in Proceedings of the Third Federal Interagency Hydrologic Modeling Conference, Reno, Nevada, April 2-6, 2006: Subcommittee on Hydrology of the Interagency Advisory Committee on Water Information, ISBN 0-9779007-0-3.

HYDROECOLOGICAL MODELING OF THE LOWER MISSOURI RIVER

Harold Johnson, Hydrologist, CERC, USGS, Columbia, Missouri, hejohnson@usgs.gov;
Robert Jacobson, Research Hydrologist, CERC, USGS, Columbia, Missouri, rjacobson@usgs.gov;
Aaron DeLonay, Ecologist, CERC, USGS, Columbia, Missouri, adelonay@usgs.gov

Abstract: The Lower Missouri River (LMOR) has been altered in both its channel form and flow regime by channelization and upstream dams. As a result, habitat availability for many fish species has been greatly modified or lost. One fish species, the pallid sturgeon (*Scaphirhynchus albus*), is on the federal endangered species list. Although the habitat needs of the pallid sturgeon throughout its life cycle are poorly understood, the perceived needs of this fish are having an increasing influence on river management decisions. Current management debate addresses the tradeoff between rehabilitating channel form and altering flow regime to improve habitat. To evaluate habitat availability on the LMOR, we developed a 2-dimensional, depth-averaged hydrodynamic model of a representative 8-km reach near Boonville, Missouri. The model provides an inventory of hydraulic habitat over discharges ranging 1-99 % flow exceedance. To evaluate habitat use, we used acoustically tagged shovelnose sturgeon (*Scaphirhynchus platorynchus*), a closely related species to the pallid sturgeon. Hydroacoustic maps of depth, velocity, and substrate at fish locations provide objective measures of habitat use. Results indicate that adult sturgeon select areas with high gradients of depth and velocity, typically found in wakes downstream of wing dikes and along steep banks and margins of sandbars. Using these criteria, the 2-d model results can be evaluated to map the occurrence of selected wake habitat. We also modeled another habitat class thought to be important for early life stages of native Missouri River fishes: shallow-water habitat (SWH, taken as 0-1.5 meters deep and 0-0.75 $m*s^{-1}$ current velocity). Although these two classes cannot describe the entire habitat needs of sturgeon on the Missouri River, they serve as indices of habitat availability that can be used to evaluate sensitivity to flow-regime management. With the intensively engineered channel form of the LMOR, wake habitats are relatively insensitive to flow regime, whereas SWH availability is highly sensitive, reaching a minimum during normal navigation discharges.

INTRODUCTION

Ecohydrological understanding of rivers requires integration of physical, chemical, and biological processes. In many rivers it is useful to begin assessment with physical habitat because it forms the template on which other processes are played out (Gorman and Karr, 1978; Jeffries and Mills, 1990) and because it has often been intensively altered (Gore and Shields, 1995). Single and multiple dimension hydraulic models are conventionally used to assess how much physical habitat is available (in terms of depth and velocity characteristics), and how availability varies with discharge (for example, Bovee et al., 1998). In some cases, physical habitat requirements for particular species are well known, so habitat needs can be compared directly with habitat availability. In the case of sturgeon species of the Lower Missouri River (LMOR), habitat needs have not been established and therefore have to be assessed based on documented use or other reasoning. In this paper we discuss an approach that combines fish telemetry, hydro-acoustic habitat mapping, and detailed two-dimensional hydrodynamic modeling to assess habitat use, habitat availability, and sensitivity of particular habitats to discharge variation.

Missouri River History The LMOR (Figure 1), has been heavily affected by flow regulation and channel engineering. Flow regulation began on the Missouri River in the late 1930's and was substantially completed with the closure of the Missouri River Reservoir System in 1954 (Ferrell, 1993; Galat and Lipkin, 2000; Jacobson and Heuser, 2001). The system is managed for multiple purposes including maintenance of commercial navigation flows, flood control, hydropower, public water supply, recreation, and fish and wildlife resources.

Channel modifications began in the early 1800's with clearing and snagging to improve conditions for steamboat navigation (Chittendon, 1903). The current channel morphology is dominated by rock wing dikes and revetments as a result of the Missouri River Bank Stabilization and Navigation Project (Ferrell, 1996). These structures stabilized the banks, and narrowed and focused the thalweg to create a self-dredging navigation channel from St. Louis, Missouri, 1,200 km upstream to Sioux City, Iowa. Riverine habitat loss on the LMOR has been estimated to be as much as 40,000 hectares (Funk and Robinson, 1974); substantial declines in ecosystem integrity have been associated with this habitat loss (Hesse and Sheets, 1993). Habitat loss or alteration has been implicated in the decline of several native Missouri River fishes, including the federally endangered pallid sturgeon (*Scaphirhynchus albus*) (Dryer and Sandvol 1993).

