

Flow and form in rehabilitation of large-river ecosystems: An example from the Lower Missouri River

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Abstract

On large, intensively engineered rivers like the Lower Missouri, the template of the physical habitat is determined by the nearly independent interaction of channel form and flow regime. We evaluated the interaction between flow and form by modeling four combinations of modern and historical channel form and modern and historical flow regimes. The analysis used shallow, slow water (shallow-water habitat, SWH, defined as depths between 0 and 1.5 m, and current velocities between 0 and 0.75 m/s) as an indicator of habitat that has been lost on many intensively engineered rivers and one that is thought to be especially important in rearing of young fishes. Two-dimensional hydrodynamic models for modern and historical channels of the Lower Missouri River at Hermann, Missouri, indicate substantial differences between the two channels in total availability and spatial characteristics of SWH. In the modern channel, SWH is maximized at extremely low flows and in overbank flows, whereas the historical channel had substantially more SWH at all discharges and SWH increased with increasing discharge. The historical channel form produced 3–7 times the SWH area of the modern channel regardless of flow regime. The effect of flow regime is evident in increased within-year SWH variability with the natural flow regime, including significant seasonal peaks of SWH associated with spring flooding. Comparison with other reaches along the Lower Missouri River indicates that a) channel form is the dominant control of the availability of habitat even in reaches where the hydrograph is more intensively altered, and b) rehabilitation projects that move toward the historical condition can be successful in increasing topographic diversity and thereby decreasing sensitivity of the availability of habitat to flow regime. The relative efficacy of managing flow and form in creating SWH is useful information toward achieving socially acceptable rehabilitation of the ecosystem in large river systems.

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1. Introduction

Flow regime is generally considered the primary variable driving processes in the river ecosystem (Richter et al., 1997; Poff et al., 1997; Richter et al., 2003).

Consequently, restoration of the flow regime has been cited as a necessary, and often sufficient, condition for restoration of the ecosystem (National Research Council, 1992). The biological basis for the primacy of flow regime is based on well-documented arguments that life stages of many species and many ecosystem functions depend on a dynamic flow regime (Bayley, 1995; Sparks, 1995; Poff et al., 1997; Galat et al., 1998; Middleton, 2002). Periodic variation of flow is considered important in renewal of riparian vegetation

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communities, episodically connecting fish spawning, rearing, and foraging habitats to the channel, and for transporting energy and nutrients between the channel and flood plain (Sparks, 1995).

The complementary geomorphic argument is based on the idea that rivers adjust morphology — hence available physical habitat — to periodic geomorphically effective flows (Wolman and Miller, 1960; Leopold et al., 1964). Flood flows have been identified as necessary for creation of sandbars (Webb et al., 1999), creation of new flood plain surfaces associated with channel migration (Friedman et al., 1997), and rejuvenation of spawning gravels (Kondolf and Wilcock, 1996).

Large rivers, those with drainage areas in excess of 250,000 km², are typically used by society for a variety of economic services including hydropower, navigation, and water supply. Flood plains of large rivers are valued for the extensive flat land and fertile soil and are often intensively exploited for agriculture and urban development; maximum economic value of these lands is achieved when they are protected from flooding by flow regulation and levees. Because of the large economic benefits that accrue from engineering and active management of large rivers and flood plains, restoration to pre-managed conditions is seldom realistic (Gore and Shields, 1995; Stanford et al., 1996). Hence, attempts to restore ecosystem integrity of large rivers tend to focus on specific functions or goals of species populations that can be accomplished without compromising traditional economic benefits, rather than holistic restoration (Gore and Shields, 1995). The process of restoring components of the ecosystem has been called *rehabilitation* or *naturalization* to distinguish it from holistic restoration (National Research Council, 1992; Sparks et al., 1998; Rhoads et al., 1999).

Many large rivers have flow regimes that have been altered by dams, diversions, and hydrologic changes in the watershed, and they have channel forms that have been altered by bank stabilization, channel training structures (wing dikes), and levees. Whereas the natural flow paradigm (Poff et al., 1997) assumes that channel form is substantially adjusted to flow, morphology of an engineered river can be practically independent of flow. This limits the efficacy of restoring the flow regime alone. On intensively engineered rivers, restoring the hydrograph may restore important flow-related factors like timing of floods, water temperature, and turbidity. Without a naturalized morphology, or flow capable of maintaining channel-forming processes, however, the hydrologic pulses will not be realized in habitat availability. Conversely, completely natural channel form without temporal hydrologic cues would also not be expected to support natural ecosystem functions. In large, engineered rivers,

flow regime and channel form can be (and often must be) manipulated independently. Separate adjustment of flow and form gives managers additional flexibility to achieve ecological, social, and economic objectives, but this ability also implies the need to develop a detailed understanding of the interplay between flow and form in setting the physical template for ecosystem processes.

Social and economic factors may provide hard constraints on achievement of some rehabilitation goals. For example, rehabilitation activities on rivers used for navigation may achieve greater habitat diversity within the engineered channel, but it is typically unacceptable to allow the channel to migrate freely. Although the full natural range of lateral erosion and deposition processes may not be possible under engineered conditions, some increased geomorphic dynamism may be achievable within the banks.

2. Physical habitat in river rehabilitation

In this paper we explore the interplay between channel form and flow regime in determining the spatial and temporal distribution of physical habitat in large, intensively engineered rivers. We use the Lower Missouri River (LMOR) as an example (Fig. 1). The LMOR is defined as the Missouri River downstream of Gavins Point dam near Yankton, South Dakota, to its confluence with the Mississippi River near St. Louis, Missouri. The Missouri River is the longest river in the United States (more than 4000 km long) and drains more than 1,300,000 km². Like many large rivers, the LMOR is intensively managed and subject to conflicting management objectives, including flood control, navigation, hydropower production, irrigation, water supply, recreation, and support of threatened and endangered species. The history and environmental context of management conflict of the Missouri River are summarized by the National Research Council (2002).

Our emphasis is on understanding the template of physical habitat that results from interactions of channel form and flow regime. We use the definition of physical habitat as the three-dimensional structure in which riverine organisms live, modified to emphasize that time (frequency, duration, sequence, rate of change) adds a critical fourth dimension (Gordon et al., 1992). Aquatic habitat typically includes physical and chemical characteristics of the space occupied by organisms, however this paper is confined to physical characteristics, including water depth, flow velocity, and substrate. Water temperature and turbidity are typically also strongly associated with depth and flow velocity. Physical aquatic habitat results from interaction of water with the

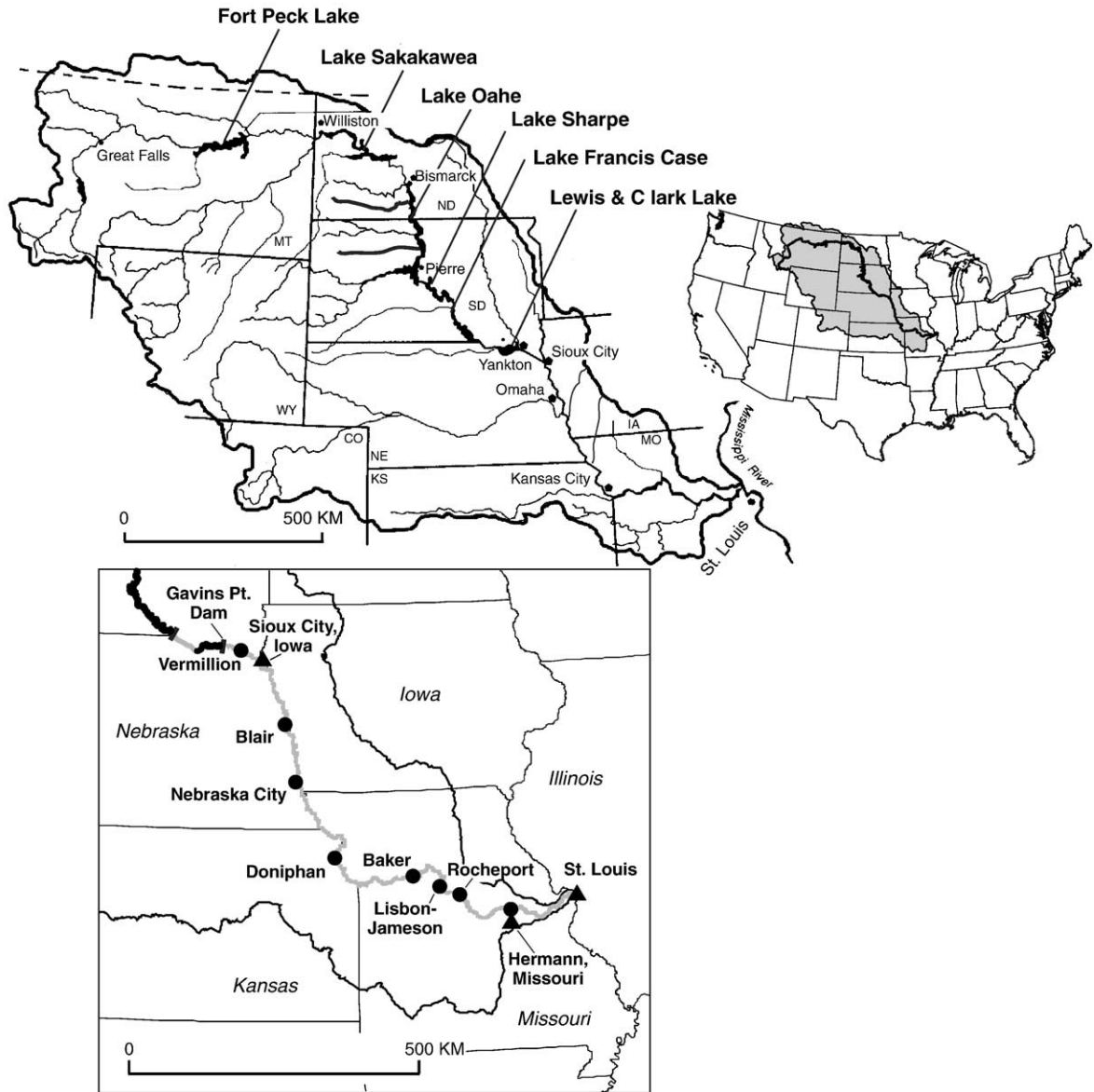


Fig. 1. Missouri River basin, the Lower Missouri River, and locations of modeling reaches and streamflow gaging stations addressed in this study. The Lower Missouri River is the part of the river downstream of Gavins Point Dam near Yankton, South Dakota, and extending to the junction with the Mississippi River near St. Louis.

morphology of the stream channel and adjacent flood plain. River hydrologic characteristics determine how much water is in the channel, when, and for how long. Hydrologic characteristics can be assessed using the five aspects of flow regime listed by Poff et al. (1997): magnitude, frequency, duration, timing, and rate of change. The form of the river channel determines how the water is distributed across the channel, thereby creating the spatial distribution of depth, velocity, and substrate.

