132.7	22.6	0.3	19.7	24.7	8.0
0.0074	0.40	0.13	1,198.6	3,809.8	0.27	132.8	26.2	0.2	19.7	23.4	7.3
0.0080	0.40	0.08	1,174.1	3,767.0	0.27	132.8	24.5	0.2	19.8	24.0	7.2
0.0067	0.32	0.05	1,114.2	3,685.2	0.26	132.7	22.5	0.3	19.7	24.6	7.8
0.0067	0.36	0.05	1,085.7	3,535.5	0.26	132.7	22.6	0.3	19.8	24.8	8.0
0.0067	0.40	0.05	1,113.5	3,653.4	0.26	132.7	22.6	0.3	19.7	24.7	8.0
0.0067	0.44	0.05	1,092.5	3,569.5	0.26	132.7	22.7	0.3	19.8	24.5	7.8
0.0067	0.48	0.05	1,087.4	3,559.0	0.27	132.7	22.7	0.3	19.8	24.7	7.9
-19%	0%	142%	6.0%	6.6%	-2.9%	-0.3%	-42.2%	3.6%	0.2%	5.0%	1.1%
-10%	0%	45%	-0.6%	-1.1%	-1.5%	-0.1%	-5.9%	-1.8%	0.4%	2.7%	-3.4%
0%	0%	0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
10%	0%	165%	7.6%	4.3%	2.8%	0.1%	15.9%	-17.1%	-0.2%	-5.2%	-9.8%
20%	0%	71%	5.4%	3.1%	1.5%	0.1%	8.3%	-11.7%	0.2%	-2.9%	-10.6%
0%	-20%	0%	0.1%	0.9%	0.0%	-0.0%	-0.6%	-5.4%	-0.1%	-0.5%	-2.6%
0%	-10%	0%	-2.5%	-3.2%	0.0%	-0.0%	0.0%	4.5%	0.1%	0.5%	-1.1%
0%	0%	0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0%	10%	0%	-1.9%	-2.3%	0.0%	-0.0%	0.1%	4.5%	0.1%	-0.5%	-2.8%
0%	20%	0%	-2.3%	-2.6%	0.0%	-0.0%	0.2%	-2.7%	0.1%	0.3%	-1.4%

Table 5. Sensitivity analysis results from varying drag coefficient and lateral eddy viscosity coefficient at Little Sioux reach, 2006 topography, 768 cubic meters per second.—Continued

[m²/s, square meters per second; m, meters; h, hour; km, kilometer; ha, hectare]

		Benthic terrain map classes				Reach-scale patch statistics				
Drag coefficient (dimensionless)	Eddy viscosity (m^2/s)	Depression area (ha)	Ridge area (ha)	Planar-flat area (ha)	Planar-steep area (ha)	Mean nearest neighbor (m)	Interspersion juxtaposition index (percent)	Edge density (m/ha)	Patch density (number/ha)	Simpkins diversity index (dimensionless)
0.0054	0.40	46.3	44.8	37.4	3.9	25.2	67.8	755	12.1	0.862
0.0060	0.40	46.5	44.7	37.5	3.9	26.4	68.5	757	11.3	0.859
0.0067	0.40	46.7	44.7	37.5	3.9	26.4	67.6	748	11.3	0.847
0.0074	0.40	46.8	44.6	37.5	3.9	27.7	65.1	723	12.0	0.826
0.0080	0.40	46.8	44.6	37.5	3.9	27.8	66.2	697	11.3	0.808
0.0067	0.32	46.7	44.7	37.5	3.9	26.2	67.7	746	11.3	0.847
0.0067	0.36	46.7	44.7	37.5	3.9	26.8	67.5	748	11.3	0.847
0.0067	0.40	46.7	44.7	37.5	3.9	26.4	67.6	748	11.3	0.847
0.0067	0.44	46.7	44.7	37.5	3.9	26.7	67.4	748	11.3	0.846
0.0067	0.48	46.7	44.7	37.5	3.9	26.9	67.6	745	11.3	0.846
-20%	0%	-0.8%	0.2%	-0.2%	-0.6%	-4.7%	0.2%	0.9%	7.0%	1.8%
-10%	0%	-0.4%	0.1%	-0.1%	-0.3%	-0.2%	1.4%	1.1%	0.1%	1.5%
0%	0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
10%	0%	0.3%	-0.1%	-0.0%	0.3%	4.9%	-3.6%	-3.5%	6.6%	-2.5%
20%	0%	0.2%	-0.1%	-0.0%	0.6%	5.0%	-2.1%	-6.8%	-0.1%	-4.5%
0%	-20%	0.0%	-0.0%	0.0%	-0.1%	-0.9%	0.1%	-0.3%	0.0%	0.0%
0%	-10%	-0.0%	0.0%	-0.0%	0.0%	1.2%	-0.1%	-0.1%	0.0%	-0.0%
0%	0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0%	10%	0.0%	-0.0%	-0.0%	-0.1%	0.8%	-0.3%	-0.1%	0.0%	-0.1%
0%	20%	-0.0%	0.0%	0.0%	0.0%	1.6%	-0.1%	-0.4%	0.0%	-0.0%

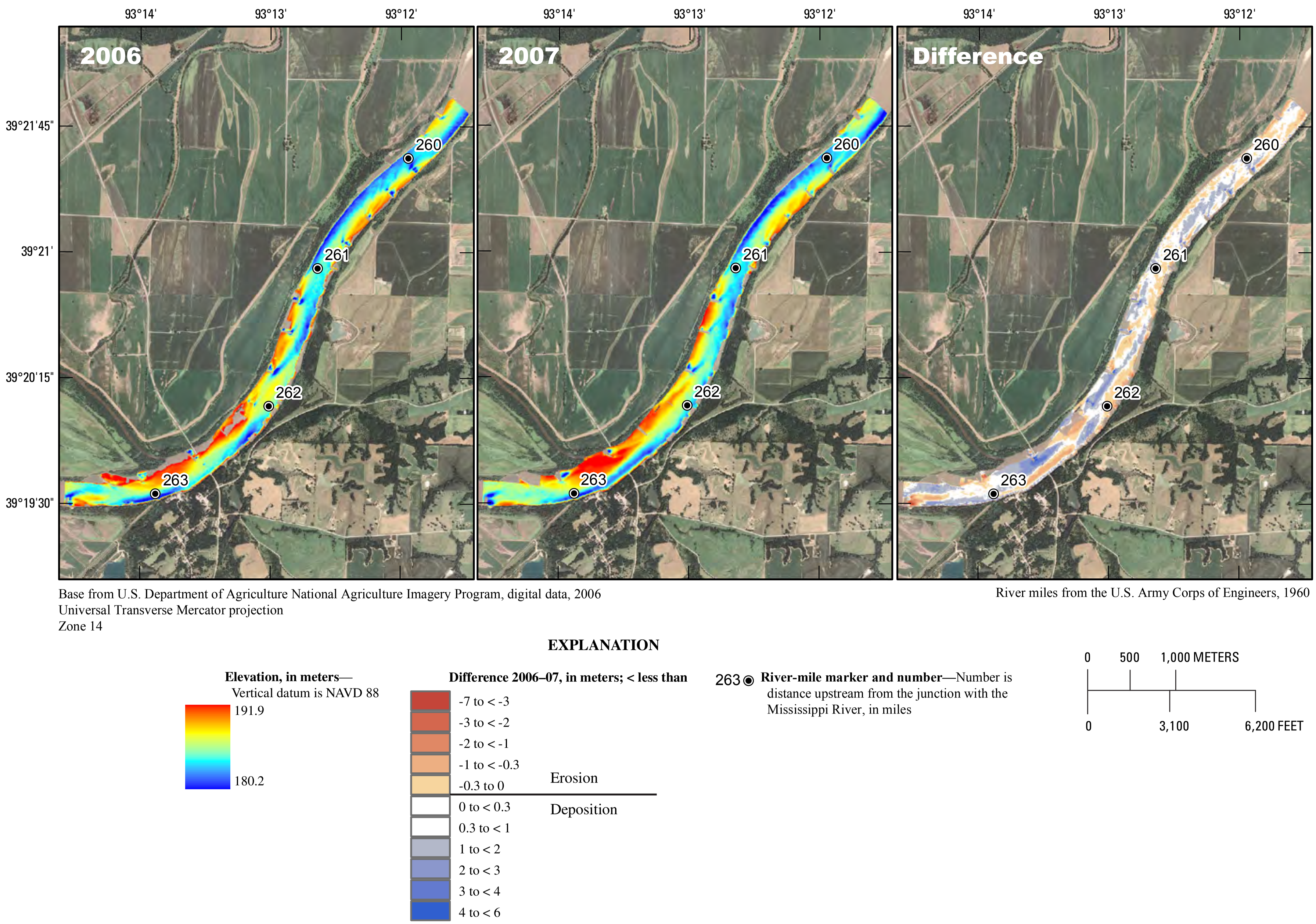


Figure 11. Elevation, Miami, Missouri reach, 2006, 2007, and elevation difference between the two years.

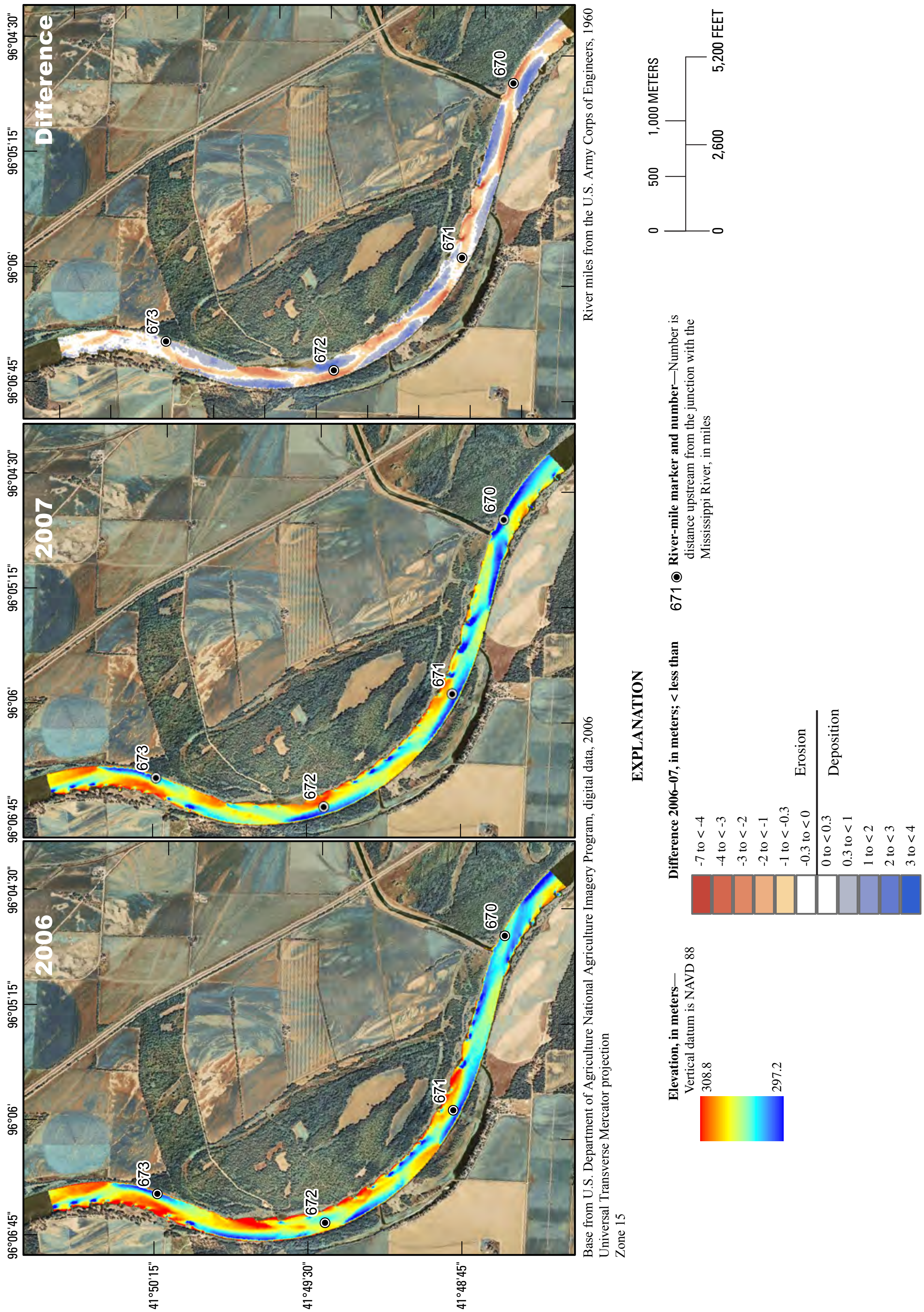


Figure 12. Elevation, Little Sioux, Iowa reach, 2006, 2007, and elevation difference between the two years.

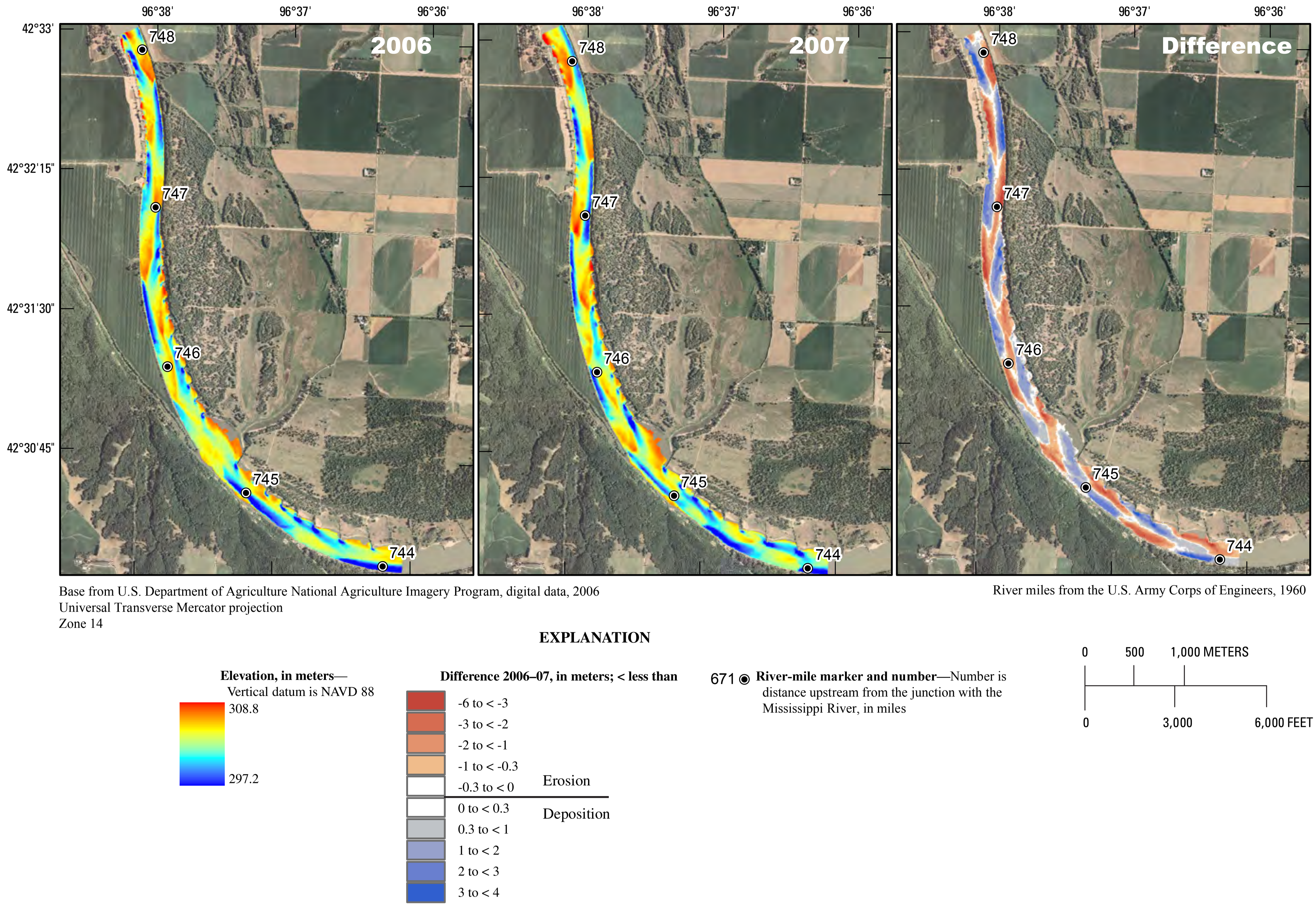


Figure 13. Elevation, Kenslers Bend reach, 2006, 2007, and elevation difference between the two years.