Figure 1 Lower Missouri River and location of modeling reach. BNV = Boonville, Missouri.

Recently, there has been increased interest in restoring elements of natural variability to the annual hydrograph of the LMOR (National Research Council, 2002, U.S. Fish and Wildlife Service, 2000; 2003). Redesign of the hydrograph requires an understanding of what specific habitats are required by biota of interest, in this case the pallid sturgeon, and how habitats vary with discharge. In addition to altering flow characteristics, extensive efforts are underway to re-engineer channel form (U.S. Army Corps of Engineers, 2003). Assessment of habitat availability must therefore include methods that can integrate form and flow through hydraulic modeling.

While habitat availability can be addressed using conventional multidimensional hydrodynamic models, little is known about specific habitat needs for the pallid sturgeon. Historical changes to the river indicate that the availability of shallow, slow-moving water has probably substantially decreased because of channelization (U.S. Fish and Wildlife Service, 2000; 2003). Moreover, there is broad ecological agreement that slow, shallow water is important to support rearing of young fish (Scheidegger and Bain, 1995; Bowen et al, 1998; Freeman et al, 2001), although specific requirements for young pallid sturgeon are unknown. Previous habitat analyses on the LMOR have focused on a specific combination of depth and velocity: shallow-water habitat (SWH) with depth 0-5 ft (0-1.5 m) and velocity 0-2 ft/s (0-0.75 $m*s^{-1}$) (U.S. Fish and Wildlife Service, 2000; 2003, U.S. Army Corps of Engineers, 2004). In addition to SWH, we address habitat use by adult pallid sturgeon by defining a new metric based on spatial variability of depth and velocity. This metric has been developed by hydroacoustic habitat mapping around locations of shovelnose sturgeon (*Scaphirhynchus platorynchus*), a widely used surrogate in the same genus as the pallid sturgeon.

Scope and Objectives Our objective was to assess sensitivity of two metrics of sturgeon habitat to discharge variation in a representative reach of the LMOR. Availability of physical habitat defined by these two metrics cannot be considered to be a complete assessment of the ecohydrological needs of *Scaphirhynchus* sturgeon on the Missouri River, but can be considered a start to improve understanding of how managed flow and form may affect these species. We selected a reach of the LMOR near Boonville, Missouri that has a channel form representative of much of the 1,200 km of the river from Sioux City, Iowa to St. Louis, Missouri (Figure 2). The hydrograph in the study segment retains some natural variability because of un-regulated tributary inflows downstream of Gavins Point dam. Effects of regulation are mainly apparent in decreased peak flows in early summer and increased flows to support navigation in late summer, early fall (Figure 3).

APPROACH

We used 2-dimensional hydrodynamic modeling to assess habitat availability over a range of discharges that could be affected by flow regulation. Specific habitats assessed were SWH, as conventionally defined on the LMOR, and a new habitat type we defined for adult sturgeon based on hydroacoustic mapping of fish locations.

Model Reach The selected reach was approximately 8 kilometers long with one major tributary (Lamine River) intersecting near the reach midpoint (Figure 2).