Ecologists generally accept the concept that physical habitat is the organizational template for aquatic ecosys-

tems (Gorman and Karr, 1978; Schlosser, 1987; Power et al., 1988; Jeffries and Mills, 1990). Factors other than physical habitat (for example, nutrients, energy, competition, predation, and contaminants) are also important in determining ecosystem functions. Most management emphasis on rivers, including the LMOR, however, has been on physical habitat because the magnitude of human-induced change to physical habitat is large, and because of the direct connection of physical habitat to management actions (U.S. Fish and Wildlife Service, 2000, 2003; Clarke et al., 2003; U.S. Army Corps of Engineers, 2004).

In addition, we have chosen to simplify this analysis by concentrating on one measure of physical habitat: areas of shallow and slow velocity water, known as shallow-water habitat (SWH). We focus on SWH because survival and growth of young fishes are associated with the availability of shallow, low velocity water (Scheidegger and Bain, 1995; Bowen et al., 1998; Freeman et al., 2001). The bounds of depth and velocity vary among studies. For example, Bowen et al. (2003a) use water less than 1-m deep and current velocities less than 0.25 m/s. Recent habitat analyses on the Missouri River have used a rather arbitrary definition of SWH as 0–5 ft (0–1.5 m) and 0–2 ft/s (0–0.6 m/s) (U.S. Fish and Wildlife Service, 2000, 2003; U.S. Army Corps of Engineers, 2004). Although the complex interactions among water properties, substrate, topography, and biota cannot be fully described by this one class or the dimensions assigned to it, we adopt it for the purpose of analysis as an operational index of a habitat type that is in short supply in the river system.

3. History and management of the Lower Missouri River

Flow regulation began on the Missouri River in the late 1930s with the construction of Fort Peck Dam in Montana, but regulation achieved significance with the closure of the Missouri River Reservoir System in 1954. The Missouri River Reservoir System, consisting of six mainstem dams (Fig. 1), is now the largest water management system in the nation, with nearly 92,500 km³ (73.4 million acre feet) of water storage (U.S. Army Corps of Engineers, 2004). The system is managed for multiple purposes including: maintenance of navigation flows, flood control, hydro-power, public water supply, recreation, and fish and wildlife resources. A historical perspective on hydrologic changes is discussed in Galat and Lipkin (2000) and hydrologic effects of alternative dam management scenarios are illustrated in Jacobson and Heuser (2001). Pegg and Pierce (2002) and Pegg et al. (2003) classified the river into hydrologically distinct reaches. These

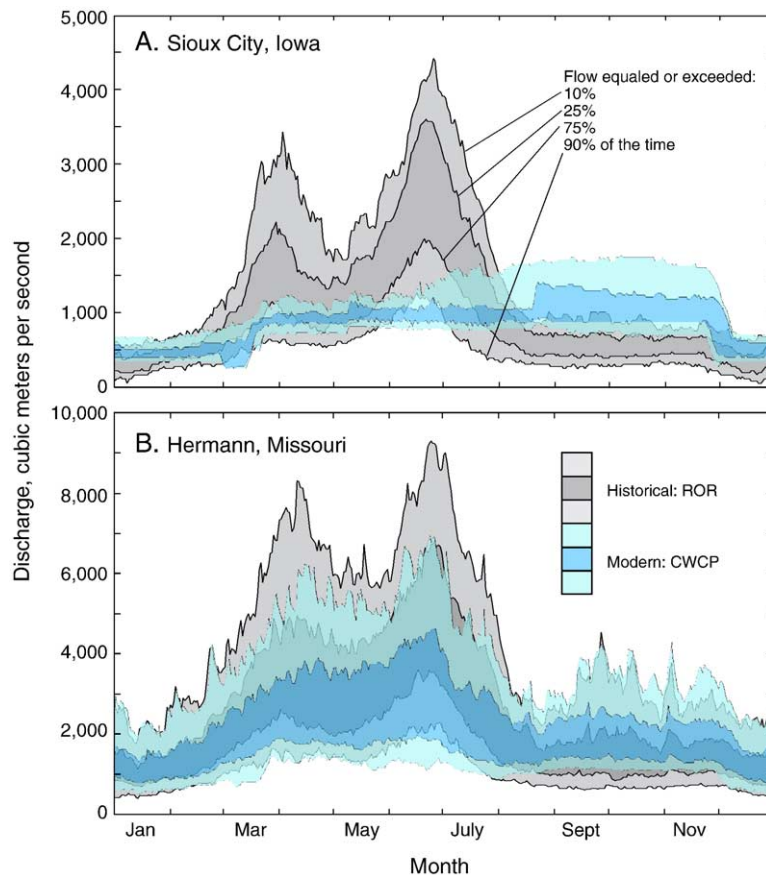


Fig. 2. Duration hydrographs illustrating effects of flow regulation, Lower Missouri River. Daily flow duration for 100 years of daily data; note differences in discharge scales. A. Missouri River at Sioux City, Iowa. B. Missouri River at Hermann, Missouri. ROR, run-of-the-river simulation model; CWCP, current water control plan simulation model, operational control plan 1967–April 2004.

analyses document substantial alteration to the annual hydrograph below the reservoirs, with generally decreased spring pulses and increased summer low flows (Fig. 2A). The intensity of hydrologic alteration diminishes downstream from the dams as minimally regulated tributaries enter the Missouri River. The lower 590 km downstream of the confluence with the Kansas River has a notably altered hydrograph, particularly with respect to low flows, but has regained substantial variability (Fig. 2B).

Morphological alterations to the Missouri River began much earlier than hydrologic alteration. Clearing, snagging, and stabilization of the Missouri River began in the early 1800s to improve conditions for steamboat navigation (Chittenden, 1903). Most of the rock dikes and revetments in the river, however, are the direct result of the Missouri River Bank Stabilization and Navigation Project, part of the Pick-Sloan act of 1944 (Ferrell, 1996). Wing dikes and revetments have stabilized the riverbanks, and narrowed and focused the thalweg to maintain a self-dredging navigation channel from St. Louis, Missouri, 1200 km upstream to Sioux City, Iowa. The result has been to create a narrow, swift, and deep channel from what was historically a shallow, shifting, braided river. Loss of riverine habitat on the LMOR has been estimated as much as 400 km² (Funk and Robinson, 1974). Substantial declines in integrity of the ecosystem have been associated with this habitat loss (Hesse and Sheets, 1993). Recognition of the scope of habitat loss has increased interest in rehabilitating parts of the Missouri River (Latka et al., 1993).

In addition to flow alteration and direct effects of the Bank Stabilization and Navigation Project, the LMOR has been adjusting to greatly diminished sediment load and effects of channel constriction. The channel has incised 3–5 m in the first 100 km downstream from Gavins Point Dam. Further downstream, floods are

attaining higher stages than they did before extensive river engineering, and the reach around Kansas City has degraded (Fig. 3; U.S. Army Corps of Engineers, 1996). Increased stages for larger discharges have been attributed to channel constriction by revetments and levees, whereas channel degradation has been attributed to sediment deficits and constriction by wing dikes (Pinter et al., 2002). The downstream most 400 km is characterized by modest channel incision, resulting in decreased stages for low discharges. Channel degradation downstream from Gavins Point dam is a continuing process that limits present-day rehabilitation strategies and may affect future habitat availability in the LMOR.