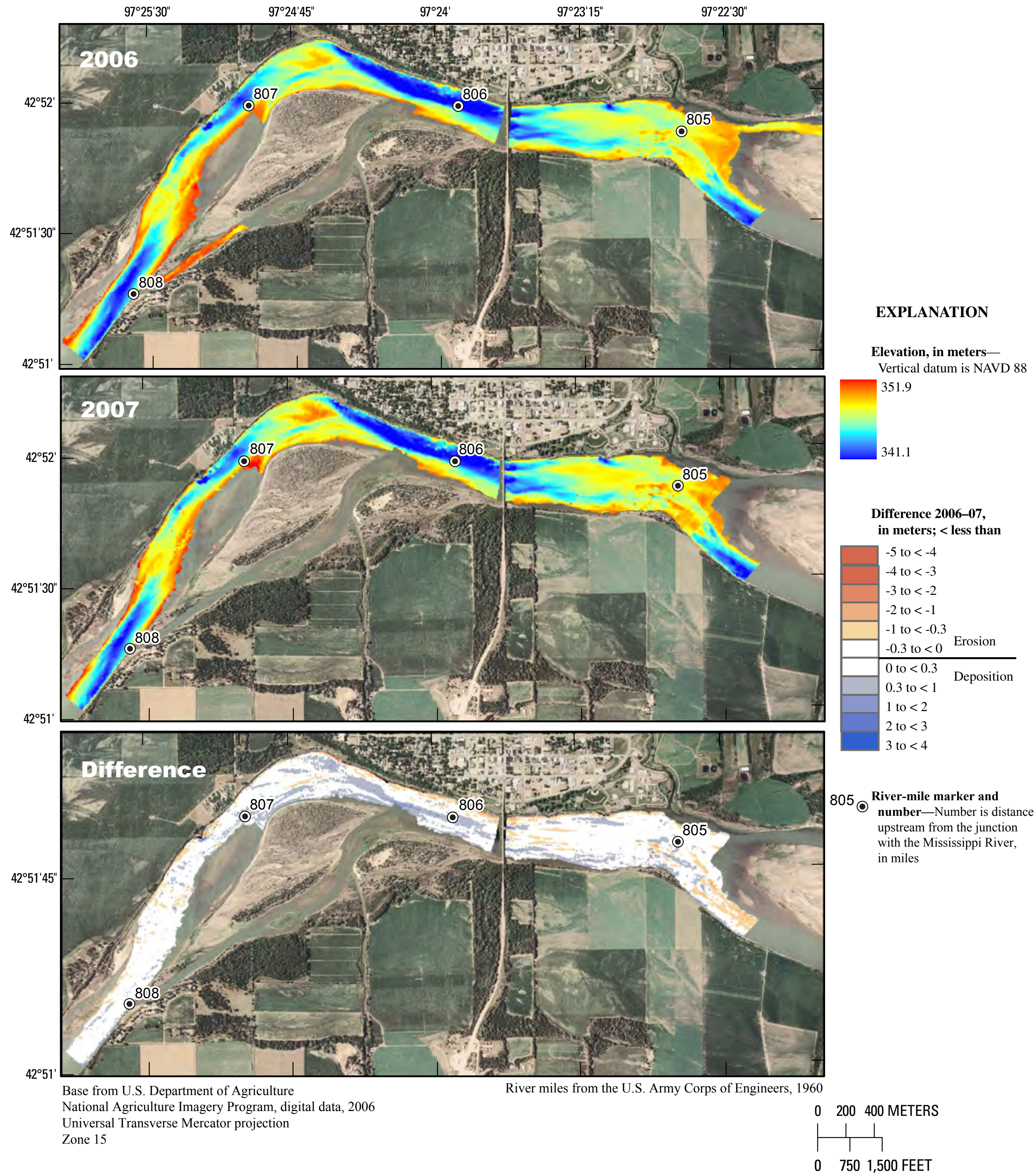


Figure 14. Elevation, Yankton, South Dakota reach, 2006, 2007, and elevation difference between the two years.

Biological Opinion (U.S. Fish and Wildlife Service, 2000; 2003). In the Kenslers Bend reach, the shallow-water habitat classes increase near 0.75 of the median discharge. This increase reflects water overtopping mid-channel and marginal bars in the Kenslers Bend reach and also overtopping bars in an anomalously widened reach near river mile 745.5 (fig. 7). Shallow-water habitat classes in the Yankton reach have substantially different functional relations with increasing discharge (fig. 17). The generally wider channel accommodates more shallow-water habitat classes over a wider range of discharge.

Deep, slow depth-velocity patches are exemplified by class 41 (table 3). The upstream reaches at Yankton and Kenslers Bend have negligible areas of this habitat class. Area of class 41 increases with increasing size of wing-dikes in the Little Sioux and Miami reaches (fig. 17). Wing dikes are responsible for deep scours that have slow, recirculating water at low to moderate discharges.

Hydraulic Parameters and Spatial Variation

Hydraulic parameters provide derivative measures of depth and velocity fields that may be useful indicators of ecological functions. Remapping depth and velocity fields from the model results allows for inventory of total area of habitat units and for assessment of the spatial patterns.

Low Froude Number Areas

Because Froude number is calculated from the ratio of velocity and depth, habitat analysis by Froude number yields slightly different results from analysis by depth and velocity fields. Shallow and deep water can have similar Froude numbers if the velocities scale similarly. Froude number has been used by other researchers to quantify habitat suitability (Jowett, 1993; Quinn and Hickey, 1994; Yu and Peters, 1997; Reuter and others, 2003). On the Missouri River, areas of low Froude number seem to be indicative of habitat for Asian carps that inhabit areas of slack water upstream and downstream from wing dikes (Kolar and others, 2005). These areas also may retain passively floating particles of organic matter, plankton, and larval fish.

We selected areas of Froude number less than 0.05 as a preliminary indicator of the slack water areas. Areas of low Froude number are mapped on insides of bends, at tributary mouths, and upstream and downstream from wing dikes (fig. 18). In the Miami reach, the relatively large and stable area of low Froude-number habitat results from slow, deep water associated with wing dikes. The area decreases with increasing discharge as wing dikes are overtopped, then increases sharply as water flows over the banks onto low-lying flood plain areas (fig. 19). Overbank flows at all modeling reaches would be expected to have similar low Froude numbers, but the Miami reach is the only one with calibrated flows that achieved near bankfull stage. Areas of low Froude number are limited and relatively insensitive to discharge variation in the Little Sioux and Kenslers reaches because of short wing dikes. Areas of low Froude number decrease with increasing discharge in the Yankton reach because the channel lacks structures to retard flow.

Convergent Flow Areas

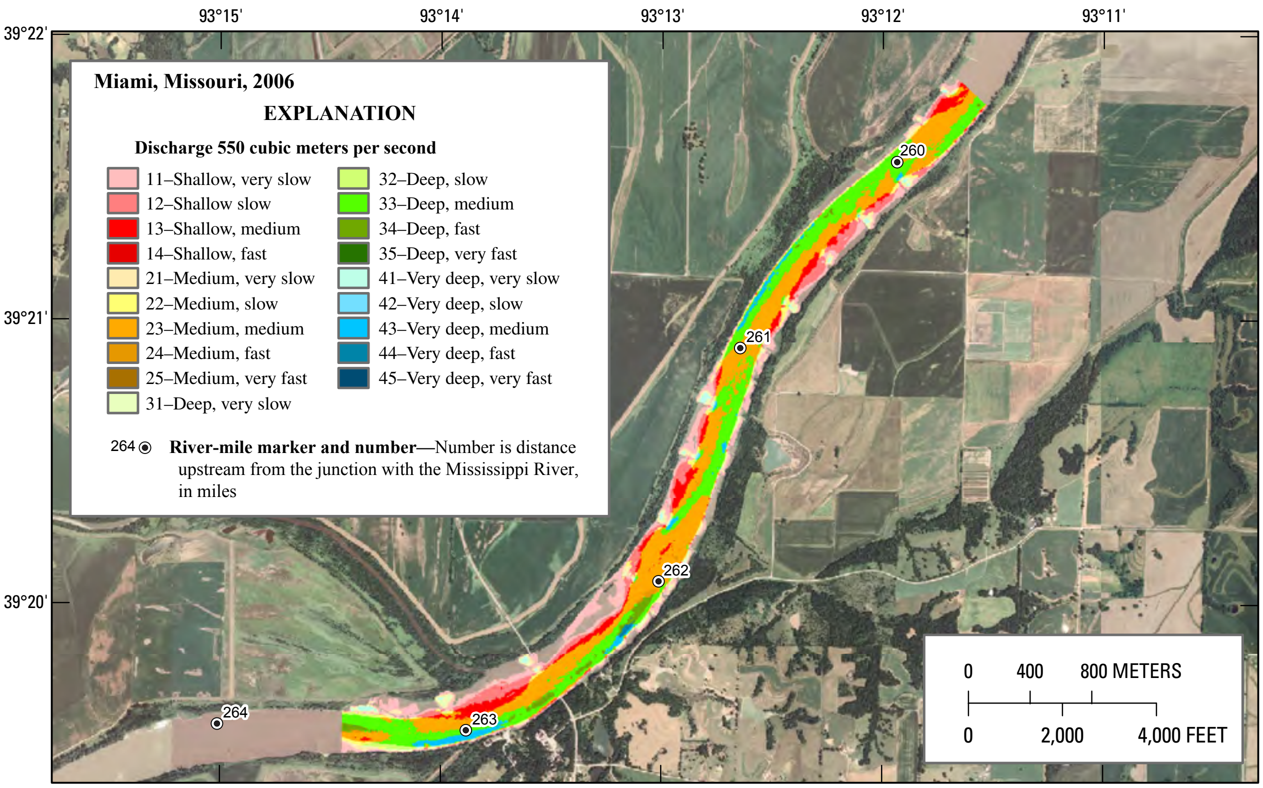
Areas of convergent flow are of special interest because of indications they are associated with spawning of some sturgeon species (Paragamian and others, 2001; Paragamian and others, 2002; McDonald and others, 2006; Fu and others, 2007). In addition, three gravid female pallid sturgeon were tracked during 2008 to convergent-flow areas on outside bends where they were inferred to have spawned (A. DeLonay, oral commun., U.S. Geological Survey, January, 2009). To derive convergent-flow areas from the model results, we used cells with unit discharges greater than the reach-average plus one standard deviation. This criterion maps areas on outsides of bends and in areas downstream from mid-channel bars where flows converge (fig. 20). Total areas of convergent flow are stable over years and relatively insensitive to discharge variation although the location may change (fig. 21).

Spawning habitat probably also requires the presence of coarse, hard substrate (Bemis and Kynard, 1997; Kynard, 1997; Paragamian and others, 2001). Many of the convergent-flow areas identified occur on the outside of revetted bends in the Miami, Little Sioux, and Kenslers Bend sites; such sites are associated with riprap consisting of coarse, hard rock. In some areas (Yankton, fig. 20) there are convergent-flow areas that exist away from revetted banks. Coarse substrate exists in some of these areas (Reuter and others, 2008) but has not been uniformly confirmed.

Energy-Dissipation Zones: Kinetic Energy Variance, Vorticity, Strain, and Wakes

Energy-dissipation zones are areas of fluid shear, flow separation, and turbulence. Such zones have been associated with fish foraging strategies (Orth and White, 1999) and fish migration (Nestler and others, 2008). Recent telemetry studies in the LMOR confirm that migrating adult pallid and shovelnose sturgeon are found disproportionately on the edges of the channel in areas of high energy dissipation (Jacobson and others, 2007; Reuter and others, U.S. Geological Survey, written commun., 2009).

Maps of kinetic energy dissipation spatial standard deviation, vorticity, total strain, and velocity gradient show similar patterns (figs. 22, 23). Similarity indicates that at the resolution of our models, deformation of the flow field can be captured in a variety of ways. Although, the simplest indicator is the slope of the velocity map (velocity gradient), the other metrics serve to illustrate related hydrodynamic phenomena that may be better correlated with some ecological functions. As a simple indicator, we identified areas of high



Base from U.S. Department of Agriculture National Agriculture Imagery Program, digital data, 2006
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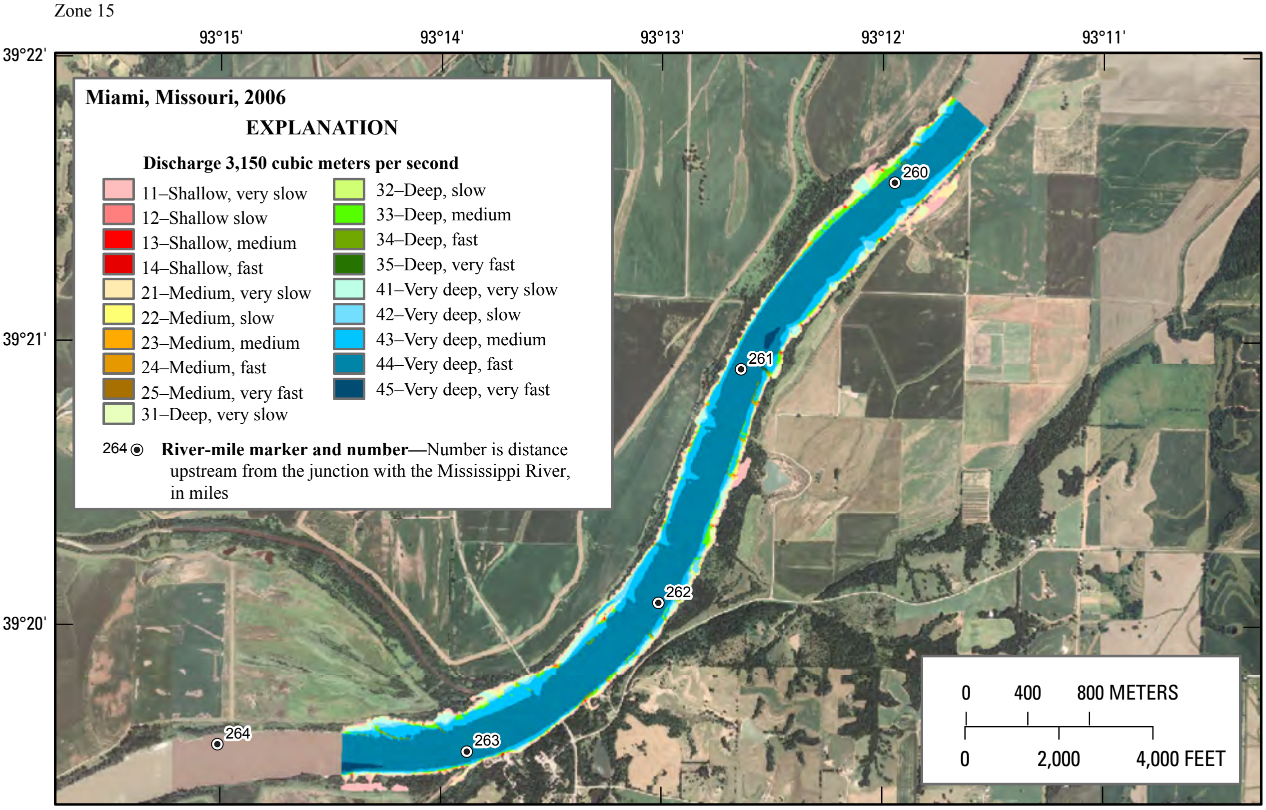

Base from U.S. Department of Agriculture National Agriculture Imagery Program, digital data, 2006
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River miles from U.S. Army Corps of Engineers, 1960

Figure 15. Depth-velocity field patch structure at the Miami, Missouri reach.