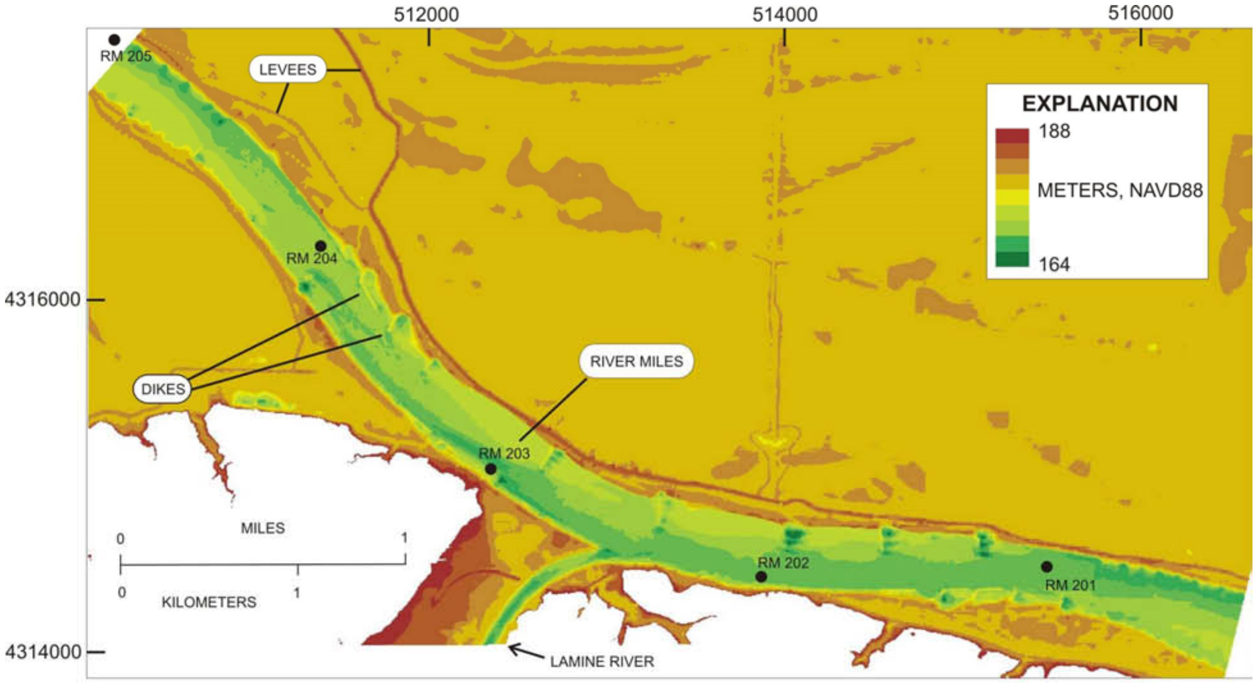

Figure 2 Modeled reach of the LMOR, just upstream of Boonville, Missouri

The selected reach includes two bend-crossover-bend repetitions, thereby ensuring replicates of major macrohabitats occurring on the river. The reach is approximately 6 km upstream of the streamgage at Boonville, Missouri (Figure 1; US Geological Survey 06909000). Discharges from the Lamine River were compiled from two gages measuring contributing flows: Lamine River near Otterville, Missouri (USGS 06906800) and Blackwater River at Blue Lick, Missouri (USGS 6908000), and periodic discharge measurements at the site.

We collected topographic data using a survey-grade echosounder and georeferencing with a real-time kinematic global positioning system (RTK-GPS) on channel cross sections spaced every 20 meters. We added terrestrial topographic surveys of navigation structures during low-water periods. Boat-survey data were complemented with simultaneous acoustic Doppler current profiler (ADCP) data and bottom-material discrimination instrumentation. Calibration and validation data (long profiles of water surfaces, discharges, and selected ADCP cross sections) were collected over a range of discharges. Details of survey procedures can be found in Elliott et al. (2004), and Jacobson et al. (2004a). The bed is dominantly fine-medium sand with admixtures of boulders (rip-rap) and bedrock on the channel margins and at navigation structures.

Flood-plain topographic data were added from existing U.S. Army Corps of Engineers high-resolution digital data (unpublished digital elevation data, DEM). Hydroacoustic elevations, terrestrial survey data, and DEM data were merged into a single data set gridded at 5 m. The gridded dataset was subsequently converted to a triangular irregular network (TIN) that was used as the initial computational grid mesh for the hydrodynamic model.

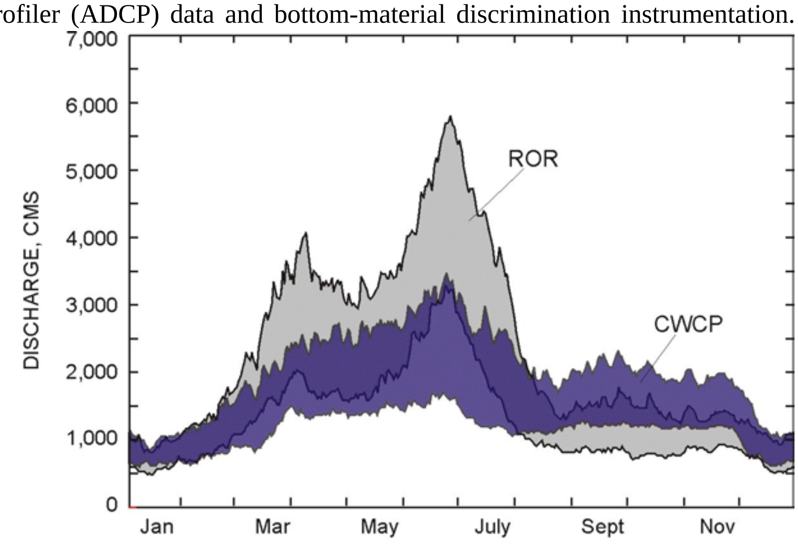

Figure 3 Duration hydrographs, Missouri River at Boonville, Missouri, showing contrast between the unregulated (run-of-the-river, ROR) hydrograph and the current water control plan (CWCP). Shaded bands depict the 75-25% range of flow exceedances. Data are from Jacobson and Heuser (2001).