Since 1989, management agencies for the Missouri River basin have been involved in the contentious process of revising the operating rules for the mainstem reservoirs, the Missouri River Master Manual. While a revised Master Manual was released in 2004 (U.S. Army Corps of Engineers, 2004), management of the river continues to be debated. Proposals to restore elements of natural variability to the hydrograph have been particularly controversial. The U.S. Fish and Wildlife Service proposed a revised annual hydrograph with a spring rise and a summer low-flow period (U.S. Fish and Wildlife Service, 2000, 2003); the need for a naturalized hydrograph was supported by a national science review (National Research Council, 2002). In these publications, specific habitat functions attributed to a spring rise were: rejuvenation of emergent sandbar habitats, seasonal connection of the channel with low-lying flood-plain lands, and a spawning cue for native fishes, especially the endangered pallid sturgeon (*Scaphirhynchus albus*). Specific habitat functions attributable to the summer low flow included exposure of sandbars for nesting by the federally threatened piping plover (*Charadrius melodus*) and federally endangered least tern (*Sterna albifrons*) and

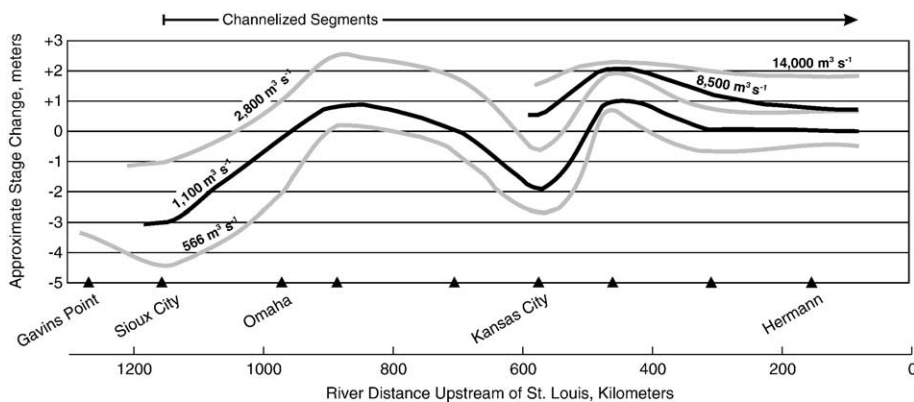


Fig. 3. General degradation trends, Lower Missouri River, shown as stage changes 1954–mid-1990's, for given discharges. Data from U.S. Army Corps of Engineers (1996).

Table 1

Combinations of scenarios explored by two-dimensional hydrodynamic modeling of physical habitat, Lower Missouri River at Hermann, Missouri

		Form	
		1894 Channel form	2000 Channel form
Flow	Run-of-the-river flow regime	Historical/Historical	Historical/Modern
	Current water control plan flow regime ^a	Modern/Historical	Modern/Modern

^a The current water control plan operated approximately 1967–2004; in 2004 it was replaced with a slightly altered water control plan.

increased area of SWH for rearing of young fishes. As an alternative, engineered rehabilitation of channel morphology has been proposed as an effective means to manage habitat availability without requiring flow changes (U.S. Army Corps of Engineers, 2003). Hence, the dominant debate on LMOR management has focused on the tradeoffs between flow and form in balancing ecosystem and traditional economic values and services.

4. Approach and methods

We address the interaction between flow and form in river rehabilitation by assessing the spatial and temporal distribution of SWH under current conditions and under a historical reference condition. Using flow and form we explore four scenarios (Table 1) that are intended to provide insight into the interaction between flow and morphology; they are not intended to model realistic rehabilitation alternatives. We use two-dimensional hydrodynamic models to create the inventory of SWH in the modern (2000) and pre-engineered (1894) channel. Understanding the limitations of models for instream flow (Hudson et al., 2003), we use hydrodynamic models to indicate trend and sensitivity rather than to predict specific biotic responses.

4.1. Hydrologic model data analysis

Hydrologic data used in the analyses came from the U.S. Army Corps of Engineers Daily Routing Model for the Missouri River (U.S. Army Corps of Engineers, 1998a). The modeled flows were synthesized from historical data on tributary inflows, calculations of streamflow depletions because of evapotranspiration and consumptive use of water, and modifications of outflows according to water-control rules that comprise flow-management alternatives. The model reproduces how reservoirs would be managed under a set of water control rules, given the actual range of variability of historical inflow data 1898–1998.

Modeled flows were used for the streamgage station at Hermann, Missouri for two management scenarios, the current water control plan (CWCP) that was in place until April 2004 and the run-of-the-river model (ROR).

The ROR model treats the reservoirs as flow-through water bodies and, therefore, produces an estimate of the natural hydrograph, with small biases during summer months when evapotranspiration in the modeled reservoirs produces somewhat lower discharges than actual (U.S. Army Corps of Engineers, 1998a). The data were analyzed to determine duration of flow for every day of the year.

4.2. Modern channel model

To model flow discharges through the modern channel, we used River2D (Steffler and Blackburn, 2001; version 0.90, July 23, 2002) and its supporting programs, R2D_Bed and R2D_Mesh. This model code solves the shallow-water, depth-averaged equations to balance mass and momentum on a finite element mesh. River2D handles wetting and drying by converting to ground-water flow equations for subsurface flow, and it explicitly handles transitions between sub- and super-critical flow (Steffler and Blackburn, 2001).

We modeled steady discharges from 566 to 6790 $\text{m}^3 \text{s}^{-1}$ (in increments of 283 and 566 $\text{m}^3 \text{s}^{-1}$), a range corresponding to 97 — 2% duration of flow under the CWCP and 96 — 4% flow duration under the ROR. This range includes low flows to just over bank (with present-day channel morphology).

Channel bathymetry was obtained by the U.S. Army Corps of Engineers in 1998 and 1999 using an echosounder to collect depth data and was supplemented with high-resolution depth data that we collected in 2000–2001 at specific locations. A combination of cross-section and feature-based design was used. Cross-sections spaced approximately every 20 m (5% of channel width) achieved an average data density of 6 points per 100 m^2 . We used a high-resolution depth sounder and a differentially corrected global positioning system to map bathymetry that resulted in positional errors estimated at ± 0.75 m and depths ± 0.07 m (Jacobson et al., 2002). Depths were converted to elevations using surveyed elevations of the water surface, and depth points were merged with U.S. Army Corps of Engineers channel bathymetry and a 5-m-cell flood-plain digital elevation model (DEM, U.S. Army Corps of Engineers, 2000).

Additional elevation points were surveyed on wing-dike crests by total station. Elevation data were gridded to 5-m cells using a kriging algorithm. The computa-

tional mesh was derived from the 5-m grid and edited in River2D. The substrate of the reach was mapped using hydroacoustic methods (Jacobson et al., 2002),

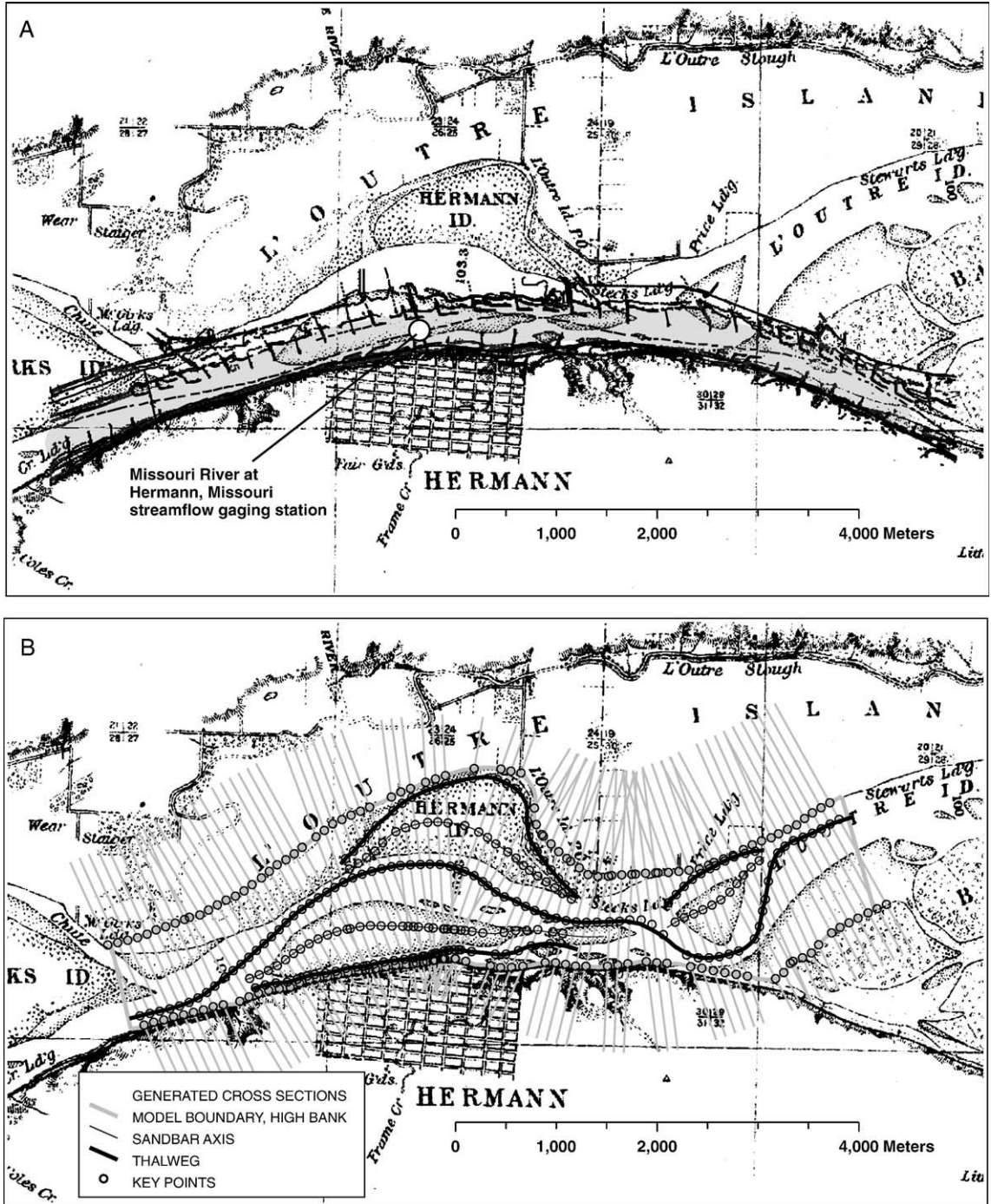


Fig. 4. A. Modern (2000) and historical (1894) channel maps, Lower Missouri River at Hermann, Missouri. Modern channel is extent of modern 2-dimensional hydrodynamic model. B. Schema for developing channel cross-sections as constrained by historical map. Extent of cross-sections indicates extent of historical 2-dimensional model.