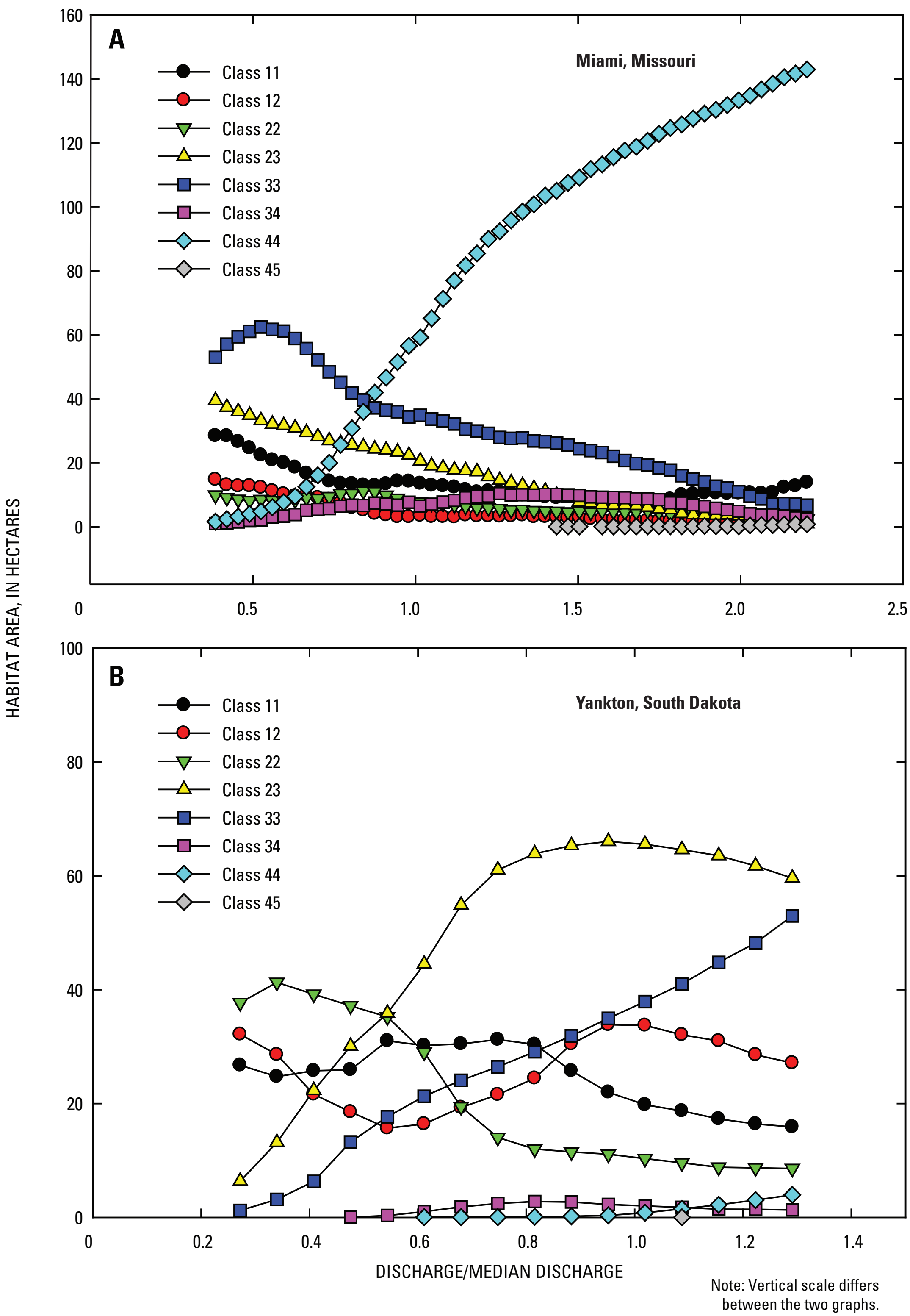


Figure 16. Depth-velocity patch area as a function of discharge at Miami, Missouri and Yankton, South Dakota.

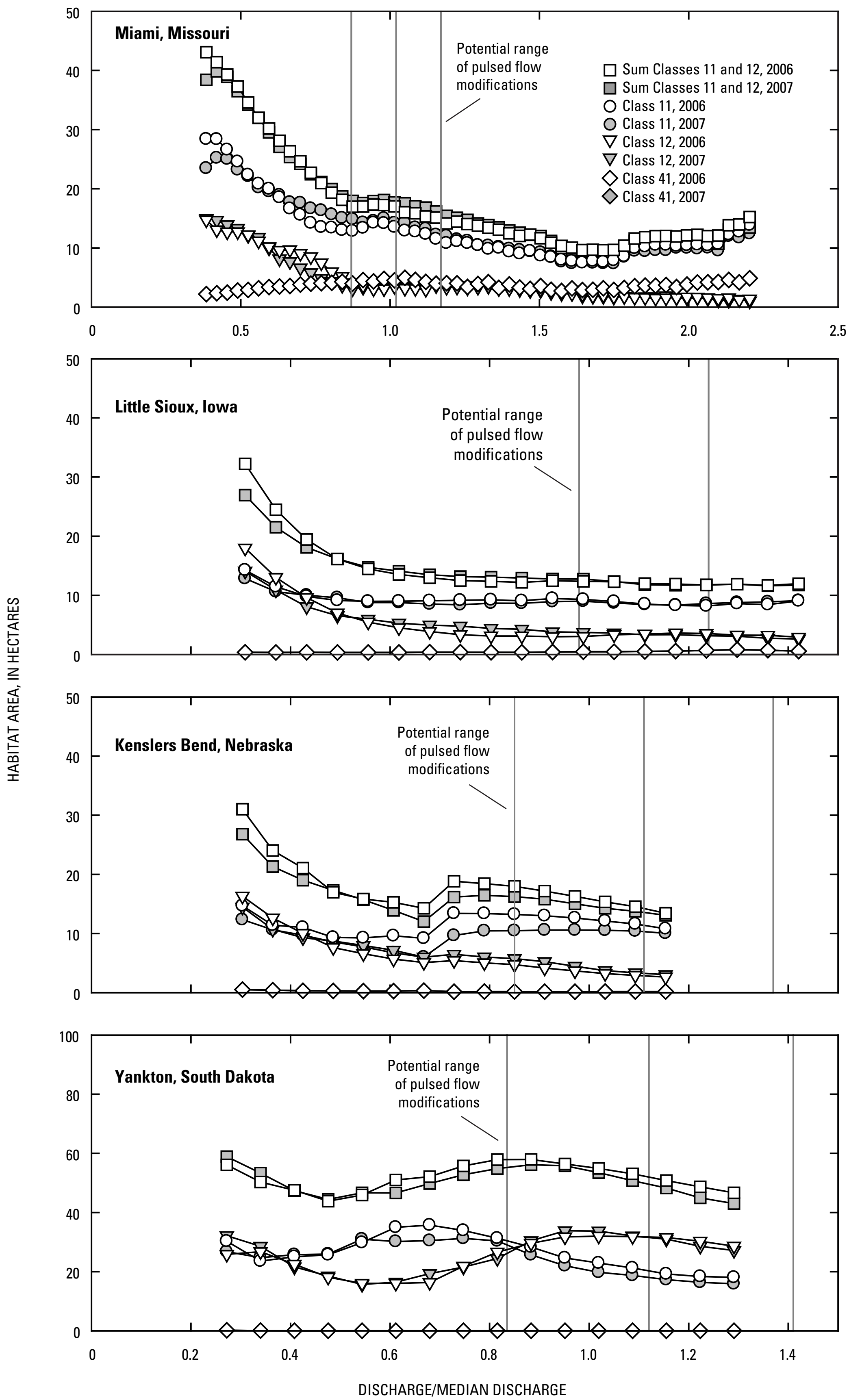
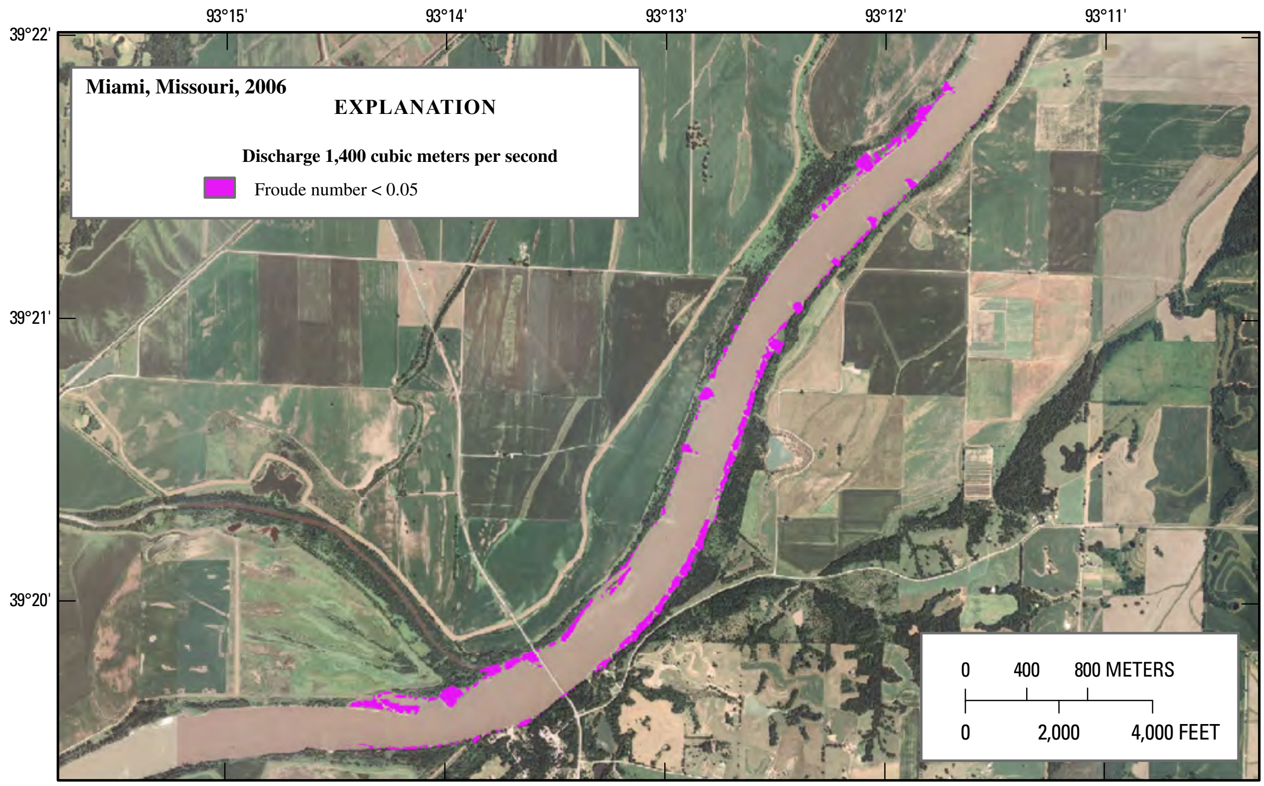


Figure 17. Depth-velocity habitat patch areas as a function of discharge at four modeling reaches.



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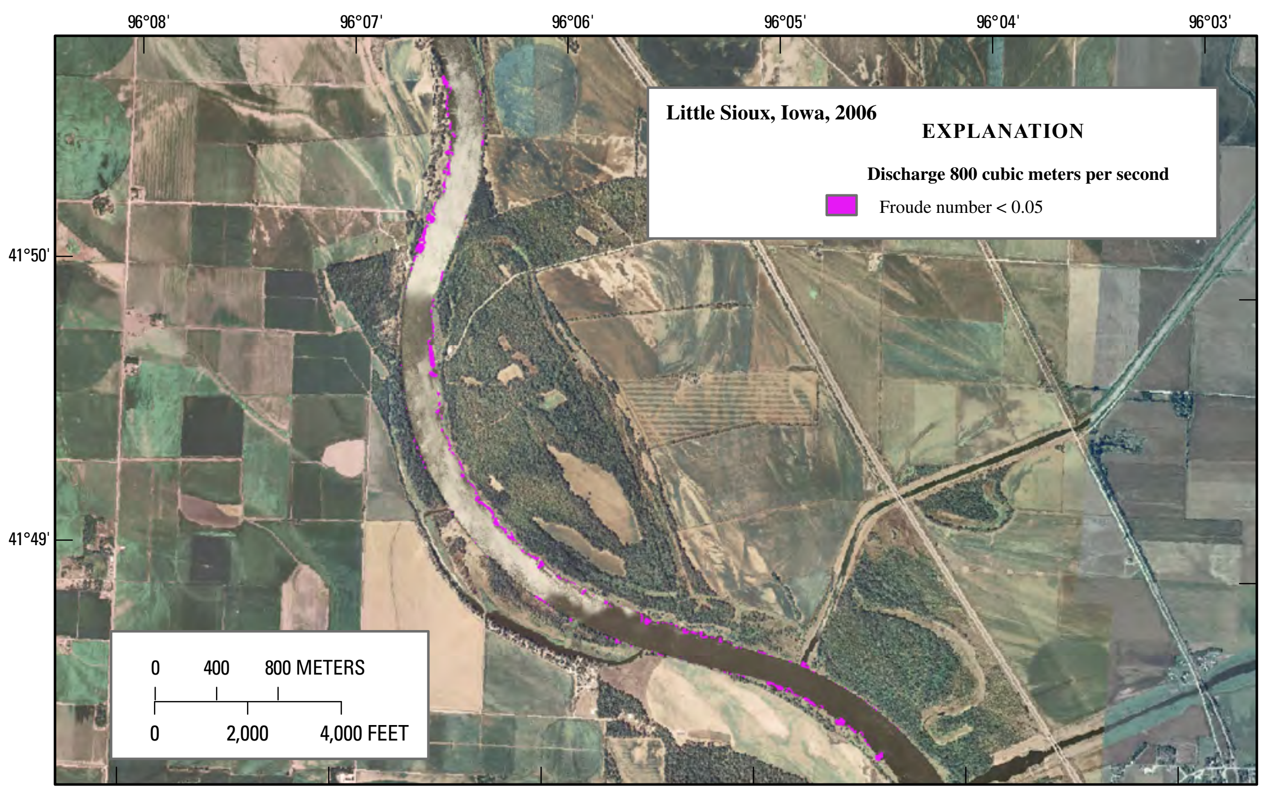

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Figure 18. Areas with Froude numbers less than 0.05 at Miami, Missouri and Little Sioux, Iowa reaches.