Hydrodynamic Modeling We used River2D v. 0.90 (Steffler and Blackburn, 2002) to model depth and velocity in the study reach. River2D is a two dimensional, depth-averaged finite element hydrodynamic model that solves shallow-water equations. Topographic inputs were based on TIN data described above, imported into utility programs to create bed and mesh files. Stage-discharge relations were measured at the downstream end of the model reach and discharges were calculated for the tributary and upstream input. Roughness height was used to calibrate the model; other parameters ($\epsilon 1$ and $\epsilon 2$ coefficients used to calculate Boussinesq eddy viscosity, an upwinding coefficient to parameterize the finite element solving scheme, and ground-water transmissivity and minimum depth coefficients for aiding in wetting and drying calculations at the wetted boundary) were kept at default values. Sensitivity analyses documented that modeled velocities in the main channel and recirculating eddies downstream of wing dikes were generally insensitive to the choice of eddy viscosity parameters. Ground-water transmissivity was set at 0.01 to minimize ground-water discharge. Once the model was calibrated, it was then run to provide depth and velocity distributions for discharges ranging from 560 to 8500 cms (cubic meters per second, or 20,000 – 300,000 cubic feet per second), approximately 1-99% flow exceedance (Table 1).

Table 1 Modeled discharges, percent exceedance, and shallow-water and wake habitat areas.

Discharge			Shallow-water habitat		Wake habitat	
Cubic feet per second	Cubic meters per second	Percent exceedance	Hectares	Percentage	Hectares	Percentage
20000	566.34	99.2%	36.84	21.00%	59.53	33.73%
40000	1132.67	78.9%	33.50	16.09%	62.53	29.84%
60000	1699.01	47.3%	7.70	3.61%	54.49	25.34%
80000	2265.35	27.5%	4.05	1.88%	46.23	21.28%
100000	2831.68	17.0%	3.88	1.79%	41.23	18.82%
120000	3398.02	11.9%	4.26	1.94%	39.08	17.73%
140000	3964.35	8.2%	4.71	2.13%	37.51	16.77%
160000	4530.69	5.7%	6.08	2.71%	34.34	15.01%
180000	5097.03	4.0%	11.52	4.96%	31.59	13.24%
200000	5663.36	2.8%	43.67	16.04%	28.50	10.37%
220000	6229.70	1.9%	53.47	18.79%	28.21	9.83%
240000	6796.04	1.3%	66.29	21.67%	27.18	8.82%
260000	7362.37	0.9%	68.63	21.12%	30.30	9.28%
280000	7928.71	0.5%	65.00	19.06%	37.69	11.02%
300000	8495.05	0.4%	54.98	15.61%	41.85	11.85%

Habitat Use Assessment We assessed habitat used by adult shovelnose sturgeon by mapping depth and velocity in reaches where fish were located by telemetry. As part of a larger scale study, fifty shovelnose sturgeon were implanted with acoustic telemetry transmitters in adjacent segments of the river, between approximately 80 km upstream and 112 km downstream from the modeled reach. Fish were tracked weekly from approximately April 15 to July 15, 2005 during daylight hours. Locations for habitat-use assessment were randomly selected from the previous day's locations. In order to assure that all possible macrohabitats available to the fish were assessed, entire reaches (bend to bend or crossover to crossover) were mapped around the fish location. Typically on the Lower Missouri River this required mapping reaches of 2-3 km in length. Sites were mapped only if discharge was stable and within 15% of the prevailing discharge on the day when the fish was located. Hydroacoustic data were collected on transects spaced at 20-40 meters, and were georeferenced with sub-meter differential global positioning systems; mapping protocols have been described in Elliott et al. (2004) and Jacobson et al. (2004a). Depth and depth-averaged velocity point data were gridded using a kriging algorithm and gridded with 5-m cells (Figure 4).