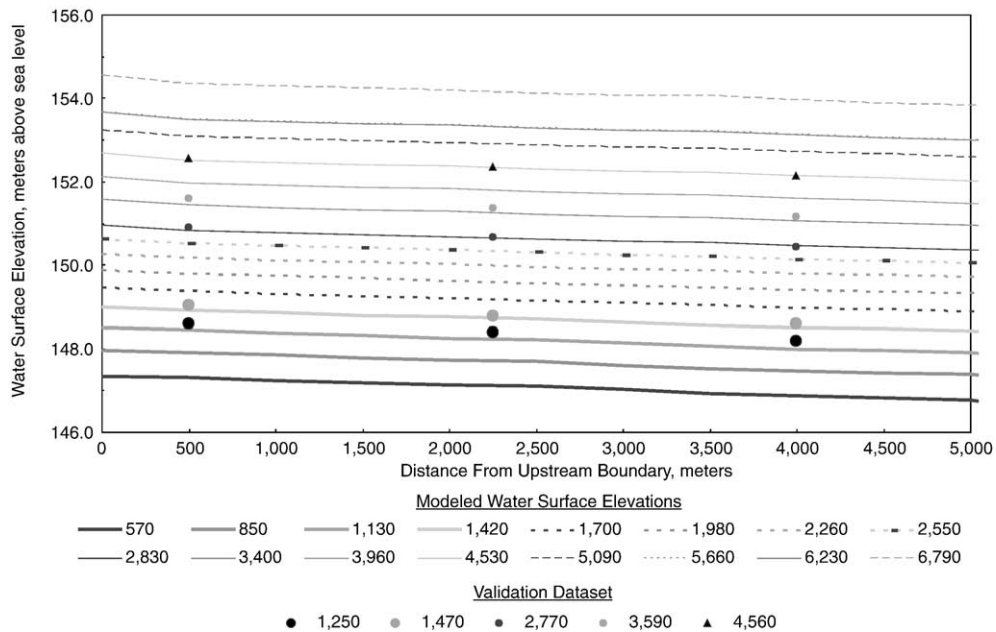


Fig. 5. Modeled and measured water-surface elevations. Measured elevations are validation dataset.

and was used to initialize roughness heights in the model.

Boundary conditions, stage–discharge curves at upstream and downstream ends of the reach, were developed by surveying water surfaces corresponding with discharges obtained from the U.S. Geological Survey streamflow gaging station 06934500, Missouri River at Hermann, Missouri, in the middle of the modeled reach (Fig. 4). Other parameters required by River2D include, 1 and 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. Eddy viscosity and upwinding parameters were kept as default values (0, 0.5, and 0.5). Sensitivity analyses documented that modeled velocities in the main channel and recirculating eddies downstream of wing dikes were generally insensitive to the choice of viscosity parameters for the eddy. Ground-water transmissivity was set at 0.01 to minimize ground-water discharge.

Elevation profiles of the water surface were used as the primary means of calibration. Elevations of the water surface for discharges 1245–4560 $\text{m}^3 \text{s}^{-1}$ were surveyed at two benchmarks, and stage was available from the streamgauge in the center of the reach. Of 14 measured elevations of the water surface, seven were used for calibration (by adjusting roughness height) and seven were used for validation of model results. Fig. 5 shows

measured and modeled elevations of the water surface for comparison. Calibration of the model was considered adequate. In addition to close agreement between measured and modeled elevations of the water surface, models were considered successful if they achieved a low net outflow (less than 5% of the flow was unaccounted by the model) over run times sufficient to achieve a steady state (usually greater than 10,000 time steps). Model results were also evaluated for whether they realistically reproduced known flow patterns — such as eddies downstream of wing dikes. In some cases, modeled local instabilities in the flow field were accepted if they affected only small areas and did not substantially affect habitat area calculations.

4.3. 1894 Channel model

Bathymetric and discharge data do not exist to construct a similarly calibrated and validated hydrodynamic model for the 1894 river. A variety of historical information is available, however, to construct a statistical model of the historical river. Combined with calibrated parameters of flow from the modern channel, and a few reasonable assumptions, the statistical model allows construction of a reference hydrodynamic model. The value of the reference model, albeit based on a series of assumptions, is that it provides a way to explore the historical reference condition using the same quantities as the modern condition. Comparison to the historical reference condition can provide insight into how

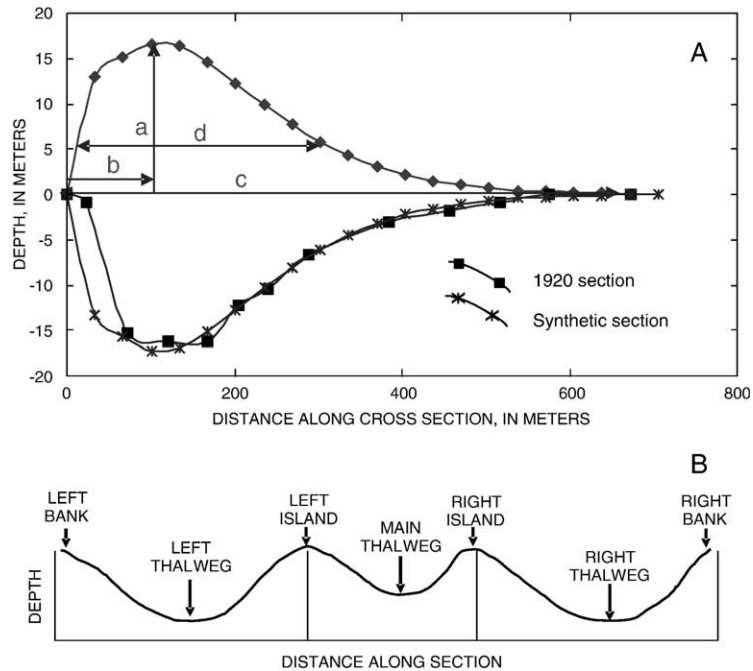


Fig. 6. Historical channel cross-section synthesis. A. Fitting of cross-sections to Weibull 4-parameter distribution, parameterized by channel width, width:depth ratio, thalweg position, and shape coefficient. B. Schema for construction of compound channel sections with maximum of three channels and two islands.

ecosystem drivers, in this case, channel form and flow regime, provide a template for ecosystem functions.

Planform maps from the late 1800s (*Missouri River Commission, 1894*) are the foundation of the channel model (Fig. 4). The 1894 planform map was used to identify and digitize key linear features: banks, thalweg, and island axes. This is the most subjective and interpretive step in the process. Cross-sections were laid out at 50 m spacing perpendicular to the main thalweg. Coordinates of the points of intersection of cross-sections with banks, thalweg, and bar medial axes were attributed with a geomorphic significance (Fig. 4B) and extracted from the geospatial database. Channel morphology was generalized so the most complicated case consisted of three thalwegs and two islands (Fig. 6); channel sections could also consist of two thalwegs and one island, or one thalweg with no islands.

The 1894 maps contain a great deal of detail on channel width and form, but do not have any depth data. Another series of maps from 1920 (*War Department, 1920*) present sparse sounding data (Fig. 7). Cross-sections from non-engineered reaches were selected and compiled to develop a statistical model for channel cross-section shape. The typical channel shape can be modeled as an upside-down, 4-parameter Weibull distribution (Fig. 6A, Eq. (1); Weibull, 1951). The parameters of the distribution relate to maximum depth

(depth in the thalweg), the width of the channel, the position of the maximum depth along the cross-section (thalweg position) and a shape parameter.

$$\text{Depth} = -a \left(\frac{d-1}{d} \right)^{\frac{x-b}{c}} \left[\frac{x-b}{c} + \left(\frac{d-1}{d} \right)^{\frac{1}{d}} \right]^{d-1} \times e \left[- \left(\frac{x-b}{c} + \left(\frac{d-1}{d} \right)^{\frac{1}{d}} \right)^d + \frac{d-1}{d} \right]$$

Where:

- a* maximum amplitude, or depth of thalweg,
- b* distance from bank to thalweg,
- c* channel width,
- d* shape coefficient, and
- x* distance along cross-section

The sample of 1920 channel cross-sections provided an estimate of pre-engineered width:maximum depth ratio (74.2) and the shape coefficient (1.5). From 1894 bankfull channel widths, we calculated maximum depth and from the interpreted position of the thalweg, we calculated distance from the bank to the thalweg. Computer code automated the calculations to generate depths at 120 points along each cross-section. The

