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ABSTRACT—In 1996 a side channel was excavated on 629 hectares of former agricultural land at Upper Hamburg Bend on the Missouri River in Otoe County, NE. This was the first side channel constructed on the Missouri River in an attempt to restore lost aquatic habitat. The initial design was for an approximately 4,200 m long side channel to be constructed with a 3 m bottom width. Development of the site was to be dependent on flows diverted from the main channel of the river with a final projected top width of 61 m. The side channel was completed in the spring, and shortly thereafter the site was subjected to a series of flood events. The side channel has been subjected to periods of both high and low water since opening. We documented physical changes at the site with the aid of aerial photography, acoustic Doppler current profiler (ADCP) surveys, and topographic surveys. By 2010 the side channel was 4,342 m long with a mean top width of 89.5 m. Channel development has occurred during periods of high and low water. ADCP surveys established that mean depths and velocities have increased since 2001. An increase in the amount of discharge through the side channel since 2001 has resulted in the loss of some of the shallower and lower velocity habitats. Modifications to the site may be necessary to reverse this loss of shallow, slow water habitat that the side channel was designed to provide. Although new off-channel aquatic habitat has been created, channel development has been impacted by the presence of rock control structures throughout the site. Reducing the number of control structures to the minimum necessary to prohibit the side channel from impacting adjacent properties may allow the continued restoration of lost alluvial processes through the ongoing process of bend development and migration.

Key Words: alluvial processes, chute, mitigation, pallid sturgeon, restoration, side channel

INTRODUCTION

Between 1912 and 1980, shallow-water, sandbar, and island habitats were intentionally eliminated as the Missouri River in Nebraska and Iowa was shortened, narrowed, and deepened to create a 2.7 m deep navigation channel. Stabilizing the river for navigation eliminated most of the cut-and-fill alluviation that constantly reformed the aquatic habitats of the Missouri River. These habitat losses have had profound effects on native fish and wildlife populations. Of 59 native fish species found in this portion of the Missouri River whose status could be discerned, 41 species, or 69%, were considered to have decreasing population levels (Galat et al. 2005). In addition, there are three federally listed species on the Missouri River: least terns, listed as federally endangered in 1985; piping plovers, listed as threatened in 1986; and pallid sturgeon, listed as endangered in 1990 (USFWS 2000).

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Efforts to restore some portion of these lost aquatic habitats and the processes that formed and maintained them began about the same time that the navigation channel was completed and have increased dramatically in response to the federal listings. Initial efforts through the Missouri River Bank Stabilization and Navigation Project Mitigation Plan focused on restoring lost habitats, both aquatic and terrestrial, thereby restoring a portion of the lost fish and wildlife resources and recreational opportunities that those lost habitats supported (USFWS 1980). More recent efforts in response to the Missouri River Biological Opinion (BiOp) have been directed at restoring habitats to help recover federally listed species, more specifically, emergent sandbars for least terns and piping plovers and shallow-water habitat for pallid sturgeon (<1.5 m deep and <0.6 m s^{-1}) (USFWS 2000, 2003).

The Mitigation Plan, enacted in the 1986 Water Resources Development Act (WRDA) (Public Law 99-662) and subsequently expanded in the 1999 WRDA (Public

Law 106-53), authorized the development of fish and wildlife habitat on 27,309 ha of land to be acquired from willing sellers along the Missouri River in Missouri, Kansas, Nebraska, and Iowa. The restoration objective for aquatic habitat was to restore large-river habitats and the associated side channels and backwaters on the floodplain adjacent to the main channel of the Missouri River (Greenhorne and O'Mara, Inc. 1994). Habitat was to be developed by dredging filled-in areas, reopening historic side channels, notching river-training dikes, stabilizing banks, constructing some dikes and levees, pumping river water into wetlands, and planting natural vegetation. Since 2001 these habitat restoration projects have been incorporated into the U.S. Army Corps of Engineers Missouri River BiOp's reasonable and prudent alternative to "implement a habitat restoration program with the goal of restoring habitat quality, quantity, and diversity, so that the benefits of adequate dynamic natural river processes are restored" (USACE and USFWS 2012). A shallow-water habitat goal of 20 to 30 acres per mile was established for the river between Sioux City, IA, and the mouth (USFWS 2003).

The large flood on the Missouri River in 1993 resulted in severe damage to thousands of acres of agricultural land on the floodplain through deep scours and deposition of sand and silt. Because of this damage, the Corps of Engineers was able to acquire what became the Hamburg Bend Mitigation Site (Figs. 1 and 2). After considering available options for this site, a side-channel restoration was determined to be the best option and a pilot channel was constructed during the winter of 1995–96, becoming the first habitat restoration project in Nebraska under the Mitigation Plan. The pilot channel was "intended to assist in restoring the natural chute channel condition by developing into a wide shallow channel that will meander across the point bar to some extent" (Greenhorne and O'Mara, Inc. 1994). By design, the Hamburg Bend restoration project was intended to restore shallow-water habitat through active alluvial processes.