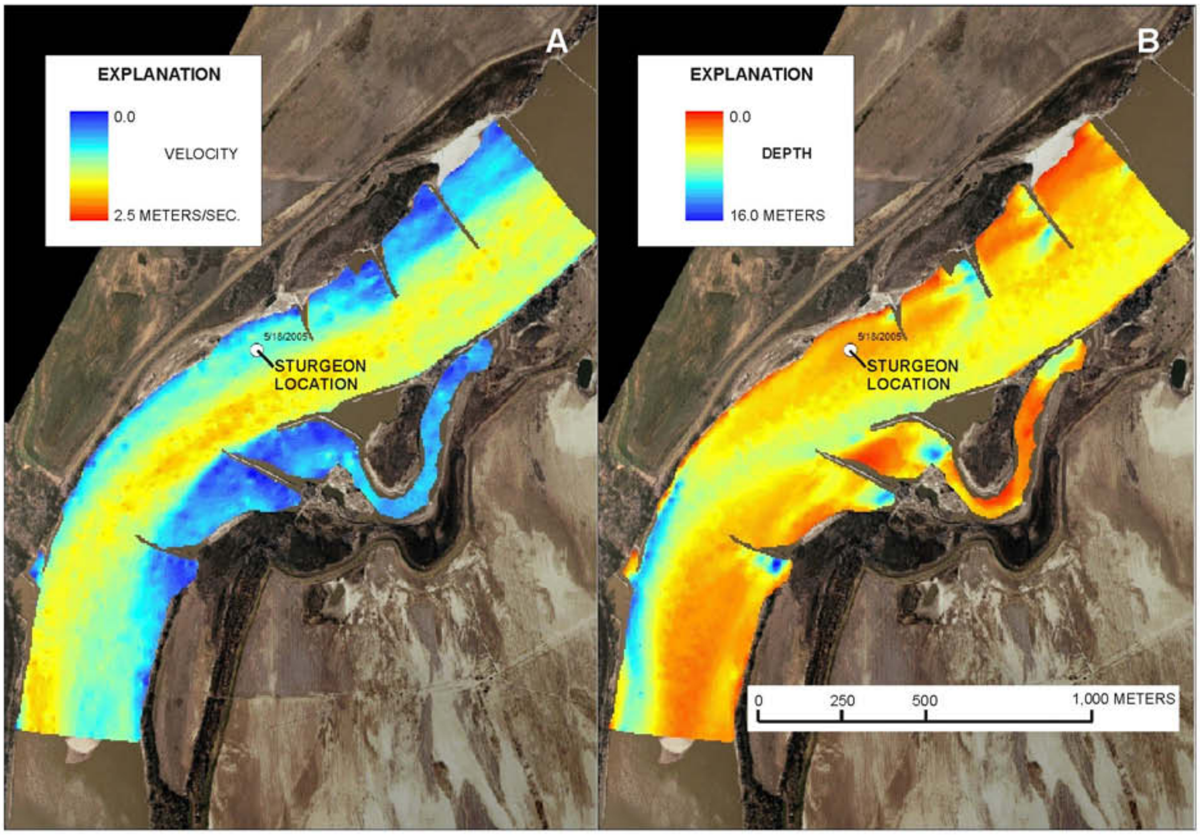

Figure 4. Continuous surface maps of current velocity and depth variables at the reach scale, Lower Missouri River, near Hartsburg, Missouri. Habitat assessment map is centered on a single telemetered fish location; habitat use assessment is based on a 15-m radius circle around the point. A. Current velocity. B. Depth.

The area "used" by a fish is dependent on an understanding of how the fish senses and moves about in its environment in a particular time frame. While it is probable that a sturgeon does not respond to point measures of depth and velocity, the optimal area for assessing habitat use has not been established. Based on fish tracking experience and typical accuracy of acoustic telemetry location, we chose to assess habitat within a 15-m radius circle centered on the fish location. Computer scripts were used to automatically extract depth and velocity data in the circle from each grid. Means and standard deviations were calculated for each approximately 700 m^2 area. Mean velocity calculated at 0.79 $m*s^{-1}$, with a mean standard deviation of 0.10 $m*s^{-1}$. Mean and the mean standard deviation of depth were 3.92 m and 0.44 m respectively.

Analysis of Model Output Depths and velocities at model nodes were exported as ASCII files and gridded for analysis in a geographic information system. SWH areas were extracted from depth and velocity grids by identifying 5-m cells satisfying both depth and velocity criteria.

Field observation and analysis of hydroacoustic habitat-use data identified areas of high depth and velocity gradients as areas of adult habitat use. These are areas typically characterized by flow separation downstream of wing-dike tips, along steep revetted banks, or along the margins of sandbars. Presence of abundant macroturbulence in these areas suggests that the fish might be feeling and responding to complex, 3-dimensional flow structure that could perhaps be measured in terms of turbulent eddies or vorticity (Crowder and Diplas, 2002). These features cannot be modeled with simple 2-dimensional hydraulic computations and must be considered to be sub-grid scale features at the resolution of our model. Nevertheless, they are consistently associated with areas of high velocity and depth gradients that are captured in our model. Analysis of fish locations yields preliminary estimates of standard deviations of depths and velocities where the fish are found.

Model output depth and velocity grids were processed for focal standard deviations over 50-m circular areas. Cells with velocity standard deviations greater than 0.16 $m*s^{-1}$ and depth standard deviations between 0.5 and 1.5 m were assigned to the high-gradient habitat class. For simplicity we named this *wake* habitat, as these areas resemble turbulent wakes downstream of flow obstructions.