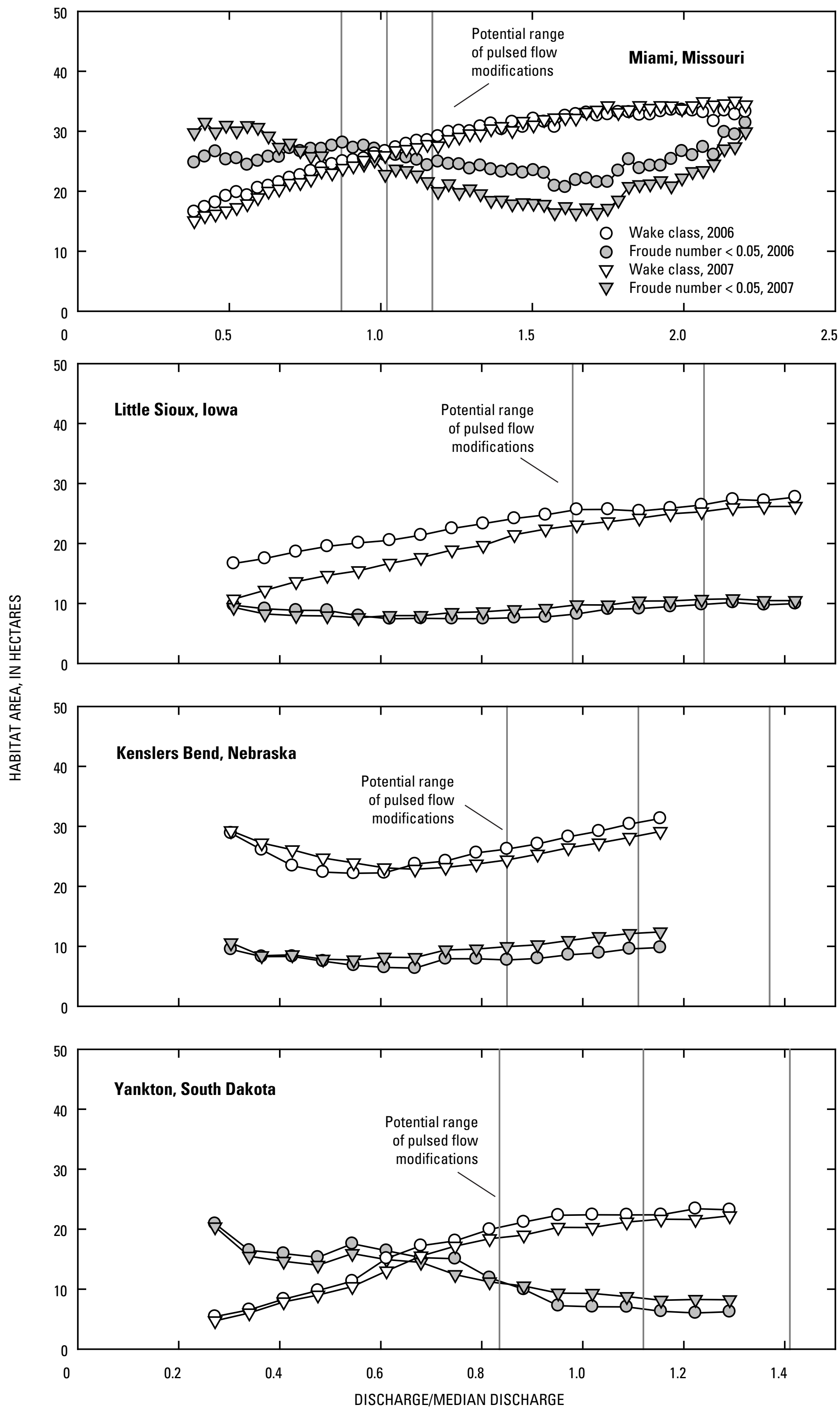


Figure 19. Wake and low Froude number patch areas as a function of discharge at four modeling reaches.

velocity slope (hereafter referred to as wakes) as those cells with greater than a 2 percent change in velocity over a meter, or 10 percent change over a 5-m cell. These wake areas occur preferentially along the margins of banks, bars, and wing dikes (figs. 23, 24).

Wakes comprise greater area in the downstream modeled reaches than at Yankton, indicating the effect of river size, and perhaps engineering structures, on increasing flow deformation (fig. 19). There are somewhat higher areas of wake habitat at low flows in 2006 compared to 2007 at the Little Sioux and Kenslers Bend reaches, probably as a result of high flows in early spring 2007 that decreased sandbar-margin areas. Wakes area generally increases with increasing discharge (fig. 19).

Reach-Scale Integrative Measures

Several measures of hydraulic habitat can be aggregated at the reach scale to indicate broad trends along the LMOR. These include benthic terrain mapping classes (BTM), spatial statistics that assess relations among habitat patches, residence time of water in the reach, and a measure of total fluid strain.

Benthic Terrain Mapping Classes

Benthic terrain mapping (BTM) classes are defined using measures of local topography derived from depth grids. The approach classifies cells into ridges, depressions, planar areas with low slope, and planar areas with high slope (Weiss, 2001; Lundblad and others, 2006; Jacobson and others, 2007). The units derived depend on scaling parameters that determine the area to be evaluated for local concavity/convexity, the elevation threshold for determining that a cell is above or below neighboring cells, and a slope steepness threshold (Jacobson and others, 2007). We used one set of parameter values for all four modeling reaches. The parameters were selected to resolve landforms of consistent size along the river rather than scaling the landforms relative to the size of the channel, although either approach could be justified. The parameter values generally resolve sandbar complexes (ridge areas), the thalweg (depression areas), steep banks (planar and steep), and flat areas like crossovers and sand-bar margins (planar and not steep). Examples are shown in figure 25.

BTM depression and ridge areas are relatively insensitive to discharge variation over the range of discharges evaluated and did not change much from 2006 to 2007 (fig. 26). Because of this, BTM classes may be useful in evaluating relevant landforms without the complication of varying discharge. Because BTM classes resolve landforms rather than patches, they serve to delineate habitat complexes that may host a suite of ecological functions. For example, the ridge BTM class generally maps shallow sandbar complexes marginal to the navigation channel. This class may be an effective descriptor of the suite of habitats intended to be restored under the SWH program on the LMOR.

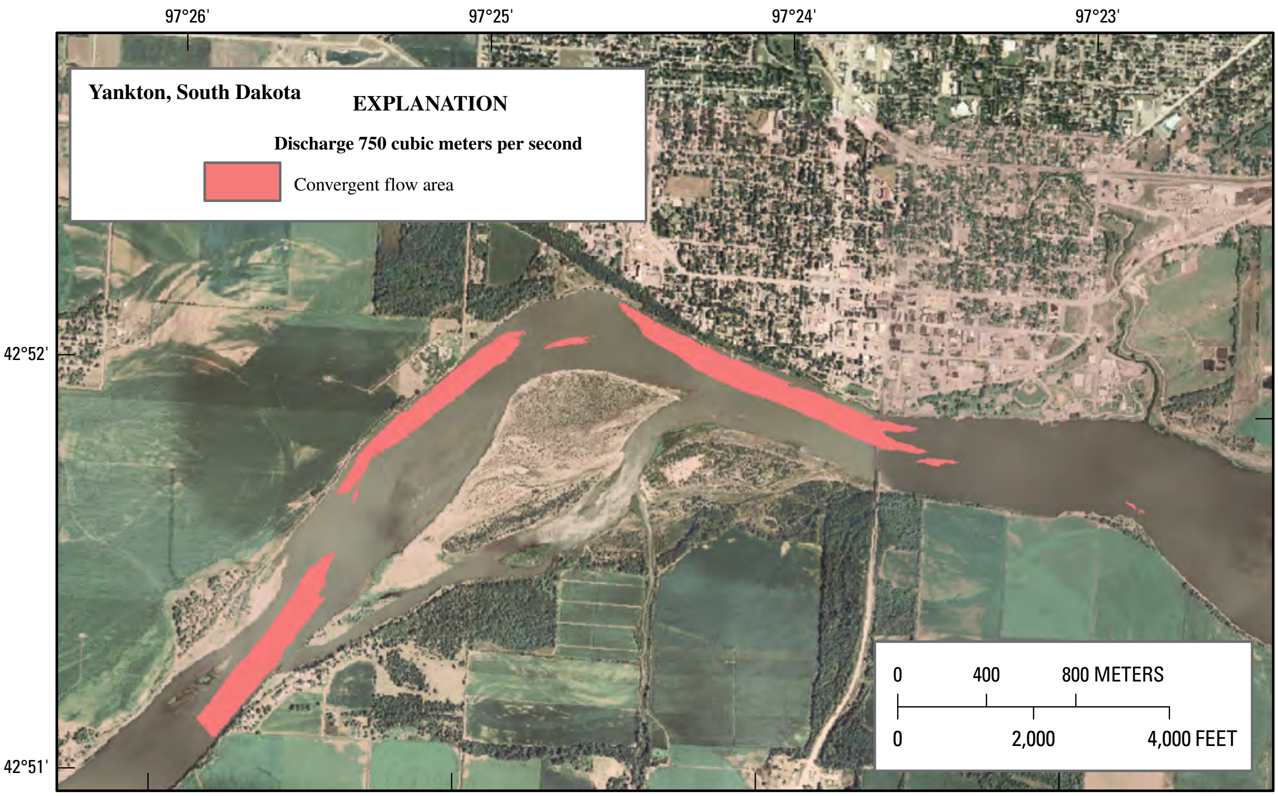
Habitat Patch Statistics

Patch density (number of depth-velocity patches per 100 hectares) is highest in the Little Sioux and Kenslers Bend reaches, indicating greater complexity in those two reaches relative to Yankton and Miami (fig. 27). Conversely, mean patch size (not shown) is larger in Yankton and Miami than the other two reaches. Edge density tends to co-vary with patch density, as increased patchiness generally increases edges between patches. Patch and edge density at Little Sioux decreased from 2006 to 2007. High flows during March 2007, arising from the Vermillion, James, and Big Sioux tributaries to the Missouri River, had a peak discharge approximately 1.4 times the median daily discharge (fig. 3). Substantial sediment transport and geomorphic change during this period (Elliott and others, 2009) resulted in simplification of habitat patches as shown by the decrease in patch and edge density. At Kenslers Bend, which was subjected to the same flood event but at a lower relative magnitude, density and edge density increased during the same time period. The Yankton reach was not affected by these high discharges, and patch and edge density remained relatively constant. The Miami reach was affected by even greater relative discharge during May, 2007 (5.6 times median discharge), but topography and patch structure were not simplified or changes did not persist (fig. 11).

Diversity of habitat patches can be quantified by the Simpsons Diversity Index (SDI, fig. 28) which represents the probability that any two patches selected at random from the reach will be different (McGarigal and Marks, 1995); high values of the index indicate a more diverse reach. The four reaches have four different functional relations between discharge and SDI. In the Miami reach, SDI increases with increasing discharge to approximately 0.9 times the median discharge, after which it falls. Simplification of patch structure with increasing discharge also is evident from the maps in figure 15. There is little difference between SDI in 2006 and 2007 at Miami. The increase in diversity as discharge increases to approximately median discharge coincides with flows that emerge from the thalweg and flow over sandbars. As discharges increase past the median, patch structure is increasingly dominated by depth-velocity classes in the main channel.

In the Little Sioux reach SDI also increased from low flow up to approximately median discharge and then decreased; however, the 2007 SDI was uniformly lower (indicative of patch simplification) and it was less sensitive to discharge variation than in 2006 (figs. 28 and 29).

At Kenslers Bend, the SDI relation to discharge was similar in 2006 and 2007. In each year, SDI decreased as discharge increased from 0.25 to 0.75 times median discharge and then increased up to the maximum modeled discharge at approximately 1.1 times median discharge. The relatively high SDI at low discharge probably indicates high habitat complexity within the low-flow channel in this minimally engineered reach. Diversity decreases as the thalweg fills, then increases as flows interact with channel-marginal bars.



Base from U.S. Department of Agriculture National Agriculture Imagery Program, digital data, 2006
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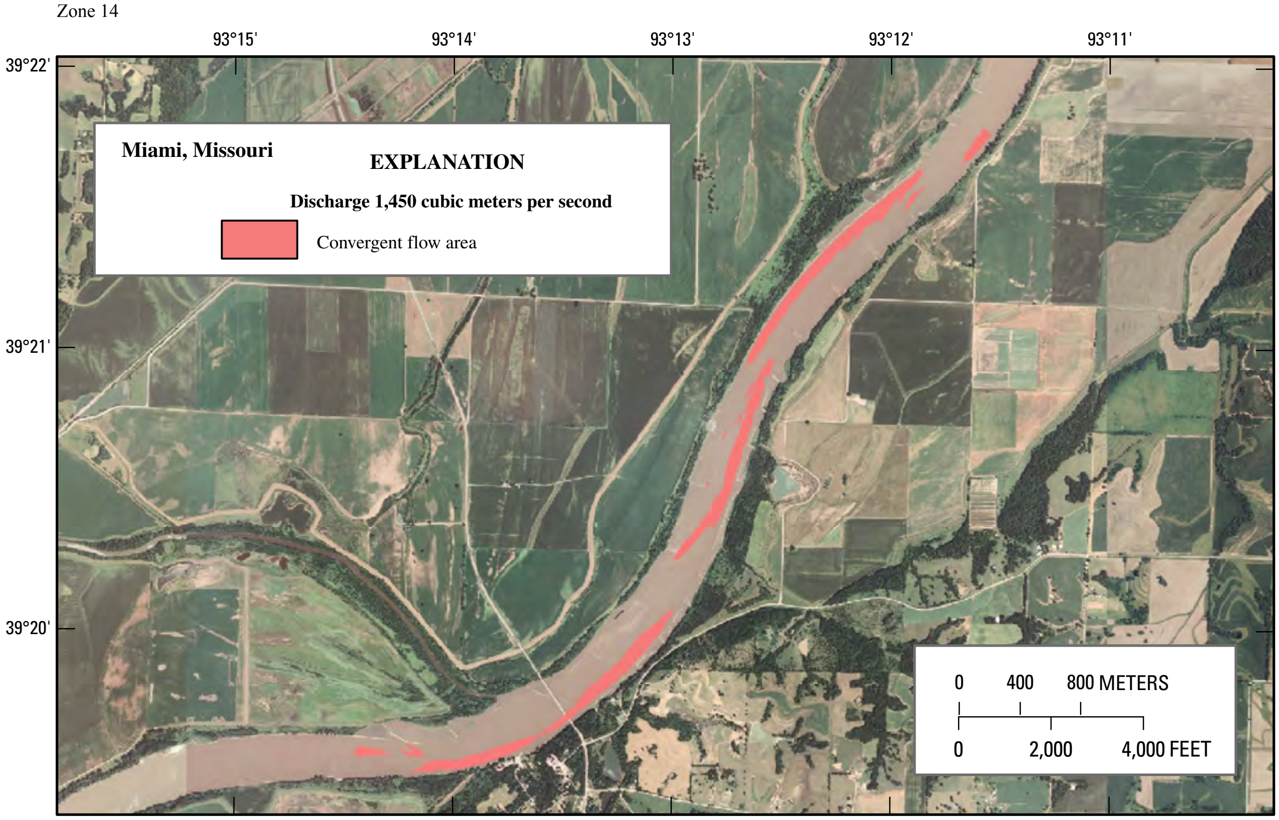

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Figure 20. Examples of convergent flow classes at Yankton, South Dakota and Miami, Missouri.