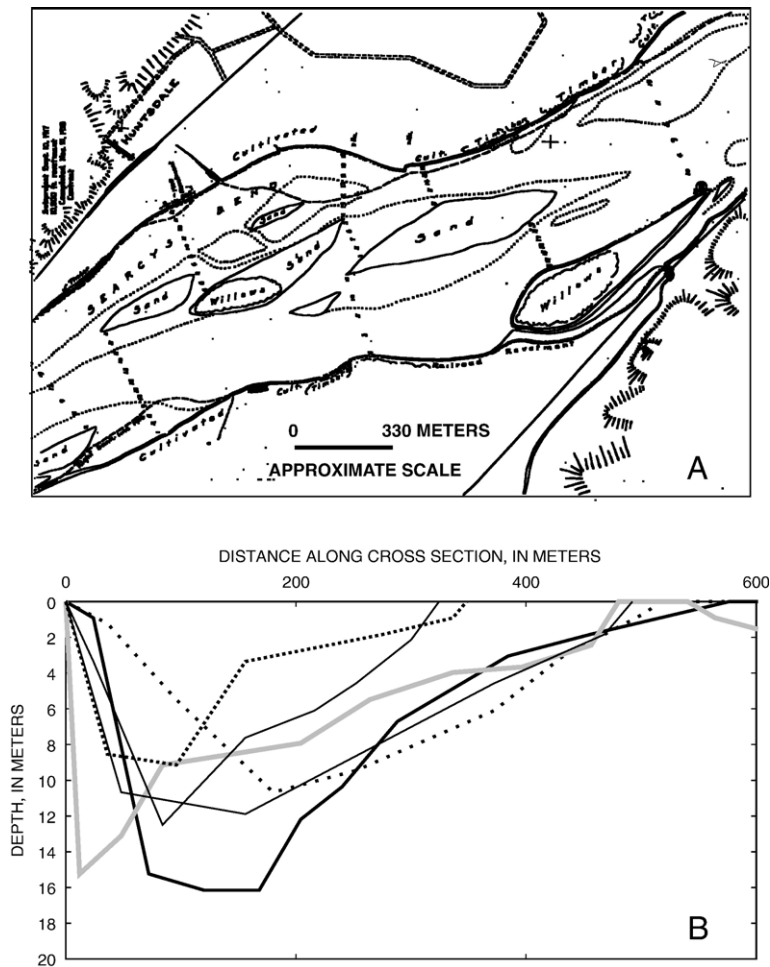


Fig. 7. Channel morphology, Lower Missouri River in 1920. A. Example of 1920 planimetric map of part of the Lower Missouri River with sparse sounding data. B. Examples of channel cross-sections assembled from 1920 sounding data, multiple locations along LMOR.

points provided a dense mesh from which a depth grid (depths as negative numbers) was generated. An elevation grid was calculated by adding the depth grid to a grid representing the mean bankfull elevation of the present flood plain. This last calculation was based on the assumption that valley slope and bankfull elevation have not changed significantly since 1894.

A computational mesh was generated from the synthetic elevation grid, and the same series of discharges were modeled for the synthetic 1894 condition (historical) as for the 2000 condition (modern). The calibrated roughness height (similar to medium sand) was retained from the 2000 model runs. Stage–discharge relations were generated from the measurement data for discharge at the Hermann streamgage using 1928–1935, prior to extensive channel engineering in the Hermann reach. The relations were extended to the upstream and downstream margins using a streamwise slope.

It was impossible to calibrate or validate the 1894 model; the validity of the model depends on the 2000 calibration of roughness height and the many assumptions that went into constructing the topographic mesh. Early 19th century paintings (e.g., Karl Bodmer; [Joslyn Art Museum, 1984](#)) and the long history of steamboat wrecks on the Missouri River ([Chittenden, 1903](#)) document that large woody debris (LWD) was common in the channel. LWD certainly created hydraulic roughness that is not captured in the model, and it was probably responsible for fine-scale topographic features in the bed that also are not represented in the topography.

The degree to which the synthetic morphology of the channel agrees with the 1894 reality depends on several interpretations, statistical models, and assumptions. As such, it is not expected to be an accurate depiction of the 1894 condition, but it is expected to be realistic. Its

value lies in its ability to show general conditions of the pre-modern reference condition. Because no other quantifiable reference condition exists for large rivers like the Lower Missouri, we believe these assumptions are justified.

4.4. Habitat assessment

Simulation models of hydrodynamic habitats can produce a continuum of depths and depth-averaged velocities for a modeled area at each modeled discharge. Many different combinations of depth and velocity may be important habitat characteristics for some species or some life stages, and a complete assessment of habitat should probably consider a myriad of measures of spatial relations of habitat patches as well as temporal measures of sequence, duration, and timing. For the purposes of this analysis, however, we look at only at

the SWH class: 0–1.5 m, depth and 0–0.75 m/s current velocity.

Grids with 5-m cell size were constructed from 2-dimensional model outputs of depth and velocity. Cells meeting depth and velocity criteria were classified as SWH in a third grid. The SWH grid was analyzed for total area, total edge, and mean patch area to characterize some basic spatial statistics (McGarigal and Marks, 1995).

5. Results

Results of hydrodynamic modeling were evaluated in terms of the relations between discharge and habitat area in the historical and modern channel, and by looking at the distribution of SWH during the year under historical and modern flow regimes. Results from the Hermann reach are compared to upstream reaches to assess affects

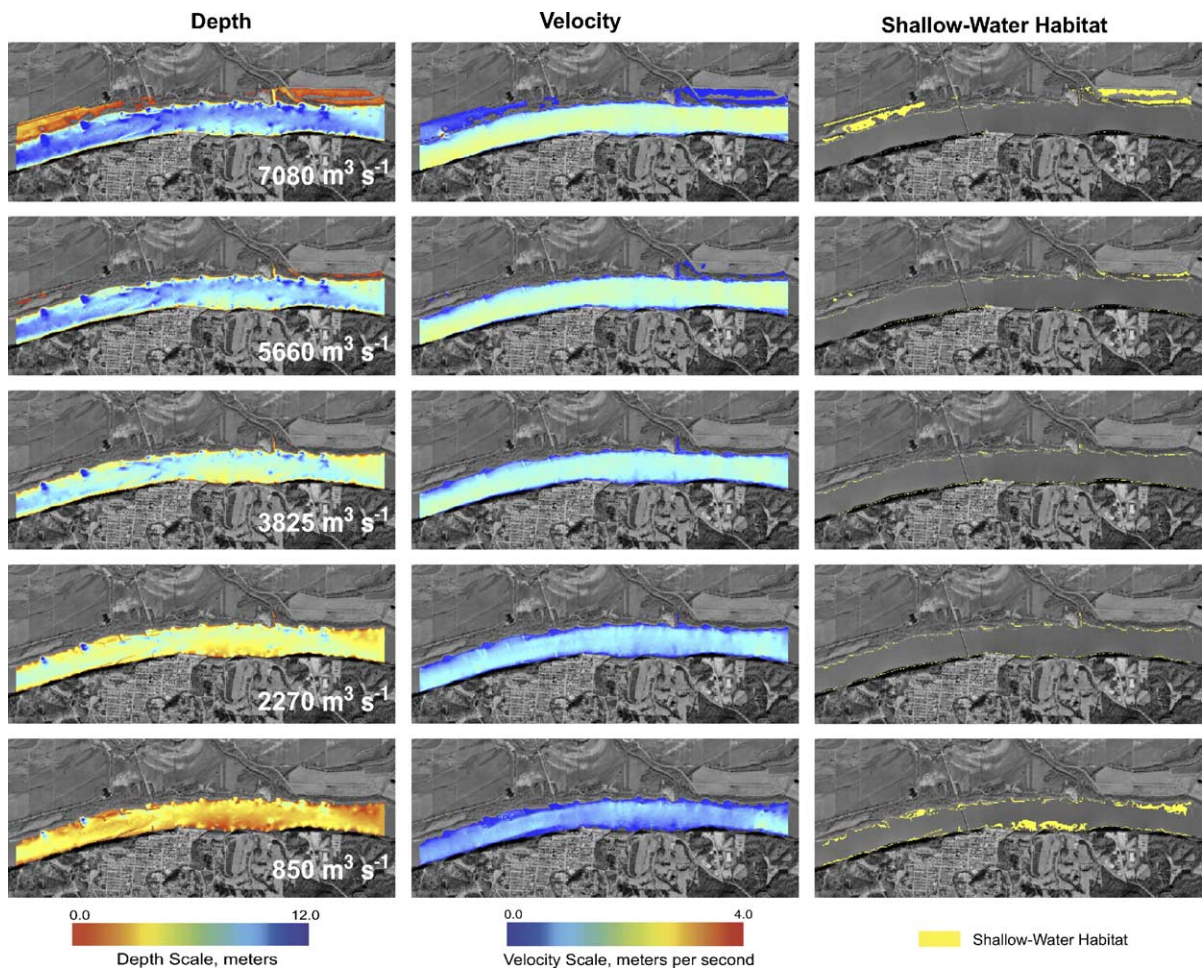


Fig. 8. Two-dimensional hydrodynamic modeling results for selected discharges, modern channel of the Lower Missouri River at Hermann, Missouri, showing the mapped distributions of depth, current velocity, and shallow-water habitat.

of the alteration of more severe flow and spatial variability within the LMOR.

5.1. Shallow-water habitat in the historical and modern channel

Hydraulic conditions in the modern channel are generally more uniform than in the 1894 channel (Figs. 8 and 9), with the exception of deep, slow areas associated with wing-dike scours. Maximum current velocities are greatest in the 1894 channel in the discrete area where multiple channels converge in a relatively narrow reach (Fig. 9). Whereas it is commonly accepted that channelization of the Missouri River increased mean velocity (Latka et al., 1993), spatial variability was clearly much greater before channel engineering and discrete areas of very high velocity existed in the historical river. The

Lewis and Clark Corps of Discovery commented on high velocities in the Missouri River in 1804: “...the Boat run on Logs three times to day, owing [to] her being too heavily loaded a Sturn... I saw a number of Goslings to day on the Shore, the water excessively rapid, and Banks falling in.” May 15, 1804, William Clark (Moulton, 2002).