The Hamburg Bend Mitigation Project, designed and built during 1994–96, was one of the first large-scale riverine habitat restoration projects in the world. The project was conceived and completed at a time when the science of ecological restoration was still in its infancy (Palmer et al. 1997). The goals and objectives for the project reflect the state of the science at this time, which Palmer et al. (1997) call the "Field of Dreams" hypothesis, or "build it and they will come." Tens of thousands of hectares of habitat had been lost on the river, and the goal was to restore habitat heterogeneity as defined by historic conditions. Although the designers estimated depth and velocity ranges for the side channel, the only metric included in the project design was a "200 foot wide ultimate chute channel condition" (Greenhorne and O'Mara, Inc. 1994). Biological metrics were probably never even considered, because at the time "the assumed relationship between habitat heterogeneity and biodiversity *in a restoration context* remains largely untested" (Palmer et al. 1997).

Because of the cost associated with acquiring and developing a site such as Hamburg Bend and because this was the first project of its kind on the Missouri River, the engineers' major concerns were the longevity of the side channel and the possibility of the side channel capturing the main channel of the river. The amount of water and sediment that a side channel carries is critical to its evolution and stability. Designers on the River Rhine asserted that sediment entering the side channel would eventually lead to filling the channel (Barneveld et al. 1994; Schropp 1995) and recommended preventing any sediment from entering side channels (Schropp 1995). Shields and Abt (1989) found that a decreasing sine of angle of approach and increasing discharge in the side channel increased the likelihood of filling in. A side channel's stability is also reliant on the lip height, particle size of the moving bed of the main channel, and the ratio of side-channel slope to main-channel slope (Slingerland and Smith 1998). These issues were addressed by significant rock entrance and exit structures and onsite grade-control structures. Repairs, maintenance, and modifications to the site have been ongoing since its opening, and great measures have been and are being taken to prevent both filling and capture of the main channel.

In the period following the construction of the Hamburg Bend side channel the number of river restoration projects worldwide have increased exponentially (Bernhardt et al. 2005) as have attempts to understand the complex nature of large rivers. There have been recommendations that river restoration efforts should be more holistic, and that to be considered successful, the river's ecological condition must show measurable improvement and the river system must be more self-sustaining and resilient to external perturbations (Palmer and Allan 2006). Recently these ideas were synthesized into the concept of "process-based restoration" (Beechie et al. 2010). Restoration projects that are designed to reestablish the processes or the natural variation that sustained habitat conditions would (1) address multiple ecosystem components concurrently, (2) be more sustainable and resilient, (3) require minimum maintenance, and (4) allow the habitats and biota to adjust to long-term stresses