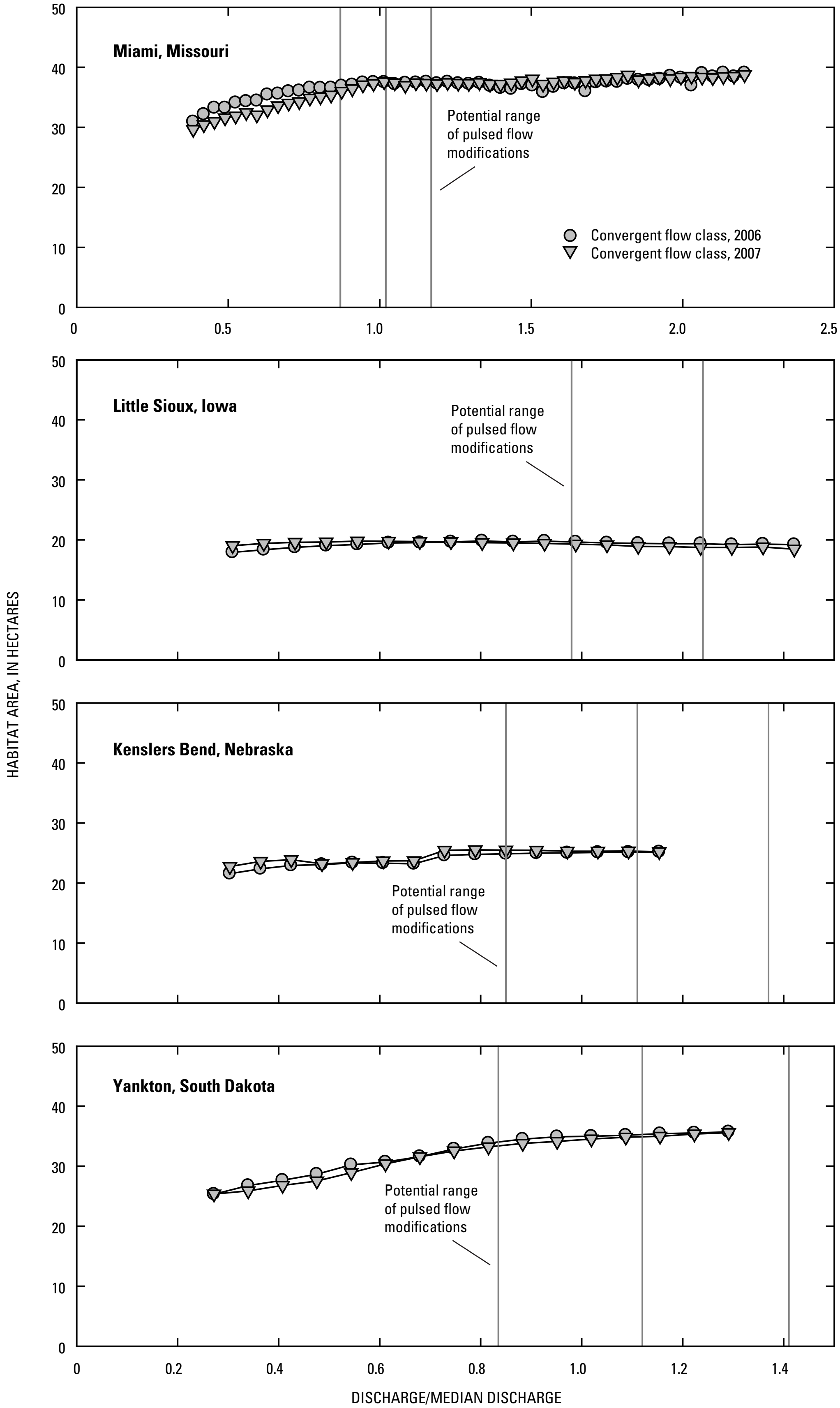


Figure 21. Convergent flow class areas as a function of discharge at four modeling reaches.

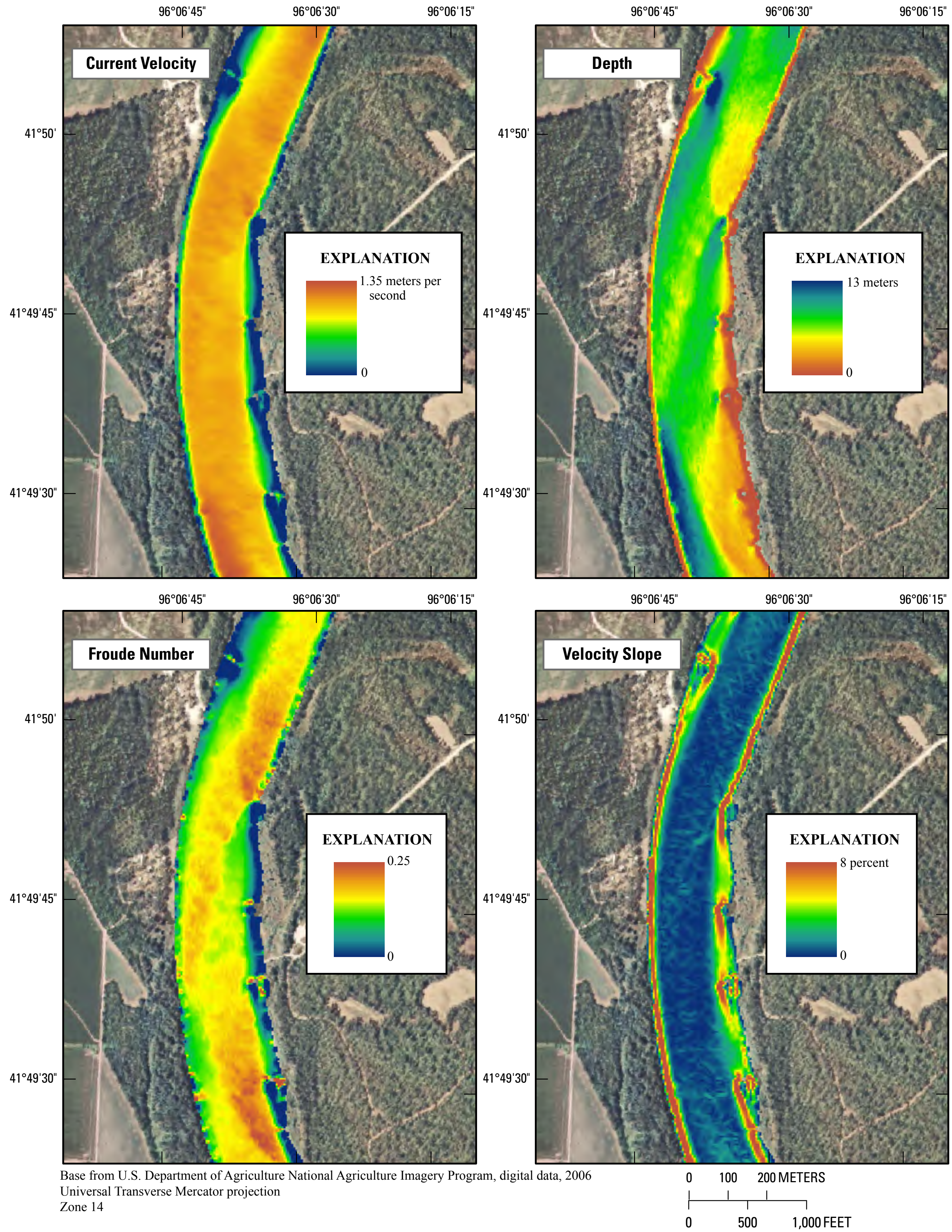


Figure 22. Examples of derivative hydraulic metrics at Little Sioux, Iowa reach: velocity, depth, Froude number and velocity slope.

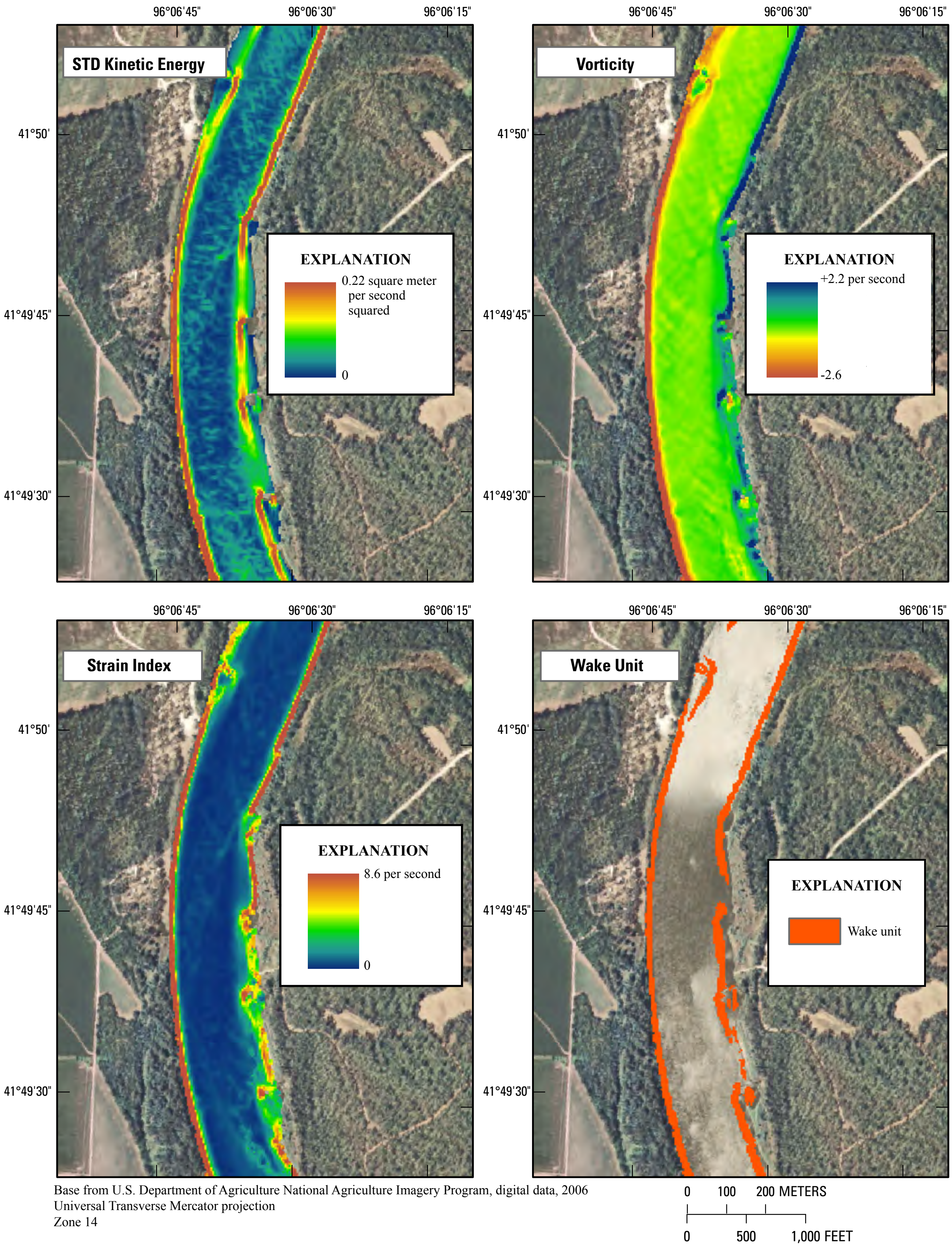


Figure 23. Examples of derivative hydraulic metrics at Little Sioux, Iowa reach: standard deviation of kinetic energy, vorticity, strain index, and wakes.

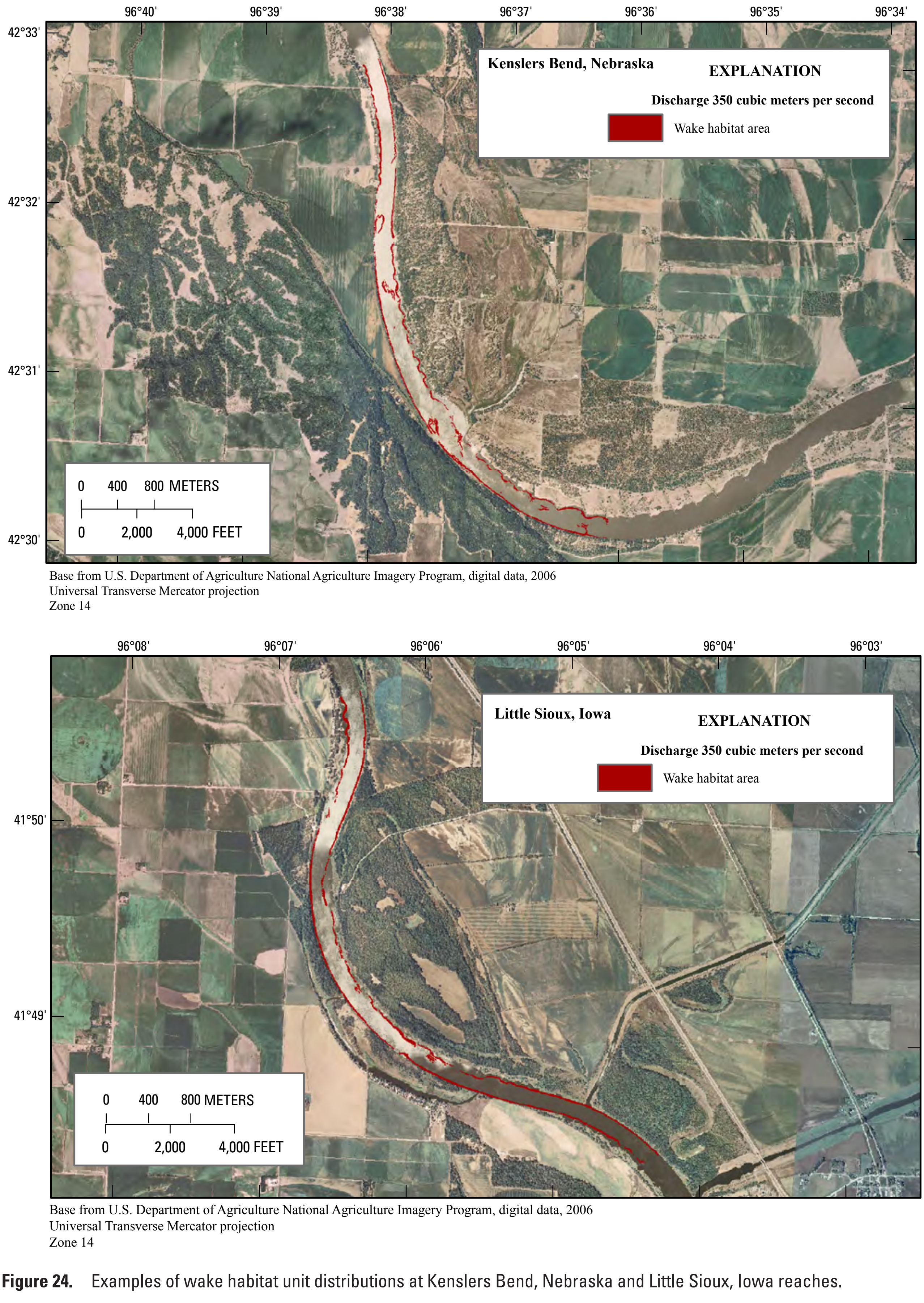
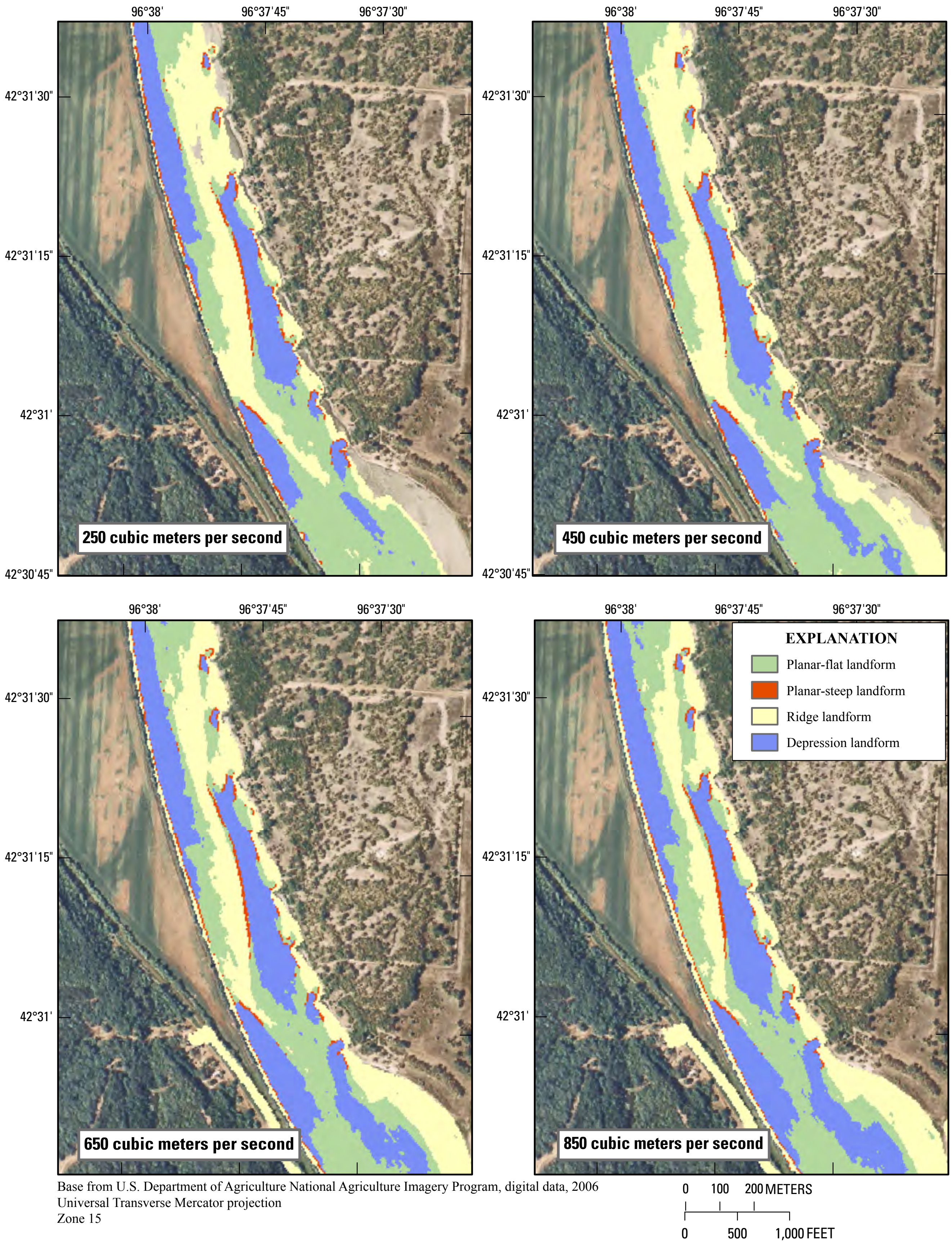


Figure 24. Examples of wake habitat unit distributions at Kenslers Bend, Nebraska and Little Sioux, Iowa reaches.