Total SWH is much greater over all discharges under historical conditions (Fig. 10A, Table 2). Unlike the modern channel in which SWH increases with decreasing discharge (for flows less than bankfull), SWH in the historical channel increases with increasing discharge. The continuous and gradually varying distribution of topographic surfaces from the thalweg to the flood plain supported abundant SWH at all discharges. Because of the broadly convex bars, more of the surface is inundated with shallow depths as discharge increases.

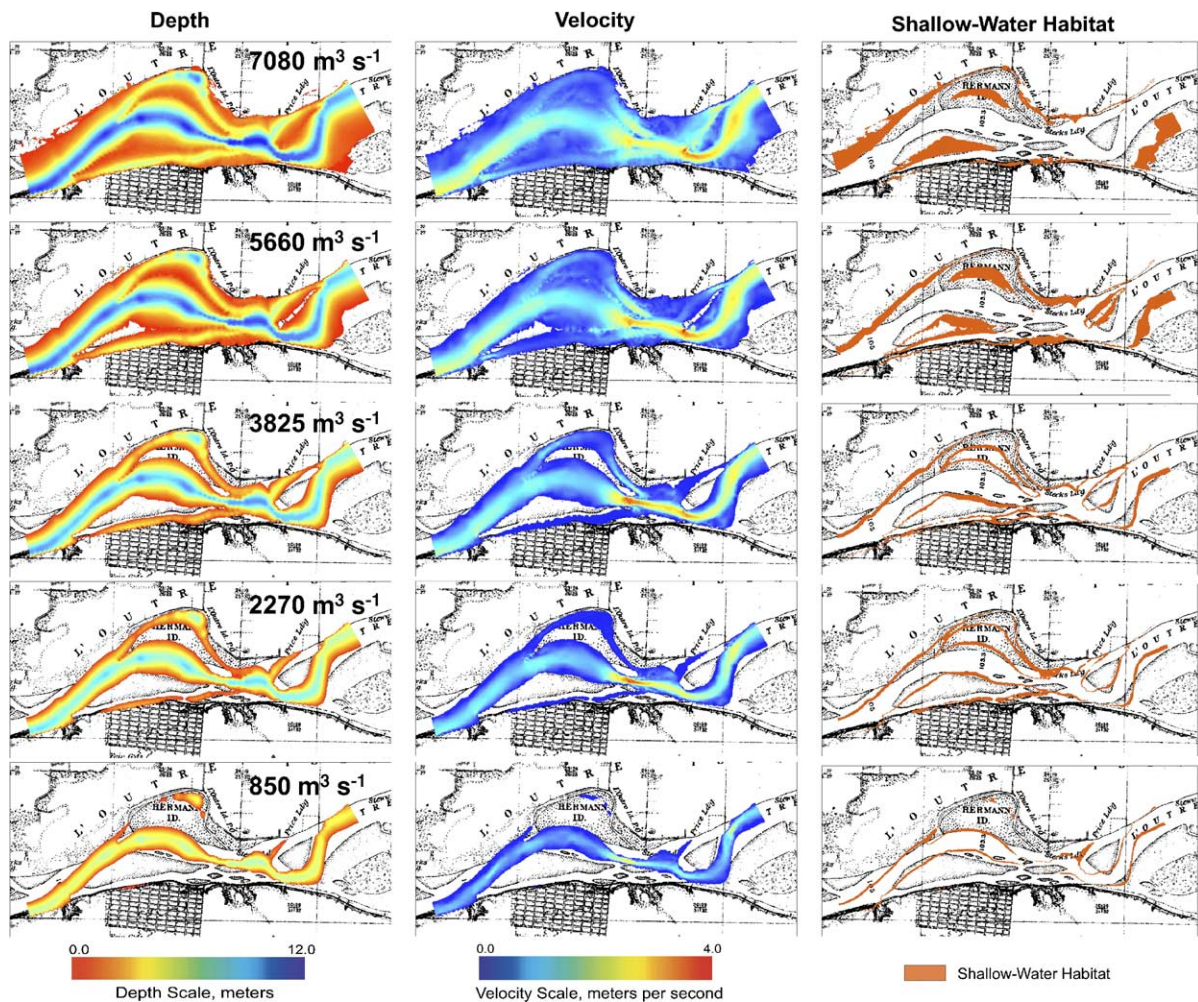


Fig. 9. Two-dimensional hydrodynamic modeling results for selected discharges, historical reconstructed channel of the Lower Missouri River at Hermann, Missouri, showing the mapped distributions of depth, current velocity, and shallow-water habitat.

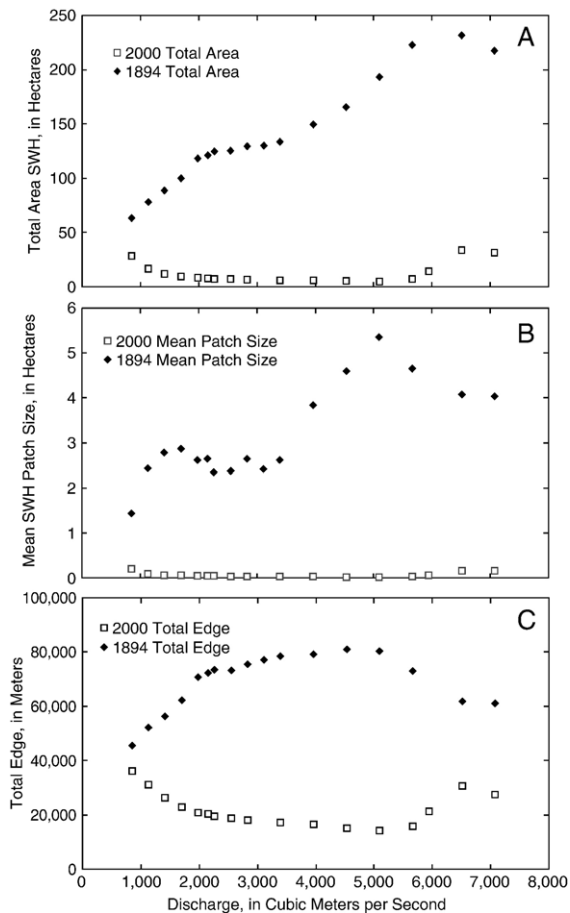


Fig. 10. Relations between discharge and selected spatial variables for shallow-water habitat, 1894 and 2000 channels, Lower Missouri River at Hermann, Missouri. A. Total shallow-water habitat (SWH) area and discharge. B. Average size of SWH area. C. Total edge length for SWH.

Average size of SWH patches is also greater at all discharges in the historical channel than the modern channel. Patches of SWH in the modern channel are fragmented whereas those in the historical channel are large and continuous (Figs. 8–10B). Historical patches are elongate compared to the modern patches, and have greater total edge length compared to the modern condition (Fig. 10C; Table 2). These conditions may have favored species with affinities for habitat edges. Edge density (total edge length divided by total patch area) is substantially higher for the historical condition for flows up to $5660 \text{ m}^3 \text{ s}^{-1}$, indicating that the historical channel had large quantities of productive edges even for the large area of SWH present.

SWH abundance over the season was assessed by interpolating total SWH area from the discharge–SWH relation, for one hundred years of daily discharges for

two flow regimes and two channel forms (Table 1). The median area of 100 years of daily values for each day of the year was plotted over the year (Fig. 11A). With the modern channel form, SWH is scarce during all times of the year for the modern and historical flow regimes (Fig. 11A). SWH area increases by a factor of 3–7 for the historical channel form for both flow regimes, demonstrating the strong affect of channel form on the availability of habitat. For historical and modern flow regimes, within-year variability is greater for the historical channel form (within-year ranges of 7.4 and 11.4 ha) compared to the modern (within-year ranges of 1.7 and 2.0 ha). The greatest within-year variability results from the historical channel form and historical flow regime (11.4 ha). The historical form/historical flow combination also contains a discrete peak in habitat availability during late June that results from the larger, second mode of the annual flow pulses (Fig. 2). This habitat availability spike would have been a persistent event (occurring at least 50% of the time) during which high bar and low flood-plain surfaces were connected to the main channel.

5.2. Comparison to other segments of the Lower Missouri River

Because the Hermann, Missouri, segment has been highly affected by channel engineering, but has less affect of flow regulation compared to segments closer to the mainstem reservoirs, we also considered the situation where the hydrograph was more intensively altered. Daily discharges at the Sioux City, Iowa, streamgaging station (Figs. 1, 2) were multiplied by the ratio of mean annual flow at Hermann to the mean annual flow at Sioux City to synthesize a flow regime for Hermann that is as intensively regulated as that at Sioux City. Similar to the previous analysis, the distribution of SWH availability during the year was calculated from the time series of SWH for the synthetic flow (Fig. 11B). As in the previous analysis, the historical form provides much more SWH than the modern form over the entire year. The combination of modern form/historical flow presents a peak of habitat availability associated with the late June flood peak as the overbank area just begins to be inundate. The regime for the modern form/modern flow has a small peak of availability related to flow reductions in March. Although regimes for modern and historical flows provide abundant SWH during the entire year with the historical channel form, the within-year variability of SWH under the historical flow regime is substantially greater than that under the modern flow regime (within-year range of 21.4 ha compared to 7.7 ha).