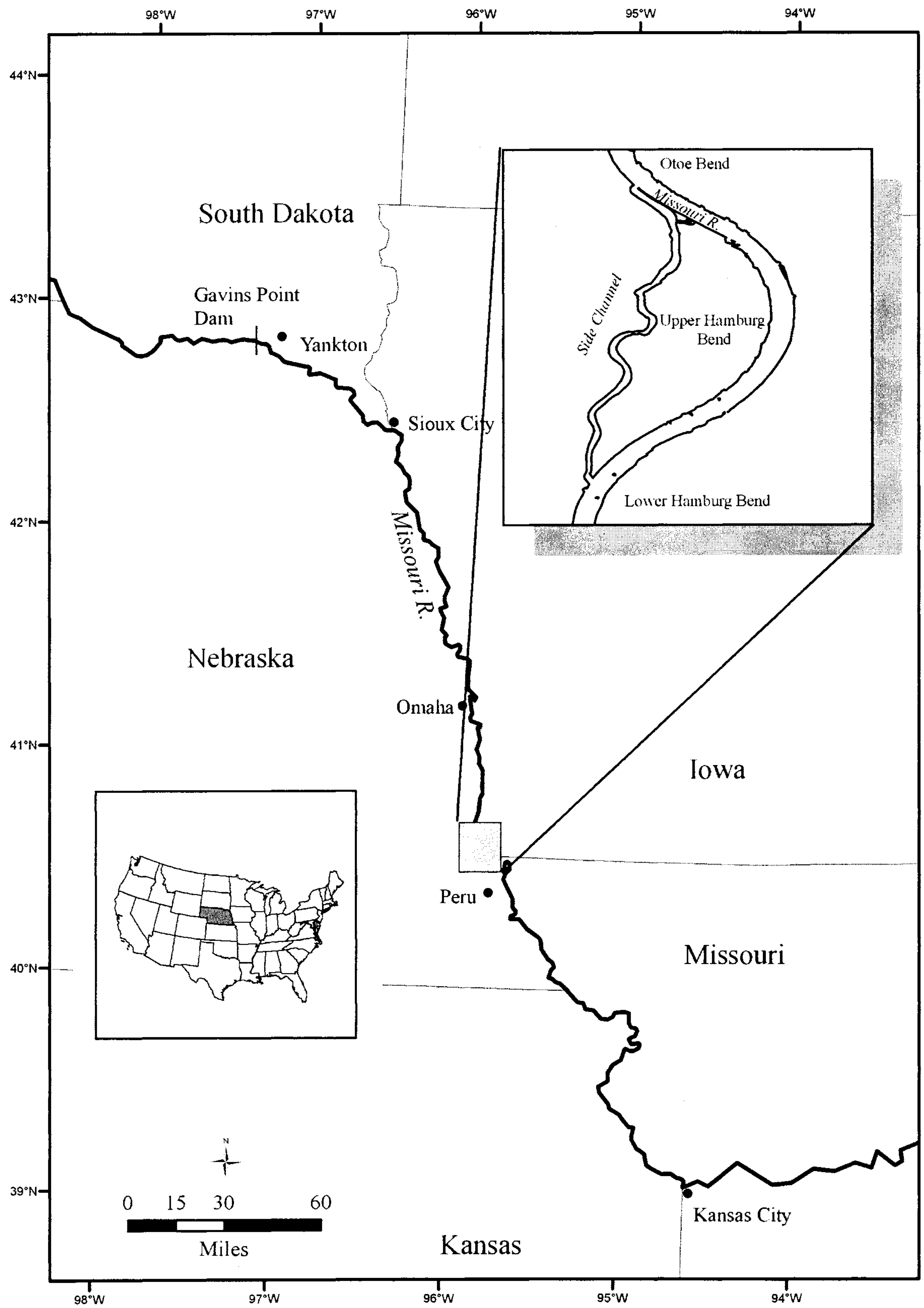

Figure 1. Area map of the lower Missouri River from Sioux City, IA, to Kansas City, MO, showing location of study site.

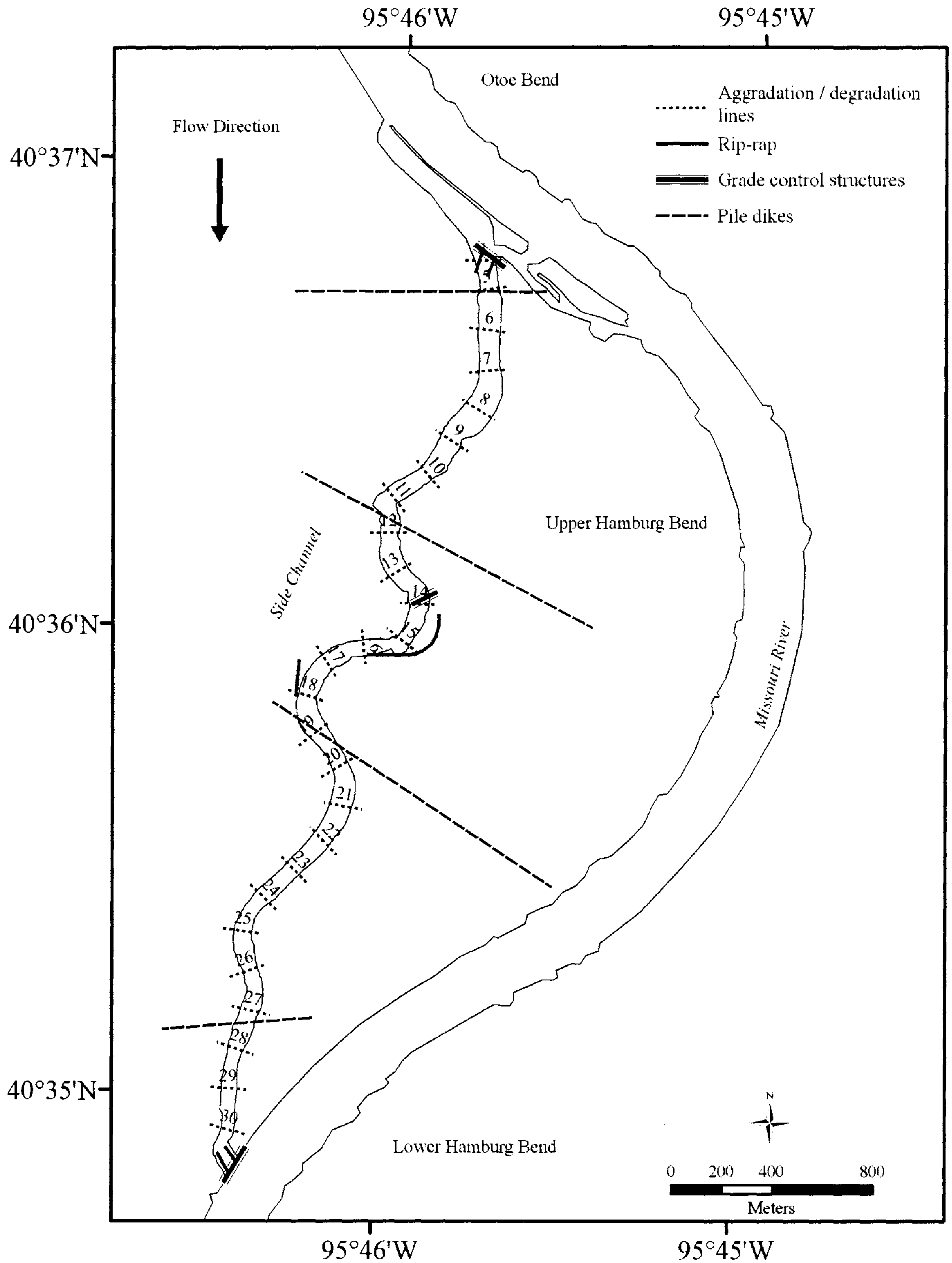

Figure 2. Map of the Upper Hamburg Bend side channel showing bankline locations circa 2001, agg/deg lines, grade control structures, pile dikes, and protective rip-rap.

such as climate change. These concepts of process-based restoration were reiterated by the National Research Council, who reported that degradation of the Missouri River ecosystem "is clear" and would continue "unless some portion of the hydrologic and geomorphic processes that sustained the pre-regulation Missouri River and floodplain ecosystem are restored" (National Research Council 2002).