RESULTS

Results of the modeling can be expressed in maps (Figure 5) and by the relation between habitat availability and discharge (Figure 6). The relation between habitat availability and discharge is of central importance in planning; however, map output also allows for consideration of spatial characteristics and relations among patches of habitat.

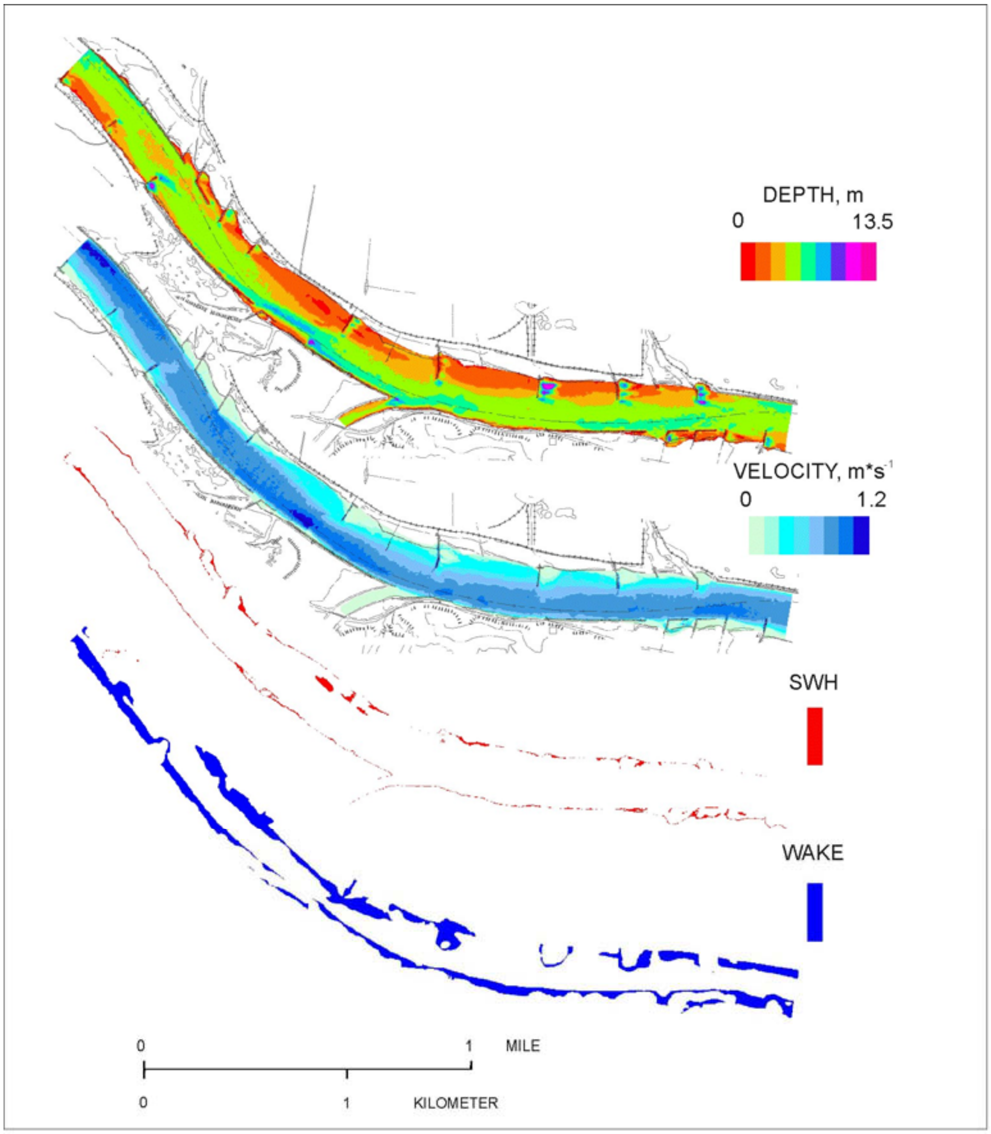

Figure 5 Maps from hydrodynamic model showing depth, depth-averaged current velocity, and areas of shallow-water and wake habitats.

Shallow-Water Habitats SWH is very sensitive to discharge variation. Because of the narrow channel, SWH availability is high at the very lowest discharges when water is shallow and slow over marginal sandbars. Availability decreases in mid-range discharges as sandbar areas become too deep; these are discharges that prevail during the late summer – fall navigation season. SWH increases again at discharges just over bankfull. Management of flows to enhance SWH availability in the present channel would require either very low flows that would fail to satisfy navigation and water-supply needs, or very high flows that would pose flooding risks to agricultural fields. This realization has prompted recent re-engineering efforts to increase SWH, and general diversity of habitat, while maintaining the navigation channel (Jacobson et al., 2004b; Jacobson et al. 2001).