Table 2
Summary patch statistics for shallow-water habitat (SWH) in the modeled modern and historical channel, Lower Missouri River, at Hermann, Missouri

Modeled discharge (m ³ /s)	Modern channel					Historical channel				
	Area (ha)	Linear density (ha/km of river)	Mean patch size (ha)	Total patch edge (m)	Total edge density (m/ha)	Area (ha)	Linear density (ha/km of river)	Mean patch size (ha)	Total patch edge (m)	Total edge density (m/ha)
850	28.6	5.0	0.2	36,100	156.8	63.4	7.9	1.44	45,600	155.3
1140	16.6	2.9	0.09	31,100	132.3	77.8	9.7	2.43	52,200	157.2
1420	12.0	2.1	0.06	26,400	110.6	88.9	11.1	2.78	56,300	152.0
1700	9.4	1.6	0.05	22,900	94.9	100.1	12.5	2.86	62,400	152.3
1990	8.3	1.4	0.04	20,900	85.8	118.1	14.8	2.62	70,700	154.5
2160	7.8	1.4	0.04	20,400	83.3	121.3	15.2	2.64	72,400	150.6
2270	7.3	1.3	0.04	19,400	79.3	124.8	15.6	2.35	73,500	148.0
2550	7.0	1.2	0.03	18,700	75.9	125.4	15.7	2.37	73,300	140.0
2830	6.7	1.2	0.03	18,200	73.2	129.5	16.2	2.64	75,600	137.2
3400	6.1	1.1	0.03	17,100	68.3	130.3	16.3	2.41	77,100	134.0
3970	5.8	1.0	0.03	16,600	65.6	133.7	16.7	2.62	78,500	130.6
4530	5.2	0.9	0.02	15,200	59.7	149.3	18.7	3.83	79,100	118.8
5100	4.9	0.9	0.02	14,300	55.7	165.7	20.7	4.6	81,000	112.0
5660	6.9	1.2	0.03	15,900	61.3	193.0	24.1	5.36	80,300	101.4
5950	14.3	2.5	0.06	21,300	79.5	223.0	27.9	4.65	73,000	83.8
6510	33.5	5.8	0.16	30,700	101.2	231.7	29.0	4.07	61,800	63.9
7080	31.2	5.4	0.16	27,600	91.0	217.7	27.2	4.03	61,000	61.2

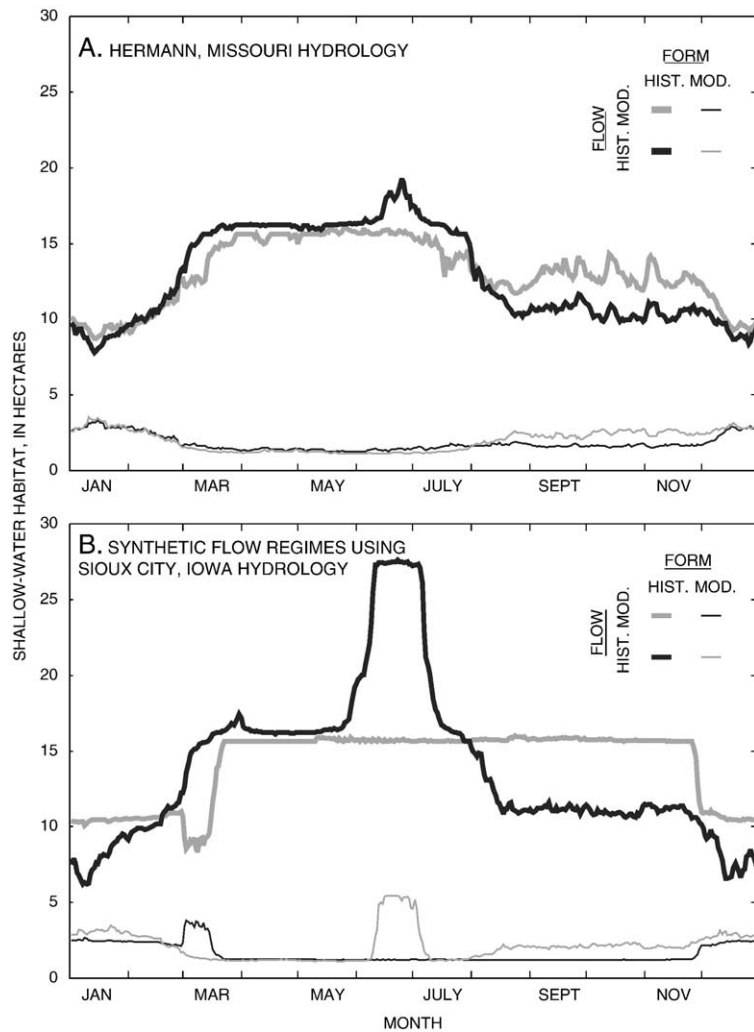


Fig. 11. Median daily distributions of shallow-water habitat during the year using modern and historical channel discharge-habitat relations, combined with modern and historical flow regimes. A. Shallow-water habitat at Hermann, Missouri using historical and modern flow regimes. B. Shallow-water habitat at Hermann, Missouri using synthetic modern and historical flow regimes reflecting flow regulation similar to that affecting the Missouri River at Sioux City, Iowa.

We also addressed how the Hermann reach compared to others along the LMOR by synthesizing the results of hydraulic modeling from seven additional reaches (Figs. 1, 12). This analysis establishes that the Hermann reach is representative of much of the altered LMOR, but that systematic deviations exist because of restoration activities or other exogenous influences on channel morphology. For six of these reaches we used 2-dimensional results of the hydrodynamic model developed by the Army Corps of Engineers (U.S. Army Corps of Engineers, 1998b); the seventh was a 1-dimensional hydraulic model reach (Jacobson et al., 2004). In the 2-dimensional models, the depth and velocity classes of the U.S. Army Corps of Engineers were combined to match the SWH definition; in the

1-dimensional model case, only the depth criterion for SWH was used.

Four distinct channel forms result in four distinct discharge–SWH area curves for the reaches (Fig. 12). The Blair (Nebraska), Nebraska City (Nebraska), Doniphan (Kansas), and Baker (Missouri) reaches have discharge–SWH relations similar to the modern Hermann reach because they are intensively engineered reaches with little diversity in elevation. In these reaches, SWH becomes abundant only at extremely low flows. The Rocheport (2-d model) and Lisbon-Jameson (1-d model) reaches provide greater abundance of SWH over a similar range of discharges because they have greater diversity of elevation. The Rocheport reach is located on a bend with an extensive

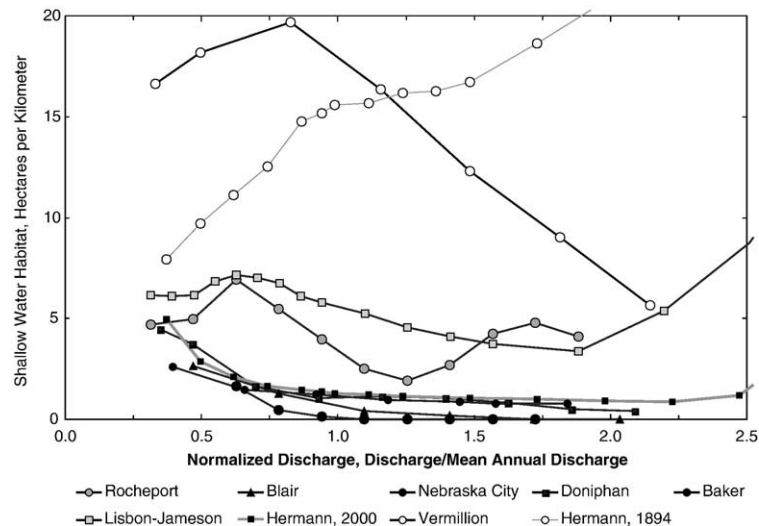


Fig. 12. Relations between normalized discharge and shallow-water habitat (SWH) hectares per kilometer of river in reaches along the Lower Missouri River. Discharge was normalized by dividing by mean annual discharge at the nearest gaging station. Closed symbols denote the engineered channel reaches; grey symbols denote rehabilitated or abnormally wide channel reaches; open symbols denote reconstructed historical reach or minimally engineered reaches.

pointbar, sandbar complex. The Lisbon-Jameson reach has been extensively rehabilitated with substantial widening of the channel and a flow-through a side-channel chute (Jacobson et al., 2004).

The Vermillion, South Dakota reach is in the non-channelized segment of the Missouri River just downstream of Gavins Point dam and upstream of the navigation channel at Sioux City, Iowa. While maintaining a braided-anastomosing morphology similar to the historical Missouri River, the channel has degraded as much as 5 m as a result of a diminished sediment load (U.S. Army Corps of Engineers, 1996). Over the modeled range of discharges, SWH peaks at about 0.75 times the mean annual discharge as flow covers abundant sandbars, and then diminishes as increasing flow encounters the near-vertical banks. Modeled discharges did not include discharges in excess of 2.0 times the mean annual discharge, which presumably reach the former flood plain and produce extensive SWH area. The Vermillion discharge–SWH relation differs from the reconstructed Hermann historical curve because the historical channel form at Hermann was not incised, and included a gradual continuum of elevations from the thalweg to bankfull.

6. Discussion: ecological and restoration implications

Although an incomplete descriptor of complex aquatic ecosystems, physical habitat models contain

abundant information from which ecological functions can be inferred (Power et al., 1988). Strictly for the purpose of this analysis, we have adopted the definition and assumed ecological importance of SWH as an indicator of ecological function (for example, Scheidegger and Bain, 1995; Bowen et al., 1998). Historical descriptions of the pre-engineered river and the effects of bank stabilization and navigation structures clearly demonstrate that shallow-water areas have been greatly diminished (Funk and Robinson, 1974; Hesse and Sheets, 1993). Moreover, shallow, slow water has been shown to be important as rearing and nursery habitat for many young fishes (Gozlan et al., 1998; Robinson et al., 1998; Schiemer et al., 2000). Shallow, slow water areas with associated fine sediment also might be expected to trap and retain organic matter in an engineered system designed to transport material efficiently downstream.