Base from U.S. Department of Agriculture National Agriculture Imagery Program, digital data, 2006
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Figure 25. Examples of benthic terrain map (BTM) units at Kenslers Bend, Nebraska.

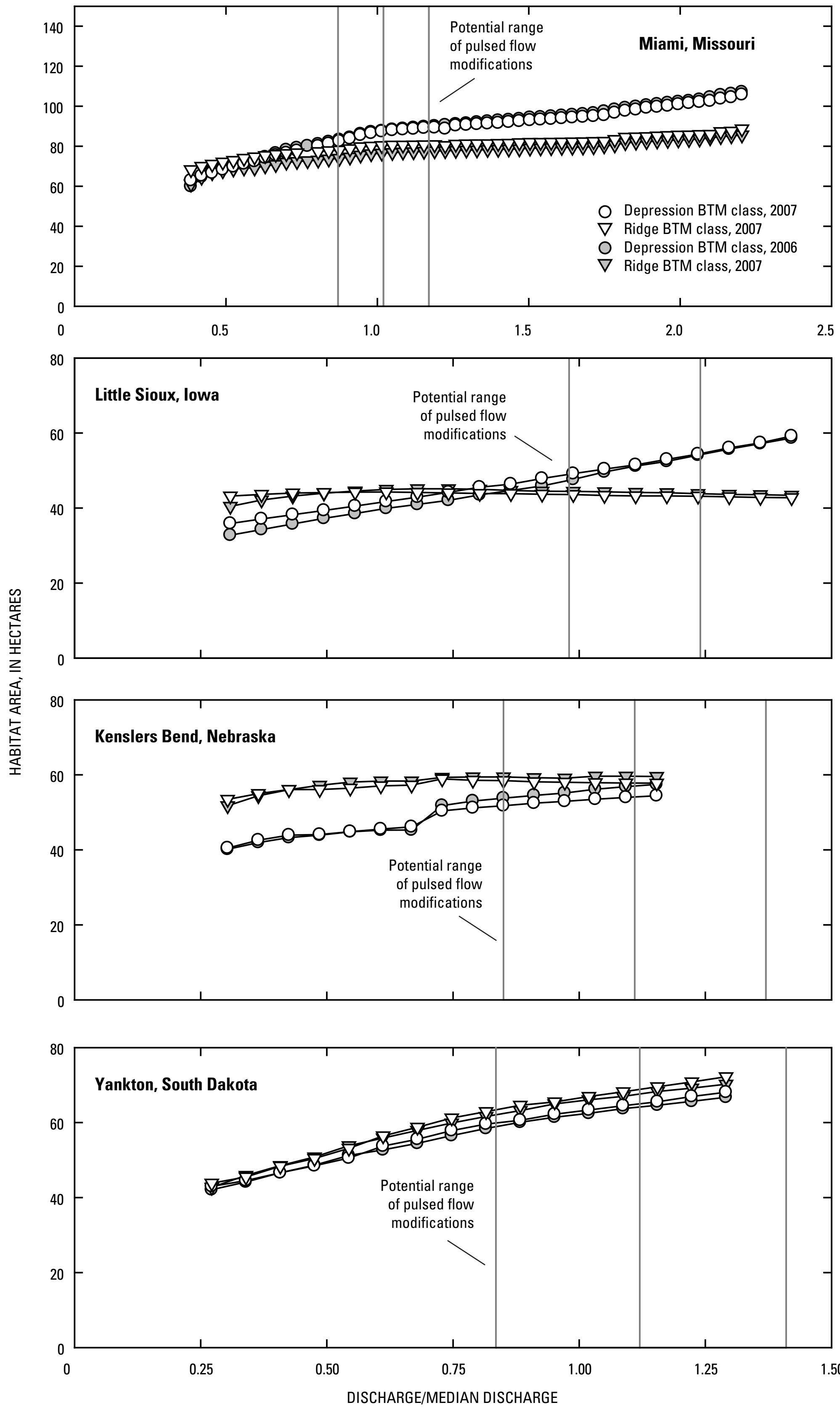


Figure 26. Areas of benthic terrain map (BTM) classes as a function of discharge for the four modeling reaches.

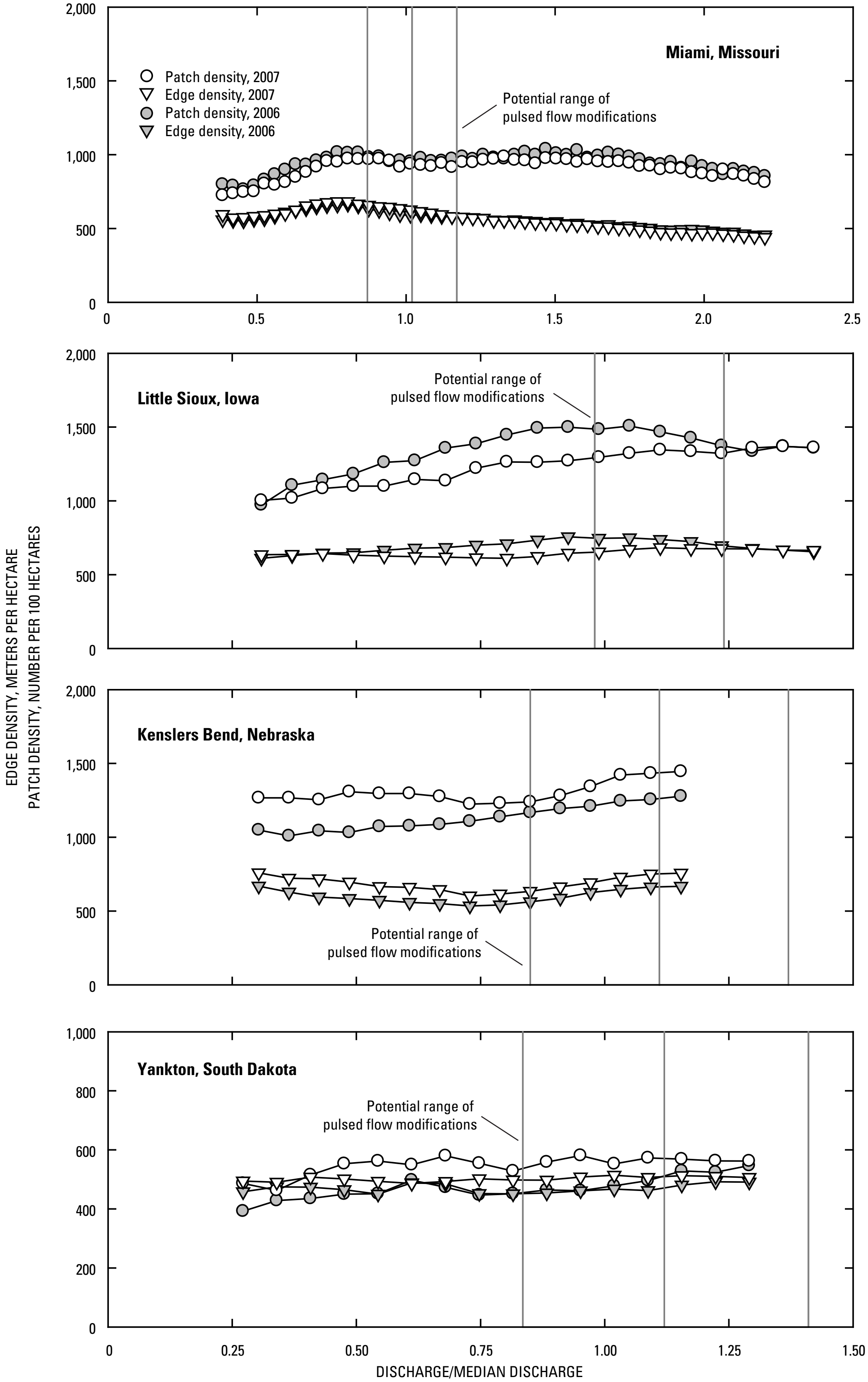


Figure 27. Patch and edge density values as functions of discharge for the four modeling reaches.

At Yankton, SDI is relatively high and relatively insensitive to discharge variation.

The interspersion and juxtaposition index (IJI) measures how interspersed different patch classes are relative to a maximum of 100 percent. In highly interspersed reaches, dissimilar patches tend to occur close together. The degree of interspersion would affect how easily organisms, energy, and materials can be transferred among similar or dissimilar habitat patches. IJI is relatively insensitive to discharge or annual variability at all sites. Decreases in IJI from 2006 to 2007, at Little Sioux and Kenslers Bend, at discharges slightly below the median probably result from patch simplification from the geomorphically effective flood of March 2007.

The mean nearest neighbor metric (MNN) measures mean distance between edges of like patches, and indicates distance an organism may need to travel to find another patch of suitable habitat. IJI and MNN are insensitive to discharge in the four modeling reaches (fig. 30). Decreases in MNN at Kenslers Bend and Yankton at low discharges probably result from expansion of shallow, low-velocity patches (fig. 17, 30).

Residence Time

Mean residence time of water in a reach is indicative of the ability of a reach to retain water and relates inversely to mean reach velocity. Longer residence time is associated with higher probability of retaining passively transporting, buoyant particles (organic matter, drifting invertebrates, and larval fish), and greater opportunity for biogeochemical interactions. As such, mean residence time of water may provide a useful integrative indicator of some ecological functions and how those functions are altered by restoration activities.

All four modeling reaches have mean residence times (measured as hours per kilometer of reach length) that decrease steeply with increasing discharge, then level off after reaching median discharge (fig. 31). The three downstream reaches have very similar residence time functions. The Yankton reach stands out with substantially longer residence times for given discharges and with a substantially steeper rate of decline as discharge increases from 0.25 to about 0.6 times median. Longer mean residence time at Yankton results from the wide, shallow channel and the effects of side channels on slowing and retaining water. The steeply decreasing residence time with increasing discharge indicates that pulsed flow modifications could substantially alter retention of organic matter, invertebrate drift, or larval fish in this reach.

Hydraulic Strain

An index of hydraulic strain was calculated by summing unit two-dimensional strain associated with each computational cell in the models and dividing by reach length to produce a total strain per unit length (TSUL) with units of $m^3/s/m^2$, or m/s. As hydraulic strain is coupled with turbulence, and turbulence may strongly influence fish migration pathways (Nestler and others, 2008), energetics (Enders and others, 2003; Liao, 2004; Standen and others, 2004; Liao, 2006), spawning site selection (Buckley and Kynard, 1981; 1985; Paragamian and others, 2001; Paragamian and others, 2002), and feeding strategies (Lupandin and Pavlov, 1996), differences in total strain among river reaches may be important to reproduction and survival of the pallid sturgeon. At present, however, ecological mechanisms are unknown.

TSUL in the Miami reach is substantially higher for all discharges than that of Little Sioux and Kenslers Bend reaches (fig. 32). Greater TSUL strain is probably associated with the longer wing dikes that exist in the Miami reach. TSUL varies considerably with discharge at Yankton and attains values substantially higher than Little Sioux or Kenslers Bend. Higher values of TSUL at Yankton are probably attributed to greater flow resistance in the wide, shallow channel, and to flow through side channels. TSUL was also substantially lower in 2007 than 2006 at Yankton. We speculate that this difference results from high sensitivity of TSUL to how flow is divided between the main channel and the side channels. Small topographic changes that limit flow down a side channel would substantially diminish total hydraulic strain in the reach.

Sensitivity of Habitat Functions to Pulsed Flow Modifications

Pulsed flow modifications during the spring have been hypothesized to affect reproduction and survival of pallid sturgeon by (1) providing an environmental/behavioral cue, (2) altering habitat through sediment transport, and (3) altering habitat availability (U.S. Fish and Wildlife Service, 2000; 2003; Jacobson and Galat, 2008). We assessed the potential for proposed spring flow modifications to alter habitat availability by looking at changes in habitat functions over a range discharges that might be affected by flow modifications. The ranges of flows modeled also were constrained by confidence in extrapolating flows beyond calibrated limits. We defined a reference for potential flow modifications by calculating median flow for the nearest streamgaging station for the period April 1–May 30 under a modeled flow scenario with no spring rise (the water control plan prior to 2005) and adding/subtracting one half of a potential pulse of 15,000 ft^3/s (414 m^3/s). This range of discharges serves as a reference for the potential effects of pulsed flow modifications on habitat availability (figs. 17, 19, 21, 26–28, 30–32). At the three upstream reaches, this interval extends somewhat beyond the upper limit of modeled discharges that was chosen to encompass 25–90 percent flow exceedances based on the entire year.