Wake Habitats Area of wake habitat is greater than SWH at all discharges up to 5000 cms, or about where flow goes overbank. As wing dikes are overtopped, (2,000 – 2,200 cms) the wakes diminish adjacent to the thalweg, but are maintained along the bank. Generally, the availability of wake habitat is less sensitive to discharge variation than availability of SWH.

Implications Water management to maximize the availability of SWH would require discharges that would either be too low to support navigation and other intended project purposes, or it would be overbank and present a risk of flooding or impede drainage of agricultural lands. Channel re-engineering presents the possibility of increasing SWH at discharges that also support navigation and water supply. Although river ecology theory supports the importance of SWH in rearing young fish, the LMOR lacks data documenting specific use of SWH by young sturgeon. Preferential use of wake habitats by adult sturgeon has been documented in this study, but it is not clear that wake habitat ever has been limiting to survival of the species. Results of this study demonstrate that management to enhance SWH would probably have little effect on wake habitat availability.

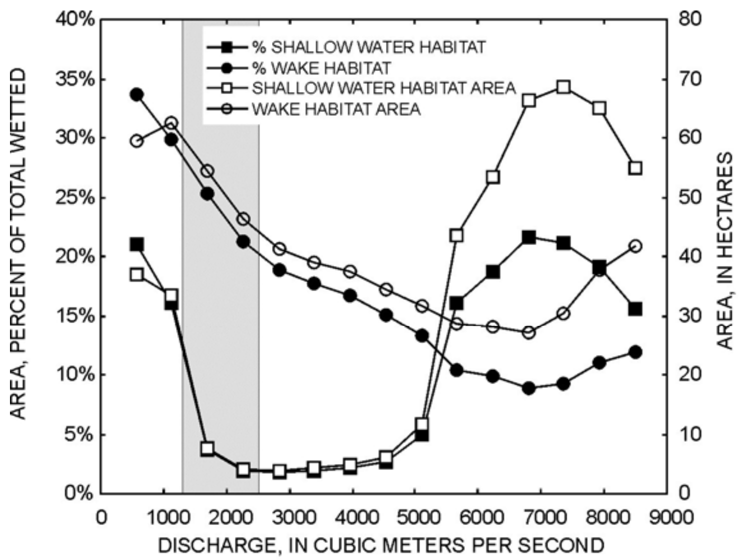

Figure 6 Relation between habitat availability and discharge. Shaded area shows typical late summer navigation flows in the study reach.

CONCLUSIONS

This study underscores the utility of multidimensional hydrodynamic modeling in assessing habitat sensitivity to discharge variability. New telemetry data on sturgeon locations in the LMOR indicate that adult sturgeon select areas of high depth and velocity gradients, and suggest that hydrodynamic model results can be analyzed to isolate areas of high variability based on spatial standard deviations of depth and velocity. Such wake habitats probably reflect sub-grid-scale processes of macroturbulence associated with flow separation downstream of wing dikes, along steep banks, and along bar margins. Whereas SWH, thought to be important for rearing of young sturgeon, is highly sensitive to discharge variation, wake habitats are more abundant and more persistent over a range of discharges up to bankfull. Multidimensional hydrodynamic modeling is clearly useful in assessing habitat sensitivity to discharge variation, but additional work is needed to establish which habitats, if any, are limiting to the survival of sturgeon populations.

REFERENCES

Bovee, K.D., Lamb, B.L., Bartholow, J.M., Stalnaker, C.B., Taylor, J., and Henriksen, J. (1998). Stream habitat analysis using the instream flow incremental methodology: U.S. Geological Survey, Biological Resources Division Information and Technology Report USGS/BRD-1998-0004.

Bowen, Z.H., Bovee, K.D., and Waddle, T.J. (2003). "Effects of flow regulation on shallow water habitat dynamics and floodplain connectivity." Transactions of the American Fisheries Society 132: pp 809-823.

Chittenden, H.M. (1903). History of Early Steamboat Navigation on the Missouri River. Francis P. Harper, New York.

Crowder, D., and Diplas, P. (2002). "Vorticity and Circulation: Spatial Metrics for Evaluating Flow Complexity in Stream Habitats." Canadian Journal of Fisheries and Aquatic Sciences, 59(4): pp 633-645.

Dryer, M.P., and Sandvol, A.J. (1993). Recovery Plan for the Pallid Sturgeon: U.S. Fish and Wildlife Service, Bismarck, North Dakota.

Elliott, C.M., Jacobson, R.B., and DeLonay, A.J. (2004). Physical aquatic habitat assessment, Fort Randall segment of the Missouri river, Nebraska and South Dakota: U.S. Geological Survey Open-Filer Report 2004-1060 80 p.