Our objective was to document and quantify geomorphic change at the Upper Hamburg Bend side channel from 1996 to 2010 and determine if there had been success at restoring a wide, shallow channel that meanders across the point bar to some extent. We addressed this objective using topographic surveys, aerial imagery, and, beginning in 2001, acoustic Doppler current profiler surveys.

SITE DESCRIPTION

The Upper Hamburg Bend side channel begins on Otoe Bend at river kilometer (rkm) 894.0, Otoe County, NE (distance measured upstream from the confluence with the Mississippi River). It dissects the point bar of Upper Hamburg Bend and rejoins the Missouri River at rkm 888.7, on Lower Hamburg Bend (Fig. 1). Historic maps and photos show the Upper Hamburg Bend area was characterized by extensive off-channel aquatic habitats. After the river was channelized for navigation, the land at the site was reclaimed for agriculture.

The side channel was initially designed as a pilot channel that was 4,267 m long and had a 3 m bottom width, 2:1 side slopes, and a slope of 0.08 m/km (Greenhorne and O'Mara, Inc. 1994). Riprap inlet and outlet structures were built to the final planned width of 61 m to allow for designed inflows and discharges. Due to the configuration of the main channel adjacent to the site, water entering through the upstream inlet is decanted, leaving the coarse bed-material sediment in the main channel. Two grade-control structures (the first being part of the inlet structure) were included in the design to prevent excessive channel degradation and to limit the amount of water withdrawn from the navigation channel. Each grade-control structure was built to the target width of 61 m, with 3:1 side slopes, and armored with riprap. Initial design criteria called for the side channel to capture 8% of the main channel discharge at median August flows, or 1,047 $m^3 s^{-1}$ (Greenhorne and O'Mara, Inc. 1994). Velocities in the side channel had been projected to be between 0.3 and 0.9 $m s^{-1}$ and depths were projected to be between 0.6 and 3.0 m (Greenhorne and O'Mara, Inc. 1994).

Approximately 189,860 m^3 of soil was excavated, and 12,400 m^3 of riprap was used to armor the inlet, outlet, and grade-control structures (Greenhorne and O'Mara, Inc. 1994). The locations of entrance and exit structures, grade-control structures, and revetment and historic training structures at the site are presented in Figure 2. Most of the riprap was placed in the upper 40% of the site, stabilizing the channel's reach and making it less susceptible to erosion than the lower 60%. The Upper Hamburg point bar also contains a series of historic pile dikes (Fig. 2) that were placed during channelization to direct flow to the new channel and promote sedimentation on the point bar, creating the bend in its present form. After initial construction, modifications at the site have included work to narrow the entrance structure and enhance grade control structures to limit the amount of water entering the side channel and armoring short reaches of bankline with riprap to protect a levee that lies adjacent to the site.

METHODS

We collected data in three manners for this study: topographic surveys, bathymetric surveys, and data digitized from orthophotographs. Data were collected over a time span that ranged from 1996 to 2010.

Topographic Surveys

The Nebraska Game and Parks Commission (NGPC) conducted two topographic surveys at the site in addition to the as-built survey prepared by the U.S. Army Corps of Engineers in 1996 upon completion of the project. Terrestrial portions of the site were surveyed in the summer of 1996 using a total station and in March 2008 using differential GPS (DGPS) survey equipment. Horizontal and vertical control points were established prior to both surveys, and multiple control points were checked before and during all survey trips to ensure horizontal and vertical measurements were accurate to less than 9 cm. The 1996 topographic survey was conducted using a haphazard approach with additional detail given to features such as banklines, ditches, and levees. The 2008 topographic survey was conducted using transects spaced 15.25 m apart and extended 30.50 m perpendicular to the bankline. Where conditions allowed, transects were extended down banks to the water line. Significant topographic features such as ditches, roads, and rock structures were surveyed in greater detail, as were significant features located between transects.

Orthophotography

We supplemented the as-built and topographic surveys with data digitized from existing orthophotographs from the Farm Service Agency's National Agriculture Imagery Program. Resolution of the orthophotographs ranged from 1 to 3 m. Banklines were digitized from orthophotographs taken in 1999, 2001, 2003, 2006, 2009, and 2010. We used the total nonvegetated channel as the basis for our digitizing to compensate for inconsistent water levels between photographs (Winterbottom 2000; Elliot and Jacobson 2006).