Empirical evidence for the ecological functioning of SWH on the LMOR relative to other areas is limited because of little comparative evaluation. Limnological studies on the Missouri River documented that turbidity generally limits light penetration and consequently rates of algal growth; as mean depths decrease with addition of SWH, more in-channel primary productivity could be expected (Knowlton and Jones, 2000). Large numbers and high species richness of fishes, particularly young-of-year (age-0), have been reported from Missouri River channel and floodplain SHW (Pflieger and Grace, 1987; Brown and Coon, 1994; Tibbs and Galat, 1997; Grady and Milligan, 1998). The one systematic sampling of

benthic fishes from multiple habitat types throughout the entire riverine Missouri showed that catches of most benthic fishes were highest in inside bends and connected secondary channel mesohabitats (Berry et al., 2004), both of which contain large areas of SWH (Galat et al., 2001). Ninety percent of shorebird use along LMOR floodplain wetlands occurs on exposed saturated mudflats and water less than 5 m³ deep (McColpin, 2002). SWH in a constructed side-channel chute near Overton, Missouri, was shown to be extremely efficient in recruiting and retaining large woody debris (Jacobson et al., 2004).

Timing of the appearance of maximum area of SWH may be as important to recruitment of riverine biota as the total amount available. Maximum amount of SWH in the historical flow-historical channel form scenarios at Hermann using both Hermann and Sioux City flow regimes was in late June (Fig. 11). Galat et al. (1998) reported that this was near the end of the annual spawning season for many Missouri River fishes and, thus, ample in-channel SWH would have been available as nursery for recently hatched larvae of obligate fluvial species (e.g., *Scaphirhynchus* sturgeons, *Macrhybopsis* chubs, *Hybognathus* minnows). Additionally, late June was also at the end of seed dispersal by pioneer sandbar colonizing cottonwoods (*Populus deltoides*) and willows (*Salix* spp.) (Mazourek, 1998).

In a modeling study of habitat availability in modified and unmodified reaches of the Upper Yellowstone River, Bowen et al. (2003b) documented similar results: bank-stabilized reaches of the river produced smaller areas of shallow, slow water at high discharges compared to unmodified reaches. The authors inferred that lack of rearing habitat during spring flows would likely diminish juvenile fish abundance.

A functioning aquatic ecosystem is much more complex than the presence or extent of one habitat unit. SWH, resulting from channel rehabilitation, exists as discrete zones along an intensively engineered river and fragmentation of the physical habitat template may diminish its ecological value. Whereas SWH may provide some of the functions necessary for some life stages of many aquatic species, most biota require a variety of physical habitats for different life stages (Fausch et al., 2002). For example, young (3–6-year old) pallid sturgeon have been associated with relatively deep and swift habitats during summer and early fall (Elliott et al., 2004) and deep, slow areas for overwintering (Grady et al., 2001; Jacobson and Lastrup, 2002). A more complete understanding of abiotic–biotic relations in the LMOR awaits more complete informa-

tion on habitat requirements of key species and at multiple life stages.

The critical and persistent policy and scientific question on the LMOR is the extent to which SWH rehabilitation can substitute for, or will interact with, a naturalized hydrograph. Two attributes of the naturalized hydrograph have been identified as particularly important: 1) a spring rise and 2) a summer low flow (U.S. Fish and Wildlife Service, 2000). Channel functions attributed to the spring rise include: a) a spawning cue for native fishes, including the pallid sturgeon, b) sandbar formation or alteration for shorebirds (including the listed interior least tern and piping plover), and c) seasonal connection with flood plain or other low-lying surfaces to allow for exchange of nutrients, energy, and biota. The functions attributed to the summer low flow are: a) sandbar availability for nesting and migrating shorebirds, and b) SWH availability in mid-late summer for fish nursery. Galat et al. (1998) illustrated the relation of many seasonally important bioevents to river stage and precipitation for LMOR floodplain wetlands.

Our conclusion that total SWH availability is highly sensitive to channel form addresses only one of these functions and should not be seen as a conclusion diminishing the value of a naturalized flow regime. This analysis also documents that timing of events of habitat availability has to be controlled by flow regime. A comprehensive perspective on ecosystem integrity needs to include habitat types and availability over many life stages of many species and on functional attributes operating at intra- and inter-annual temporal scales. Rehabilitation activities to create SWH have been proposed to reduce the need for mid-summer low flow, but would probably increase the efficacy of spring rises in seasonally connecting low-lying flood plain, similar to the historical case illustrated at Hermann.

The challenge in rehabilitating large, intensively engineered river systems like the Lower Missouri is to design a combination of channel form and flow regime that results in socially acceptable improvements to ecosystem functions. Most of the LMOR is intensively engineered and provides discharge–SWH relations similar to Hermann for which extensive SWH can only be achieved through very low flows or overbank flows. Some stakeholders consider very low flows to be incompatible with uses of the river for navigation, industrial and municipal water supply, and cooling of water from power plants. Discharge–SWH relations at Rocheport and Lisbon-Jameson indicate that channel forms with abundant SWH over a broad range of discharge can exist in the LMOR. Rehabilitated reaches like Lisbon-Jameson lie between the intensively

engineered condition and the historical reference condition, and illustrate a practical endpoint of physical rehabilitation wherein SWH is abundant over a range of discharges, thereby decreasing reliance on specific flow targets to achieve physical habitat goals. It is not known at this time, however, if achieving habitat rehabilitation goals in the absence of flow naturalization will yield ecological benefits acceptable to stakeholders.

The value of this analysis lies in identifying the large influence of rehabilitation of form on SWH availability in rivers where channel form is intensively engineered. If rehabilitation of channel form can supply sufficient SWH for essential ecosystem functions during mid to late summer months, managers would have additional flexibility in meeting multiple stakeholders' desires.

7. Summary

On large, intensively engineered rivers, like the Lower Missouri, the physical habitat template is largely determined by the interaction of channel form and flow regime. In contrast to natural rivers where form is equilibrated to a range of flows, engineering structures decouple form and flow for the lifetime of the engineering structures, thereby making them substantially independent and amenable to separable management strategies. We evaluated the interaction between flow and form by modeling the modern channel morphology and reconstructed historical channel morphology using the modern and historical flow regimes. The four combinations of flow and form cover the range of possible conditions for river rehabilitation from the present condition to the historical reference condition.

This analysis focused on one very important habitat class: shallow, slow velocity water (SWH) defined by natural resource agencies as depths between 0 and 1.5 m, and current velocities between 0 and 0.75 m/s. This habitat class is an incomplete measure of ecosystem function, but serves as an index of a critical habitat unit nearly lost because of river regulation and engineering. SWH is especially important as nursery area for young fishes.

Two-dimensional hydrodynamic models for the modern and reconstructed historical channels at Hermann, Missouri, indicate substantial differences between the two channels in total availability and spatio-temporal characteristics. In the modern channel SWH is maximized at extremely low flows and in overbank flows, whereas the historical channel had substantially more SWH at all discharges and SWH increased with

increasing discharge. The modern channel SWH occurs in smaller, more fragmented patches than the historical channel. Combining discharge–SWH area relations with modern and natural-hydrograph flow-regimes indicates the relative efficacy of flow and form regime in achieving SWH during the year. The historical channel form produces three to seven times the SWH area of the modern channel regardless of flow regime. The effect of flow regime is evident in increased within-year SWH variability with the natural flow regime, including significant seasonal peaks of SWH associated with spring flooding. A synthetic hydrologic record representing hydrology similar to that just downstream of the Missouri River mainstem dams illustrates that channel form persists as the dominant control on within-channel SWH availability even where hydrograph regulation by dams is more severe.

Comparisons of discharge–SWH habitat relations along the LMOR indicate three conditions of the modern channel that contrast with the historical reference condition. Most of the LMOR has discharge–SWH relations similar to the modeled reach at Hermann, Missouri, in which maximum SWH area is achieved by extremely low flow or overbank flows; intermediate flows within normal river regulation parameters achieve little SWH in these reaches because of the lack of diversity of elevation in the engineered channel. Two reaches show substantially greater amounts of SWH over a wide range of flows because of either existence of large pointbar sandbar complexes or intensive channel rehabilitation. SWH area is less sensitive to discharge in these reaches, indicating a condition where substantial SWH can be achieved with a variety of flow regimes. The upstream-most reach of the LMOR is unchannelized and contains many of the complex channel features of the historical channel, but it is incised substantially below the pre-dam flood plain. As a result, the discharge–SWH relation peaks at moderate flow and then decreases substantially as water over mid-channel bars deepens but does not extend to overbank flow. The reconstructed historical channel at Hermann has a continuously and gradually varying distribution of channel elevations from the thalweg to the top of bank. In contrast to the modern and rehabilitated channels, this form results in a marked increase in SWH with increasing discharge.

Examples like the Rocheport and Lisbon-Jameson reaches indicate that practical rehabilitation of channel form on the LMOR can produce habitat conditions intermediate between the modern, engineered channel and the historical reference channel. The engineering

challenge of rehabilitation will be to achieve the benefits of increased diversity of habitat while maintaining sediment transport in the navigation channel.

Focus on a single class of habitat cannot adequately describe the many relations that determine ecosystem functions. The spatial and temporal distributions of physical habitat determined by flow and form, however, determine the template upon which river ecosystem processes play out (Calow and Petts, 1992). Among the continuum of physical conditions in the habitat, SWH is a useful indicator of the diversity of habitat in multipurpose rivers where SWH has been diminished by flow regulation and engineering. Hence, recognition of the importance of channel form relative to flow regime in determining SWH should contribute increased flexibility toward achieving socially acceptable rehabilitation of ecosystems in large river systems.

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