Sensitivity of suspected spawning habitat to flow modifications is of special interest because pulsed flows have been hypothesized to improve spawning success of sturgeon on the LMOR (U.S. Fish and Wildlife Service, 2000; 2003; Quist and others, 2004; Bergman and others, 2008). With the present level of understanding (2008) provided by scientific literature on other species and emerging telemetry data from the LMOR,

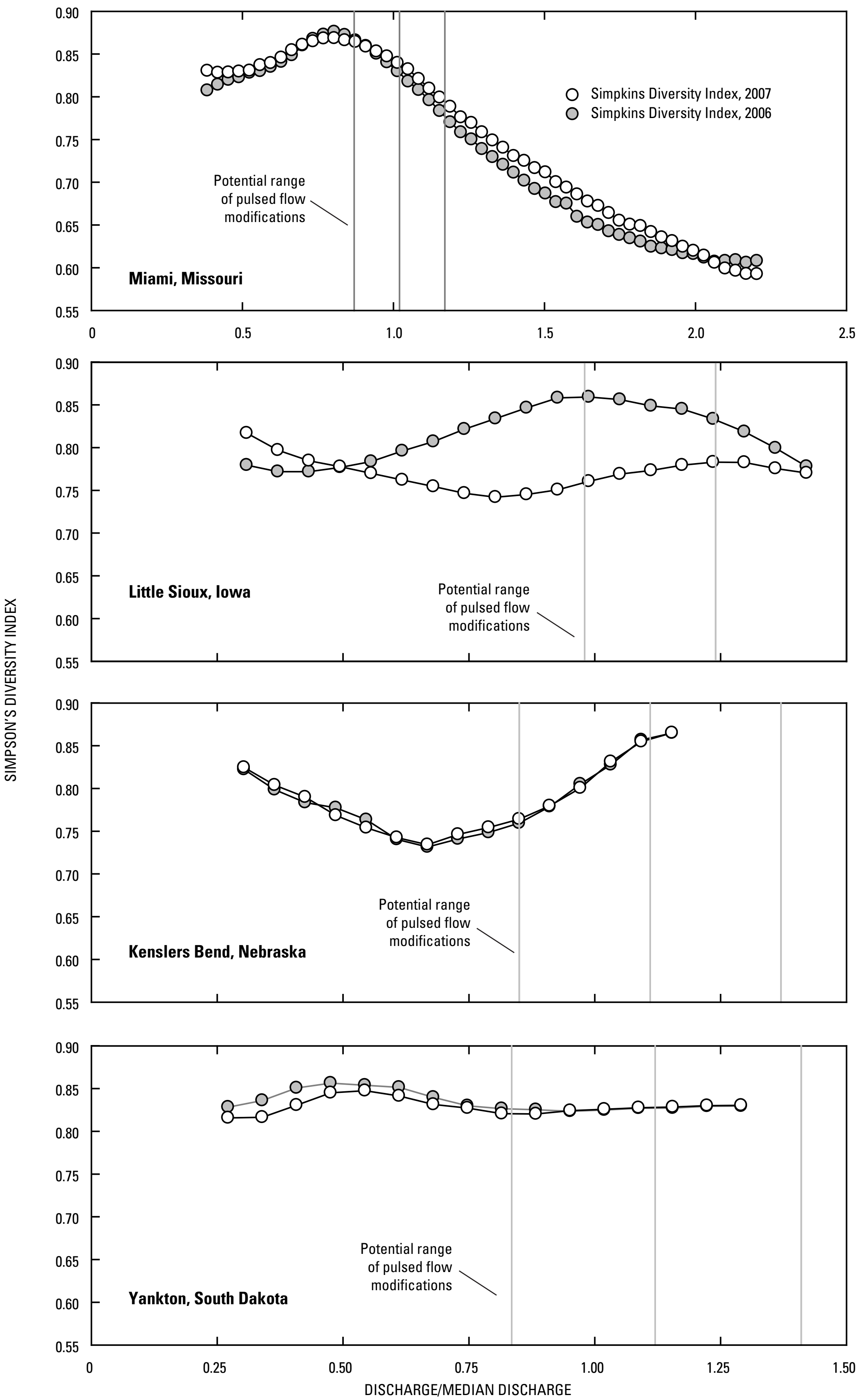
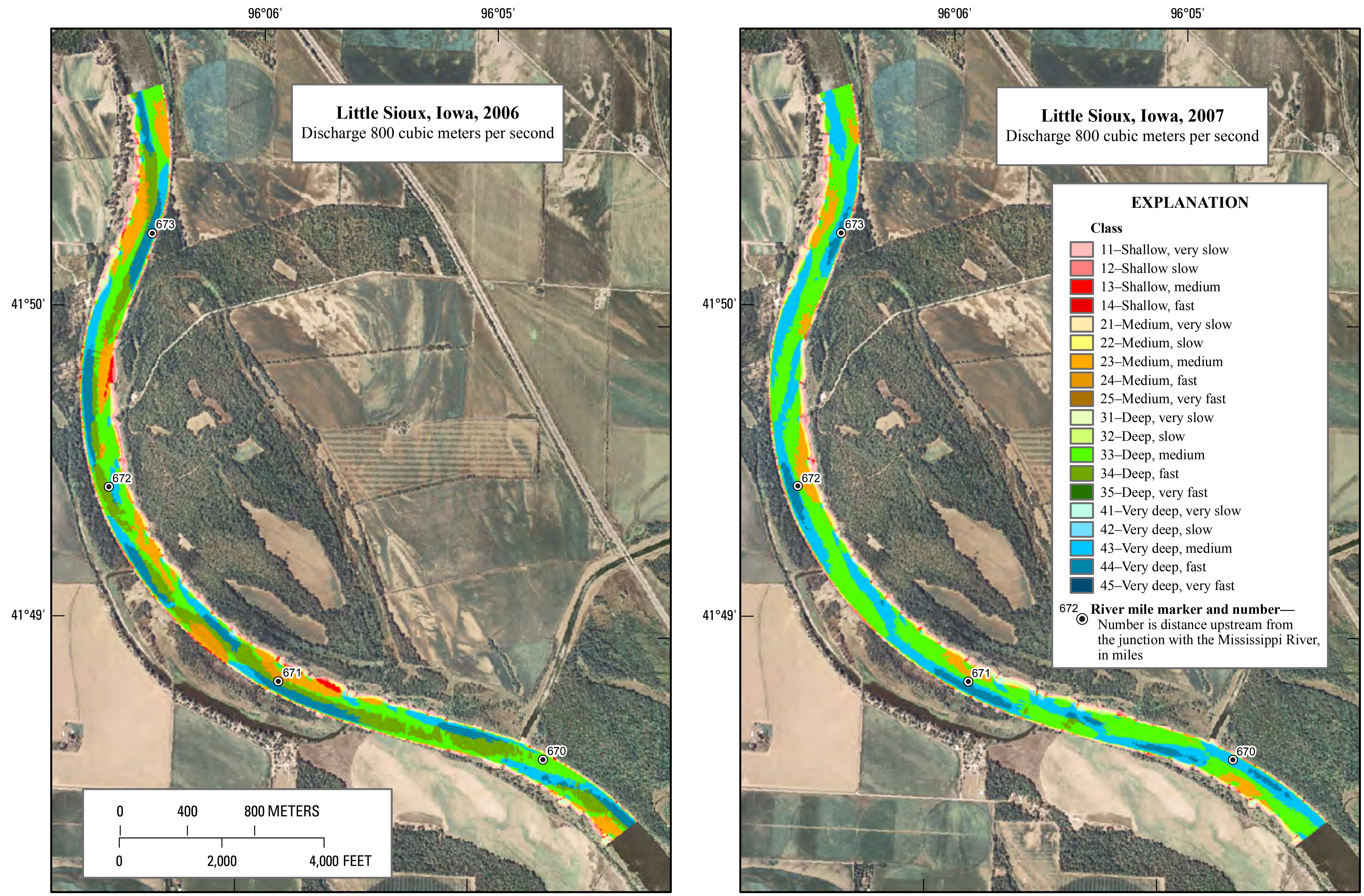


Figure 28. Simpson's diversity index (SDI) for habitat patches as functions of discharge for the four modeling reaches.



Base from U.S. Department of Agriculture National Agriculture Imagery Program, digital data, 2006
Universal Transverse Mercator projection
Zone 14

River miles from U.S. Army Corps of Engineers, 1960

Figure 29. Depth-velocity field patch maps at Little Sioux, Iowa for discharges of 800 cubic meters per second, 2006 and 2007.

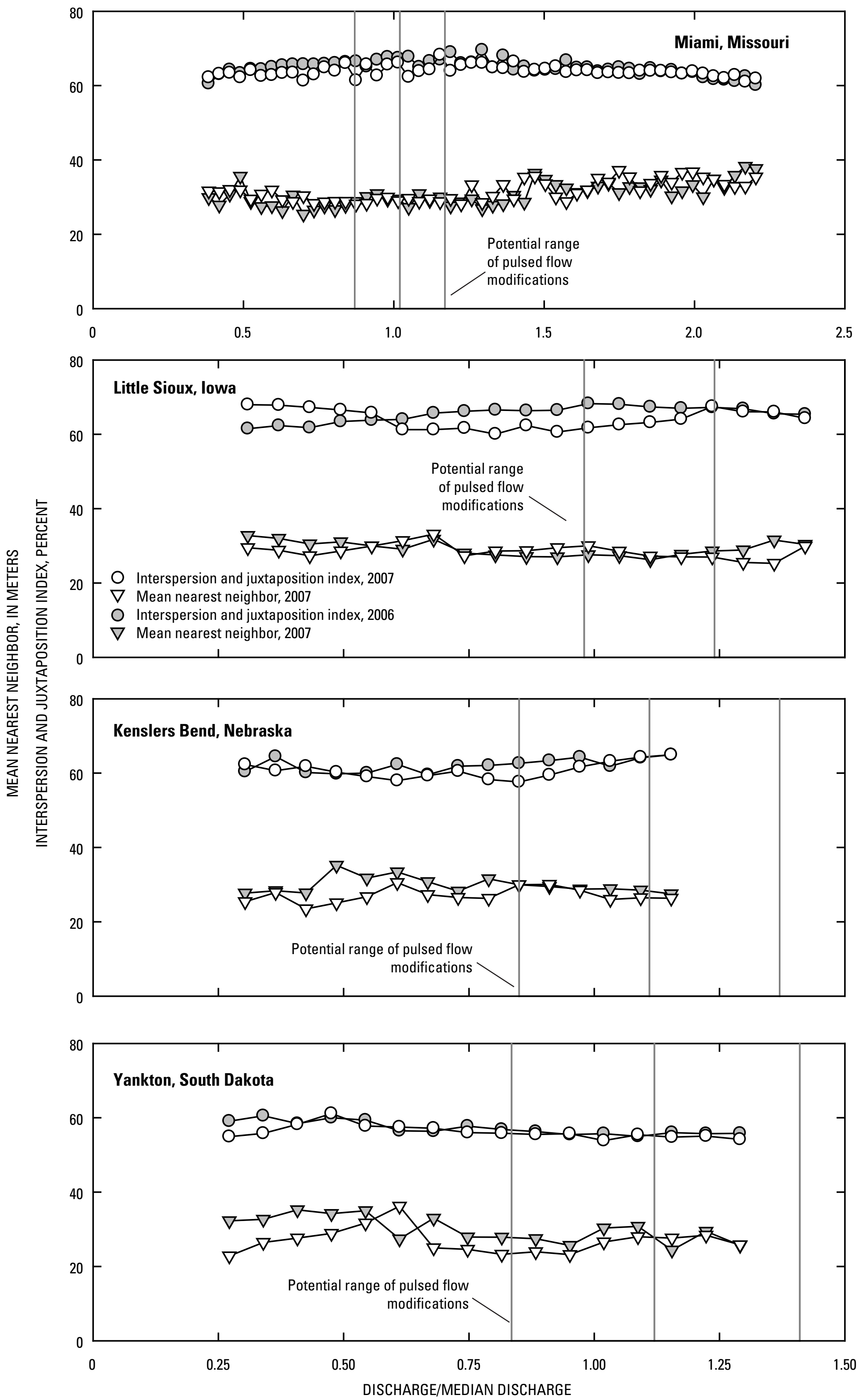


Figure 30. Interspersion and juxtaposition index (IJI) and mean nearest neighbor (MNN) between like patches as functions of discharge for the four modeling reaches.

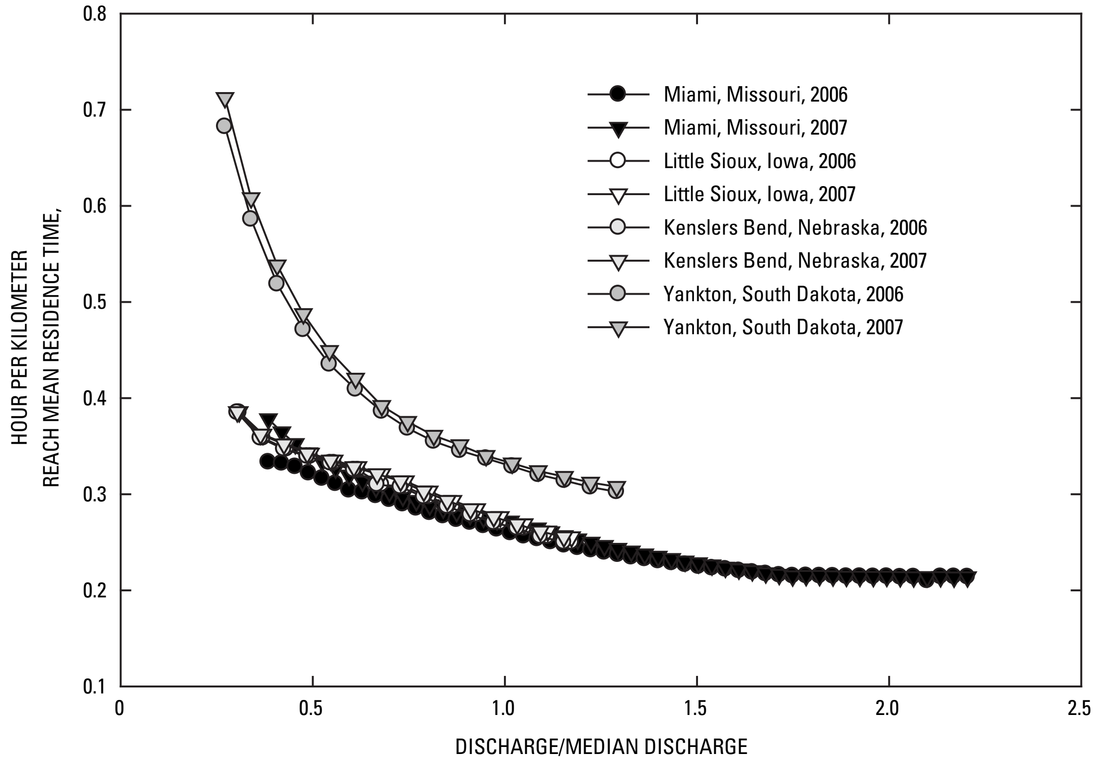


Figure 31. Mean residence time of water in hours per kilometer of reach length, as functions of discharge for the four modeling reaches.

convergent flow zones over coarse substrate appear to have the most potential for spawning habitat for LMOR sturgeon (Paragamian and Kruse, 2001; Paragamian and others, 2001; Paragamian and others, 2002; McDonald and others, 2006; Fu and others, 2007). Availability of convergent zones is not sensitive to discharges modeled in this study in the four modeling reaches (fig. 21); however, this result does not address the quality of substrate in convergent zones. Many studies on sturgeon reproductive ecology support the understanding that sturgeon spawn over clean, coarse, hard substrate like gravel, cobble, and bedrock (June, 1977; Parsley and others, 1993; Kynard, 1997; Fox and others, 2000; Paragamian and others, 2001; Hatin and others, 2002; Kolman and Aarkua, 2002; Manny and Kennedy, 2002). The substantial quantity of sediment transport that occurred in the Kenslers Bend and Little Sioux reaches between 2006 and 2007 surveys indicates that modest flows have the potential to alter substrate surface characteristics in some reaches (figs. 12 and 13). Sediment transport and habitat dynamics at the modeling reaches are addressed in more detail in Elliott and others (2009).

Low-flow discharge modifications also have been proposed as a mechanism to provide rearing habitat for larval and juvenile sturgeon, and foraging habitat for other native species including sturgeon prey fishes (U.S. Fish and Wildlife Service, 2000; 2003; Quist and others, 2004; Bergman and others, 2008). These habitat functions have been ascribed to shallow, slow-current velocity habitats (shallow-water habitat, SWH), which are assessed in this report as classes 11 and 12. Shallow-water habitat availability decreases with increasing discharge at the three downstream reaches to about 0.8 time median discharge. This is consistent with previous work has concluded that much of the increase in shallow-water habitat in the channelized section of the LMOR occurs at discharges that are too low to support other river uses, especially navigation (Jacobson and Galat, 2006; Jacobson and Galat, 2008). Areas of these habitat classes varied little over the pulsed-flow range and would not be affected by proposed pulsed flow modifications. Shallow-water habitat classes at Yankton are more extensive than the downstream reaches, and decrease at a slower rate with increasing discharge through the pulsed flow range, compared to the other reaches.

Deep, slow-current velocity habitat like those delineated by Froude numbers less than 0.05, or depth-velocity class 41, decrease by less than 20 percent with increasing discharge through the pulsed flow range at the Miami and Yankton reaches (figs. 17, 19). These habitat classes increase no more than 10 percent through the pulsed flow range at Little Sioux and Kenslers Bend. Low sensitivity of these habitat classes indicates that water retention and depth-cover functions of these habitats would not be highly affected by pulsed flow modifications.