Bathymetric Surveys

Depth and velocity data in the side channel were collected with an acoustic Doppler current profiler (ADCP) unit. The ADCP surveys will be referred to as "bathymetry" or "bathymetric" to reduce confusion with the topographic surveys. Crews from the U.S. Geological Survey (USGS) Columbia Environmental Research Center in Columbia, MO, collected bathymetry data at the Upper Hamburg Bend side channel and the adjacent main channel in 2001; methods for this survey are documented in detail in Reuter et al. (2008). Mainstem discharge measurements were taken from the USGS streamflow-gauging station on the Missouri River at Nebraska City, NE (06807000), located approximately 10 km upstream from the site. Discharge at the Nebraska City streamflow-gauging station was 1,047 $m^3 s^{-1}$ on the date of the 2001 survey. The Nebraska Game and Parks Commission conducted the second bathymetric survey on July 2, 2008. Discharge at the Nebraska City streamflow-gauging station on this date was 1,067 $m^3 s^{-1}$. Depth and velocity data were collected simultaneously using a 1,200 kHz Rio Grande ADCP (Teledyne RDI, Poway, CA). The ADCP internal compass was calibrated before each survey to within 0.3 degrees of error. All bathymetry data were collected using Bottom Mode 7 and Water Mode 1 or 12, and water velocity data were collected in bins ranging from 0.05 m to 0.25 m depending on conditions. Boat speed was maintained at or below water velocity (usually <1.5 m s^{-1}). Data were georeferenced using a DGPS and were accurate within 3 cm. Data were logged and checked for quality assurance using WinRiver software (Teledyne RDI, Poway, CA).

Bathymetry data were collected along a series of transects, spaced 40 m apart. When obstructions such as rock structures or large woody debris hindered boat navigation, bathymetry transects were ended as close to the obstruction as safely possible or conducted immediately upstream or downstream of the obstruction. The water and bottom mode settings required for the survey did not allow us to effectively measure velocities in water less than 0.8 m deep. Bathymetry transects were ended when the ADCP software indicated that velocity measurements were not being taken and therefore no depths or velocities were surveyed in water shallower than 0.8 m. Site conditions in 2001 allowed USGS crews to conduct bathymetric surveys in shallower water than the NGPC crews had surveyed. To ensure that data remained consistent, we eliminated all data points from the 2001 USGS survey that measured depth or velocity, or both, in less than 0.8 m of water. It was our intention in 2008 to duplicate transects from the 2001 survey as closely as possible.

Analysis

We classified the chute and measured changes in a GIS. Twenty-eight aggradation/degradation lines (agg/deg; Fig. 2), spaced evenly apart and corresponding to a bathymetry transect, were used to measure width and bankline movement based on the digitized banklines from the as-built survey, topographic surveys, and orthophotographs. Not all agg/deg lines were perpendicular to the chute centerline each year because of channel migration. Bankline movement along the agg/deg lines was measured as an absolute value; there was no "negative" bankline movement. Movement of both banks, regardless of direction, was used to sum lateral movement. The agg/deg lines were clipped by the digitized bankline layer to get 28 widths, which were used to calculate a mean width from each as-built survey, topographic survey, or orthophotograph. Mean widths were compared using analysis of variance in SAS 9.2 (SAS Institute Inc. 2008) with an alpha level of $p = 0.10$. Length was measured based on the chute centerline, and sinuosity (channel length/valley length) was calculated over the entire chute (reach) from both topographic surveys and all orthophotographs. It was also computed for two subreaches, the upper 40% and the lower 60% from the 1999 and 2010 orthophotographs.

Two indices based on width measurements of both topographic surveys and all orthophotographs were computed along with an index of stability. Normalized bankline movement (N) was computed as a percentage of the average width of two topographic surveys or orthophotographs:

$$N = ([\Delta r + \Delta l] / 2) / ([W_i + W_j] / 2) \quad (1)$$

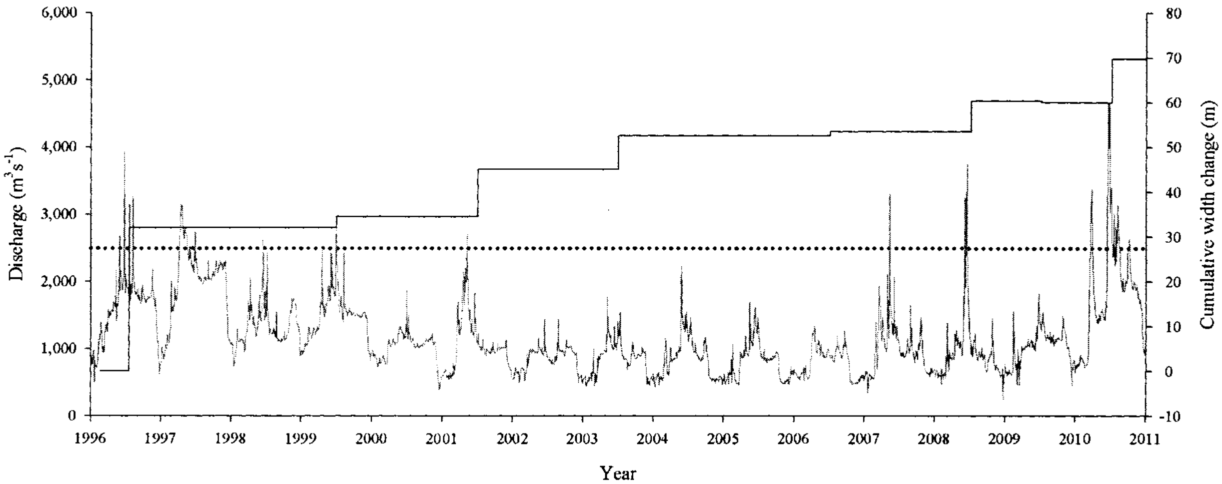

Figure 3. Daily discharge data for the USGS streamflow-gauging station Missouri River at Nebraska City, NE (06807000), from January 1, 1996, to January 1, 2011. The stepped line indicates change in width at the Upper Hamburg side channel and the dotted horizontal line represents flood stage (2,491 $m^3 s^{-1}$).

where Δr and Δl are the sum of lateral movement (absolute value) for the right and left descending banks at all agg/deg lines in a particular topographic survey or orthophotograph and W_i and W_j are the mean width of all agg/deg lines in a particular topographic survey or orthophotograph. The rate of mean width change (ΔW_{mean}) was calculated in meters of movement per year:

$$\Delta W_{mean} = (W_i - W_j) / t_i - t_j \quad (2)$$

where W_i is the mean width of a particular topographic survey or orthophotograph i, W_j is the mean width of a particular topographic survey or orthophotograph j, t_i is the time of the particular topographic survey or orthophotograph i, and t_j is the time of the particular topographic survey or orthophotograph j.

We computed the lateral stability index (LSI) each year. The LSI compares the total area of the side channel from one topographic survey or orthophotograph that has not changed since the previous topographic survey or orthophotograph (unchanged area) to the total area of the previous topographic survey or orthophotograph.

$$\text{LSI} = \text{Unchanged total side-channel area} / \text{Previous total side-channel area} \quad (3)$$

Values approaching 1 indicate a stable channel, and low values indicate instability.

Each agg/deg line was classified as being in a run (straight), bend, or exit/entrance area based on the original side-channel alignment. These classifications were then reevaluated based on 2010 morphology and subcategorized based on the amount and the rate at which development took place.

We compared the 2001 and 2008 bathymetric surveys to see if any changes in mean depth or velocity had occurred. Data were checked for normality and were found to be non-normal. Three transformation types (natural log, log, and square root) failed to normalize the data, and therefore we used a Kruskal-Wallis nonparametric test to compare the distributions. All statistical analyses were conducted with SAS 9.2 (SAS Institute Inc. 2008) with an alpha level of $p = 0.10$.

RESULTS

The pilot channel at Hamburg Bend was extensively reshaped by flooding during the first three months following construction in 1996, resulting in an increase in mean width of 31.7 m (Fig. 3). Since then, most additional widening has occurred during periods of high water. Significant changes in mean width occurred between 1999 and 2001 (10.5 m; $F = -2.51$, $p = 0.01$) and from 2009 to 2010 (9.7 m; $F = -2.28$, $p = 0.02$). There was also some increase in width during the early part of the drought in 2001–2003 (7.6 m; $F = -1.81$, $p = 0.07$). Normalized lateral movement followed a similar pattern, with the greatest values occurring between the as-built and 1996 topographic surveys ($N = 51\%$) and the 2009 and 2010 topographic surveys ($N = 1.8\%$). All other values were low, ranging from 0.1% to 1.0%. Figure 4 gives examples of the amounts of channel movement