Ferrell, J. (1993). Big Dam Era - A Legislative History of the Pick-Sloan Missouri River Basin Program: Omaha, U.S. Army Corps of Engineers, 228 p.

Ferrell, J. (1996). Soundings - 100 years of the Missouri River Navigation Project: U.S. Army Corps of Engineers, U.S. Government Printing Office: 1996-555-110, 171 p.

Freeman, M.C., Bowen, Z.H., Bovee, K.D., and Irwin, E.R. (2001). “Flow and habitat effects on juvenile fish abundance in natural and altered flow regimes.” Ecological Applications 11, pp 179-190.

Funk, J. L., and Robinson, J. W. (1974). Changes in the channel of the lower Missouri River and effects on fish and wildlife. Missouri Department of Conservation, Jefferson City, Missouri.

Galat, D.L., and Lipkin, R. (2000). “Restoring the ecological integrity of great rivers: historical hydrographs aid in defining reference conditions for the Missouri River hydrosystem.” Hydrobiologia 422/423, pp 29-48.

Gore, J.A., and Shields, F.D. Jr. (1995). “Can large rivers be restored?” BioScience, 45 pp 142-152.

Gorman, O. T., and Karr, J. R. (1978). “Habitat structure and stream fish communities.” Ecology, 59 pp 507-515.

Hesse, L.W., and Sheets, W. (1993). “The Missouri River hydrosystem.” Fisheries 18, pp 5-14.

Hudson, H.R.; Byrom, A.E.; Chadderton, W.L. (2003). A critique of IFIM—instream habitat simulation in the New Zealand context. New Zealand Department of Conservation, Science for Conservation 231, 69 p.

Jacobson, R.B. and Heuser, J.L. (2001). Visualization of flow alternatives, Lower Missouri River. U.S. Geological Survey Open-File Report 02-122.

Jacobson, R.B. Laustrup, M.L., and Chapman, M.D. (2001). “Fluvial processes and passive rehabilitation of the Lisbon Bottom side-channel chute, Lower Missouri River,” in, Dorava, J.M., Montgomery, D.L., Fitzpatrick, F.A., and Palcsak, B.B., eds., Fluvial Processes and Physical Habitat, American Geophysical Union Water Science and Application Series, v. 4, pp 199-216.

Jacobson, R.B., Elliott, C.M., and Johnson, H.E. (2004a). Assessment of shallow-water habitat availability in modified dike structures, Lower Missouri River, 2004: U.S. Geological Survey Open-File Report 2004-1409, 62 p.

Jacobson, R.B., Johnson, H.E., Laustrup, M.S., D’Urso, G.J., and Reuter, J.M. (2004b). Physical habitat dynamics in four side-channel chutes, Lower Missouri River: U.S. Geological Survey Open-File Report 2004-1071, 60 p.

Jeffries, M., and Mills, D. (1990). Freshwater Ecology: Principles and Applications. Belhaven Press, N.Y.

National Research Council (2002). The Missouri River ecosystem – Exploring the prospects for recovery. National Academies Press, Washington, DC.

Scheidegger, K.J., and Bain, M.B. (1995). “Larval fish distribution and microhabiat use in free-flowing and regulated rivers.” Copeia 1995, pp 125-135.

Steffler, P., and Blackburn, J. (2002). River2D - Two-Dimensional Depth Averaged Model of River Hydrodynamics and Fish Habitat, Introduction to Depth Averaged Modeling and User's Manual. University of Alberta, Edmonton. (http://www.river2d.ualberta.ca /description.htm).

U.S. Army Corps of Engineers (2003). Supplemental Biological Assessment for the Current Water Control Plan – Appendix B – Detailed description of the Corps’ alternative to the 2000 BiOP Gavins Point RPA. U.S. Army Corps of Engineers, Northwestern Division, Portland, Oregon.

U.S. Army Corps of Engineers (2004). Summary Missouri River final environmental impact statement – Master water control manual review and update. Northwestern Division, U.S. Army Corps of Engineers, Portland, Oregon.

U.S. Fish and Wildlife Service (2000). Biological Opinion on the Operation of the Missouri River Main Stem Reservoir System, Operation and Maintenance of the Missouri River Bank Stabilization and Navigation Project, and Operation of the Kansas River Reservoir System. U.S. Fish and Wildlife Service, Bismarck, North Dakota.

U.S. Fish and Wildlife Service (2003). Amendment to the 2000 Biological Opinion on the Operation of the Missouri River Main Stem Reservoir system, Operation and Maintenance of the Missouri River Bank Stabilization and Navigation Project, and Operation of the Kansas River Reservoir System. U.S. Fish and Wildlife Service, Minneapolis, Minnesota.