Landform units delineated by BTM classes also are relatively insensitive to discharge variation, making them potentially useful as discharge-independent indices of habitat

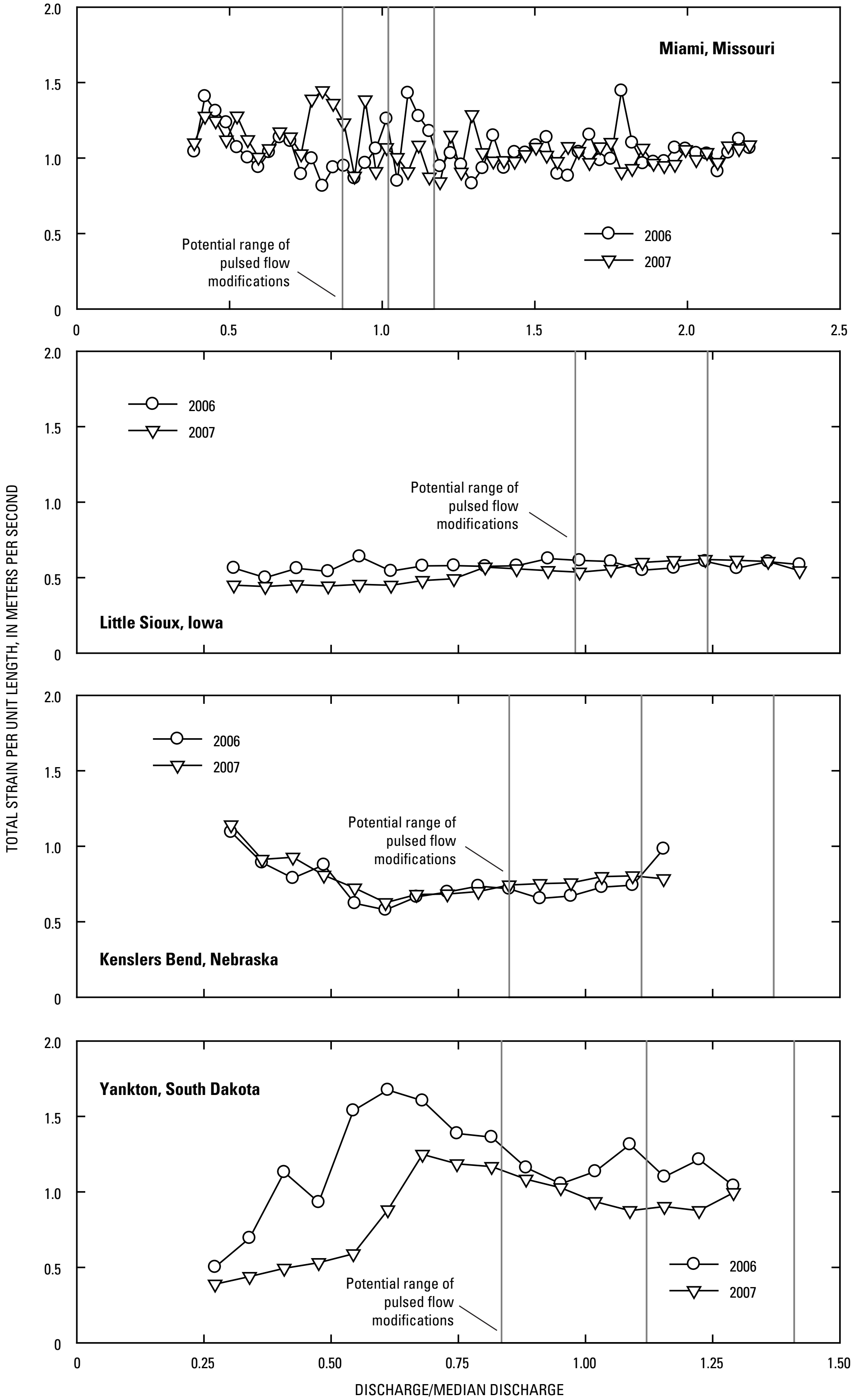


Figure 32. Total strain per unit channel length (TSUL) for the modeling reaches, 2006 and 2007.

complexity (fig. 26). BTM class area increases no more than 10 percent with increasing discharge through the pulsed-flow range at Miami, Little Sioux, and Kenslers Bend as the thalweg fills with water. Area of the ridge class, however, keeps pace by adding small quantities of area on the channel margins so total ridge area changes very little. For the Yankton reach, depression and ridge classes increase in area 3 to 8 percent through the pulsed-flow range.

Measures of patch structure like patch density and edge density, interspersion and juxtaposition index, and mean nearest neighbor vary little with discharge over the pulsed-flow range (figs. 27, 30). In contrast, SDI based on habitat patches varies substantially with discharge in the three downstream reaches over this range (fig. 28). Patch diversity decreases with increasing discharge at Miami as patch structure is increasingly dominated by the fast, deep units in the thalweg. The patch diversity function at Little Sioux was similar to Miami in 2006, but topographic changes in March 2007 resulted in overall decrease of SDI and a change in functional relation with SDI increasing from 1 to 1.25 times median discharge. We interpret this as a result of erosion and simplification of the main channel accompanied by deposition and corresponding increased numbers of patches at higher elevations. The SDI functional relation at Kenslers Bend shows a similar effect with SDI increasing as flow emerges from the thalweg and creates more diversity as it inundates marginal bars. SDI varies little over the assessment range at Yankton. These results show that habitat diversity is a sensitive function of discharge in the assessment range, although variation among sites precludes generalization for the river as a whole.

Although the mean residence time of water in the Yankton reach is substantially higher than the downstream reaches at all discharge exceedances, residence times at all four reaches fall at the same rate with increasing discharge, for discharges that would be affected by pulsed flow modifications. These relations indicate that pulsed flow modifications would be associated with decreases in mean residence time of 0.05 h/km or less.

Model Information Content and Ecological Understanding

Hydrodynamic modeling was used in this study as a tool to explore relations among discharge, channel morphology, and ecological functions with emphasis on habitat requirements for reproduction and survival of the endangered pallid sturgeon. As is common in many hydroecological studies, specific functional relations between physical processes and ecological functions (reproduction, larval drift, for example) are lacking (Jacobson and Galat, 2008). Although we cannot yet link specific biological outcomes to physical processes or management actions, modeling of physical processes provides useful information to constrain understanding of LMOR ecology.

Model Capabilities

The information content of hydrodynamic models may be limited by implicit assumptions in the coding of hydraulic equations. In this study, the hydrodynamic models are limited to depth-averaged, two-dimensional views of what are actually complex three-dimensional flow fields. In addition, model information content can be limited by the resolution of the numerical grid, errors or omission of input data, or errors arising from factors not addressed in the models, such as deformation of the bed because of sediment transport, water-temperature effects, and vegetation effects. Of these factors, dynamic changes to bed topography on seasonal to multiyear timeframes are probably the most significant in altering model predictions. Sensitivity analyses indicate that model parameter estimation errors do not propagate to substantial variation in many habitat measures (table 5). Channel morphological changes from 2006 to 2007 produced changes in some habitat measures by 10 percent or more. Changes from 2006 to 2007 were greatest for patch and edge density at Little Sioux and Kenslers Bend (fig. 27). Change in SDI was substantial at Little Sioux from 2006 to 2007 (fig. 28).

Morphological changes at Little Sioux and Kenslers Bend substantially altered locations of specific habitats as portions of the thalweg were filled in and marginal bars were scoured. On a reach-average basis, however, deposition was largely balanced by erosion, thereby minimizing reach-average habitat variation measured in terms of total area of habitat classes (figs. 11–14, see Elliott and others, 2009). Movement of habitat patches from year to year may not be a hardship for fish species if they can relocate to functionally equivalent habitats in different locations. Alternatively, change in habitats related to shape, size, or patchiness may be sensitive to such geomorphic change and may be ecologically important.

Although two-dimensional hydrodynamic models provide greater resolution and realism than one-dimensional models (Nelson and others, 2003), they do not provide the full three-dimensional flow field experienced by fish. Two-dimensional models, however, may be a cost-effective compromise in modeling complexity in cases where biological responses are largely uncertain or immeasurable. In such cases, two-dimensional results may provide indicators of underlying three-dimensional processes at a resolution commensurate with prevailing biological knowledge. For example, two-dimensional measures of velocity gradient and flow deformation do not capture the full three-dimensional, multiscale turbulence that occurs in shear zones; however, the low-resolution indicators may be perfectly adequate to address questions about habitat requirements at the resolution of biological understanding.

Sensitivity analysis at the scale of habitat units provided insight into how model requirements may vary with the specific need for biological understanding. For example, areas of the shallowest habitat classes (classes 11 and 12) were relatively sensitive to selection of drag coefficient, although other classes were not. If biological understanding supports a critical role of the shallowest habitat classes in ecosystem function or pallid sturgeon reproduction and survival, then hydrodynamic modeling should put greater emphasis on improving modeling of these classes. Conversely, if ecological functions are found to correlate better with less-sensitive, integrative measures (for example, BTM units or areas of convergent flow), then lower standards for hydrodynamic habitat modeling could apply.

Models as Exploration Tools

In addition to evaluating habitat sensitivity to pulsed flow modifications, the hydrodynamic models presented in this report are intended to provide a framework for exploration of physical, chemical, and biological understanding on the LMOR. The models present a systematic approach to understanding how physical processes vary along the river and, therefore, how chemical and biological responses may also vary. For example, one of the most visible results presented in this report is the much greater mean residence of water in the unchannelized Yankton reach compared to the downstream reaches. This observation may be a basis for hypothesizing how short residence times constrain nutrient processing or larval retention in the channelized river. Similarly, identification of convergent flow areas as probable spawning locations at the reach scale provides guidance for sampling designs for spawning adults, eggs, and larvae.

Modeling also can be used to evaluate information content of ecosystem indicators. For example, assessments of habitat restoration projects that involve reconfiguration of the channel require measures that account for varying discharge (Jacobson and others, 2004). This can be accomplished by carrying out assessments at all sites at common flow exceedance or by using ecological metrics that are insensitive to discharge. The BTM units presented in this report have potential as robust indicators of ecological structure. BTM classes are calculated from depth alone, thereby eliminating the need to measure or model velocity. Hydrodynamic modeling indicates that BTM classes are relatively insensitive to discharge variation (fig. 26). This property and the fact that BTM units can be computed using only depth data, suggest that BTM units could be an effective indicator of reach-scale ecosystem structure.

Reference Conditions

Hydrodynamic modeling also can be useful for systematic, quantitative comparison between altered systems and reference conditions. Reference conditions provide a standard for evaluating the performance of an alteration compared to a benchmark state. The benchmark state, however, can be defined in a variety of ways, including the minimally disturbed condition, the documented historical state, the best attainable condition, or the least disturbed condition (Stoddard and others, 2006). The present condition might also be added to this list, as performance can be assessed as improvement moving away from the present state, as well as improvement moving toward a conceptual improved state.

When the contemplated alteration is a change in flow regime, as in the case of pulsed flow modifications, a hydrodynamic model provides the utility to assess sensitivity of habitat availability to the range of flows under consideration. In this case, the implicit reference condition is the present state, as habitat changes were assessed as pulses were added to the present flow regime. It would also be possible to assess performance relative to the historical or minimally disturbed condition by assessing how habitat availability varies under proposed flow modifications and the natural flow regime. Estimates of the natural flow regime are available from models of unregulated Missouri River system hydrology (U.S. Army Corps of Engineers, 1998); however, spring pulses under a natural flow regime were 2 to 6 times the magnitude of those contemplated for spring pulsed flow modifications (Jacobson and Galat, 2008). The comparison is not possible, because flows of this range are far beyond the calibration of the models presented here and also would involve substantial sediment transport.

Modeling also provides for explicit comparison to a reference condition when the reference is defined as a place that has desirable characteristics. In this case, the Yankton reach presents many of the channel morphologic characteristics that were present in the pre-engineered Missouri River and could serve as a reference to evaluate habitat functions and restoration activities in other reaches. Habitat-function comparisons of the engineered reaches to the Yankton reach provide a measure of departure of the engineered river from the natural state (figs. 17, 19, 21, 26, 27, 28, 30, 31, 32). For example, the difference in shallow-water habitat class functions of the channelized river reaches compared to that at Yankton provides a measure of departure in the engineered river. Hence, the Yankton habitat functions provide a potential reference for channel reconfiguration in the lower river (fig. 17). Similarly, the interesting correspondence of low-Froude number habitat functions at Yankton and Miami suggests that large wing dikes in Miami may be providing ecological function that is present in the reference condition, although lacking at other engineered reaches (Little Sioux and Kenslers Bend; fig. 19).

Hydrodynamic modeling also can be used to develop historical reference conditions when data are sufficient to support modeling of the minimally disturbed condition (Remo and Pinter, 2007), as well as to compare present day, restored, and historical river conditions (Jacobson and Galat, 2006). Although historical data limit the resolution of historical reconstructions, such models can still resolve broad ecological questions to inform restoration.

Summary and Conclusions

We constructed computational hydrodynamic models for four reaches on the Lower Missouri River. Each reach was selected on the basis of appearing to have been used by gravid, female sturgeon for spawning or was thought to have highly favorable spawning habitat based on spawning requirements established for other sturgeon species. The Miami, Missouri, reach is the farthest downstream (river mile 259.6–263.5) and is typical of the channelized LMOR. The Little Sioux, Iowa, reach (river mile 669.6–673.5) is typical of the LMOR navigation channel upstream from the Platte River. The Kenslers Bend, Nebraska, reach (river mile 743.9–748.1) is partially channelized and revetted but is not used for commercial navigation. The Yankton, South Dakota, reach (river mile 804.8–808.4) is only 4 km downstream from Gavins Point Dam. The Yankton reach is partially stabilized but retains much of the geomorphic complexity of the unchannelized river.

Models were constructed and calibrated for channel conditions as surveyed in 2006 and 2007. Each reach had at least three calibration surveys conducted each year. We attempted to calibrate the models over a range of flows representing 25–95 percent flow exceedance, but lack of higher flows at the upstream sites prevented calibration over that range. Consequently, we extrapolated calibrated flows using discharge and roughness relations determined for the calibrated range.

The model results were analyzed to extract habitat metrics that are hypothesized to have high correlation with ecological functions based on limited biological datasets from the LMOR, ecological theory, or extrapolated from understanding of habitat requirements of other species. Emphasis was on understanding sensitivity of spawning habitat to discharge variation of a magnitude that could occur with spring pulsed flow modifications (“spring rise”); however, we also considered a broad range of derivative habitat metrics in order to explore how other habitat measures vary geographically and with discharge along the LMOR.

Most of the habitat metrics were insensitive to discharge variation over the range of modeled flows and over the range of discharges that has been considered for spring pulsed flow modifications. Therefore, pulsed flow modifications would not be expected to substantively change availability of these habitat units. In particular, convergent flow areas, which are consistent with limited LMOR biological data on sturgeon spawning areas and consistent with descriptions of spawning habitats of other sturgeon species, vary little with discharge. As with previous modeling studies, these results indicate that flow modifications to produce substantially more shallow, slow-water habitat in the channelized river would require extremely low discharges. Areas of BTM units were relatively insensitive to discharge variation and very stable from year to year, indicating possible promise as broad indicators of habitat complexity along the river. Although relatively insensitive to discharge variation, reach-scale patch statistical metrics (edge density, patch density) were sensitive to morphological changes from 2006 to 2007, especially at the Little Sioux and Kenslers Bend reaches. High flow between the two surveys in March 2007 simplified patch structure at Little Sioux but had the opposite effect at Kenslers Bend. As a habitat complexity measure, the SDI was insensitive to morphological changes at all but the Little Sioux reach and varied considerably with discharge at Miami and Kenslers Bend reaches. Mean water residence time at the Yankton reach was substantially greater than the other three reaches for a given discharge exceedance. Mean water residence time is an integrated measure of of the reach’s ability to retain water or passively transporting particles and may be useful for its links to understanding temperature, water quality, and larvae retention.

The hydrodynamic models presented provide understanding of sensitivity of a variety of habitat metrics to discharge and to inter-annual morphological changes. While a great deal of work remains to establish biological links to physical habitat variation, these models provide a framework to support systematic assessment of links from management actions to habitat enhancement and ecosystem recovery.

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