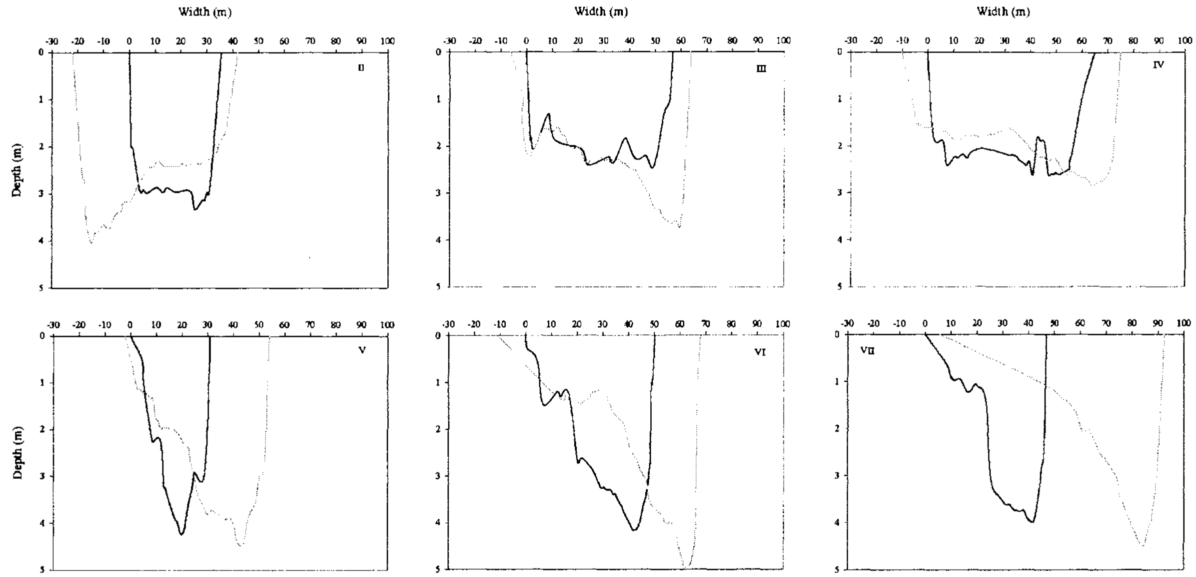

Figure 4. Longitudinal view of aggradation/degradation lines, Types II-VII, at the Upper Hamburg Bend side channel during the 2001 (black) and 2008 (gray) bathymetric surveys (2001 data from Jacobson et al. 2004). On all graphs, zero on the x-axis denotes the right-hand, descending bank during the 2001 survey. Negative numbers on the x-axis signify westward movement.

and reshaping for six of the seven agg/deg line types between 2001 and 2008.

Mean top width of the side channel increased from 16.3 m immediately after construction to 48.1 m in late summer of 1996 and to 89.5 m by the summer of 2010 (Fig. 5). The overall length of the side channel increased by 101 m in the first three years, but only increased an additional 57 m during the next 10 years (Fig. 5). In 2010 the side channel increased in length by an additional 15 m. The surface area of the side channel has expanded from 5.9 to 39.1 ha since construction. Total area has increased between each survey, although the area was nearly identical between 2008 and 2009. In addition to total area, the area common between consecutive surveys, or unchanged area, has increased every year, indicating that the channel alignment has remained stable (Fig. 6). LSI scores, although variable, have increased over time, indicating the side channel is approaching a stable condition.

Individual agg/deg line widths all increased; however, some accretion did take place (Figs. 4 and 7). Change at individual agg/deg lines was not uniform in speed or magnitude, although we did identify six patterns of change for the runs and bends (Table 1). In general, change was more rapid in the upper bends and runs (Types III, IV, and VI) and slower in the lower ones (Types II, V, and VII) (Figs. 7 and 8). By 2010, Type II and III runs and Type V bends exceed the design width by less than 50%, whereas Type IV runs and Type VI and VII runs and run/bends exceed design width by more than 50%.

The amount of water entering the chute increased from approximately 9% (97.4 $m^3 s^{-1}$) of the main channel flow in 2001 to 14% (153.6 $m^3 s^{-1}$) in 2008. Both of these measurements were taken at nearly identical main channel flow, 1,047 $m^3 s^{-1}$ in 2001 and 1,067 $m^3 s^{-1}$ in 2008, indicating that the increase in discharge within the side channel was not related to an increase in discharge in the main channel. More water entering the side channel resulted in significant changes in depth ($x^2 = 10.03$, DF = 1, $p < 0.0015$) between the two bathymetric surveys (Fig. 9). During the 2001 bathymetric survey the mean depth in the side channel was 2.6 m and the maximum depth was 8.2 m. Eighteen percent of depths were less than 1.5 m, 33% were greater than 3.0 m, and only 3% were greater than 5.0 m. By 2008 the mean depth in the side channel had increased to 2.9 m and the maximum depth to 13.8 m. Only 14% of depths were less than 1.5 m, and the percentage of depths greater than 3.0 m had increased to 35% and those greater than 5.0 m to 9%.

Velocity at the site was also significantly affected by increased discharge within the side channel ($x^2 = 10.55$, DF = 1, $p < 0.0012$; Fig. 10). The mean velocity in the side channel during the 2001 bathymetric survey was 0.82 m s^{-1} and the maximum was 2.44 m s^{-1}. Approximately 20% of velocities were less than or equal to 0.60 m s^{-1} and 41% were greater than or equal to 0.90 m s^{-1}. The mean velocity of the 2008 side-channel bathymetric survey was 0.87 m s^{-1} and the maximum was 2.31 m s^{-1}. Approximately 17% of velocities were less than or equal to 0.60 m s^{-1} and 45% were greater than or equal to 0.90 m s^{-1}.

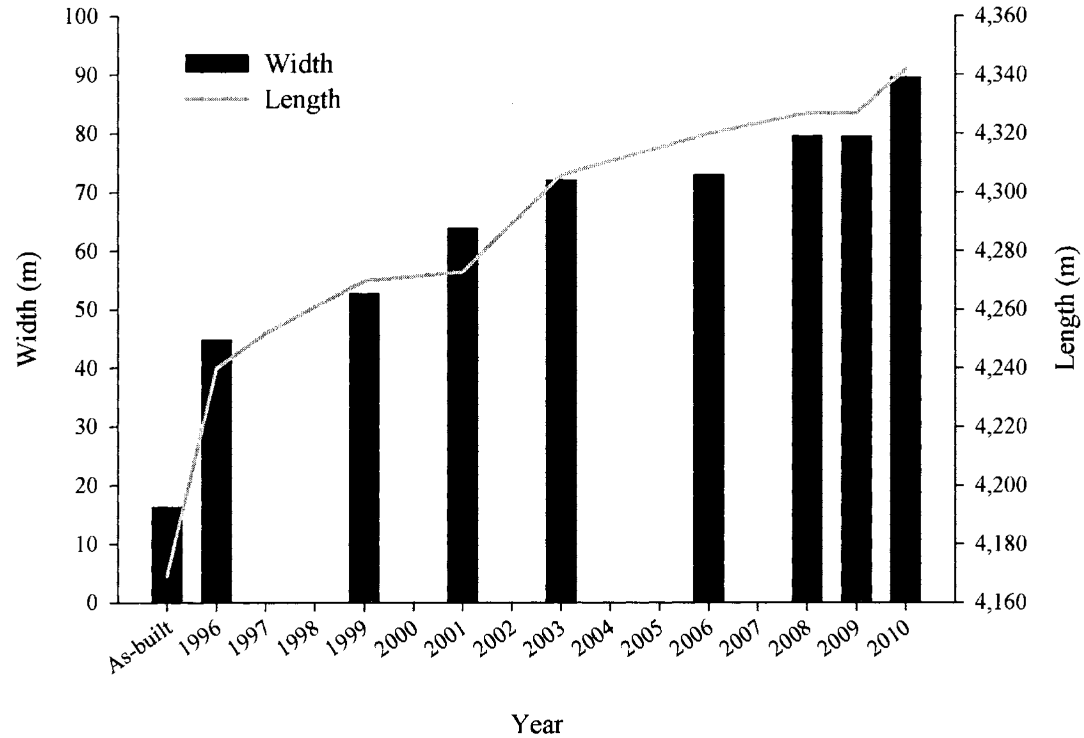

Figure 5. Width and length change at the Upper Hamburg Bend side channel from construction until 2010.

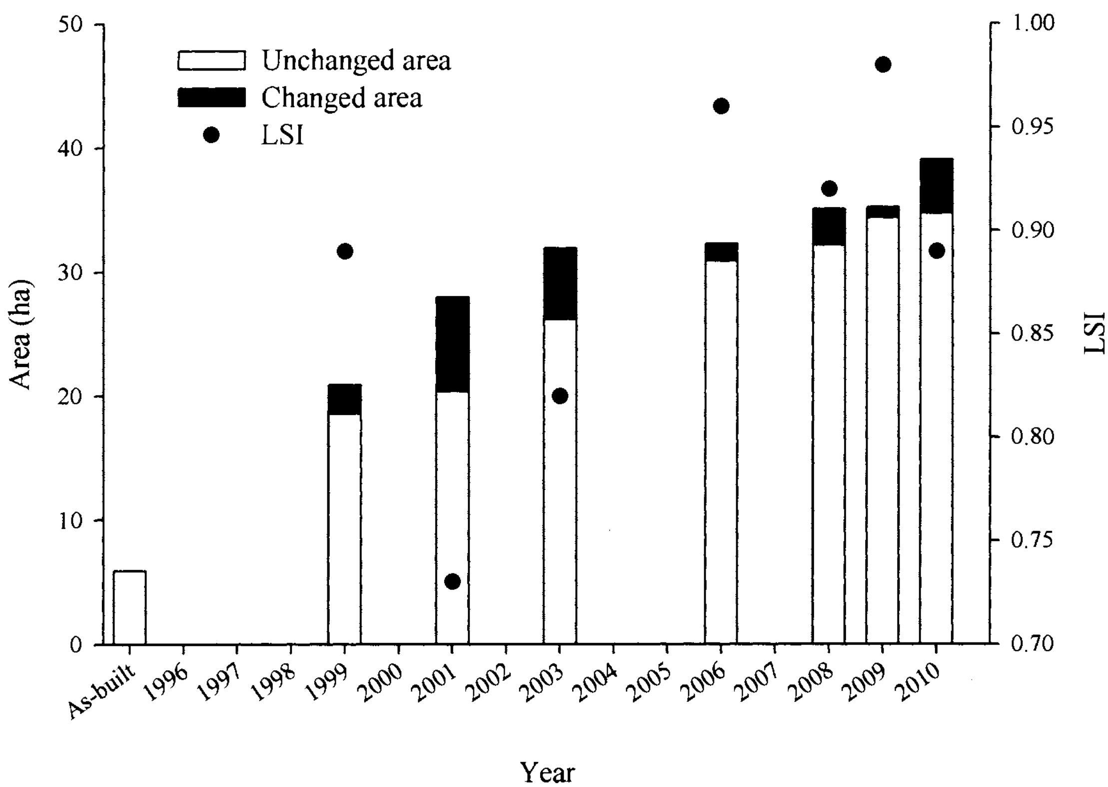

Figure 6. Unchanged area (black), changed area (white), and lateral stability index (LSI) at the Upper Hamburg Bend side channel from construction until 2010.

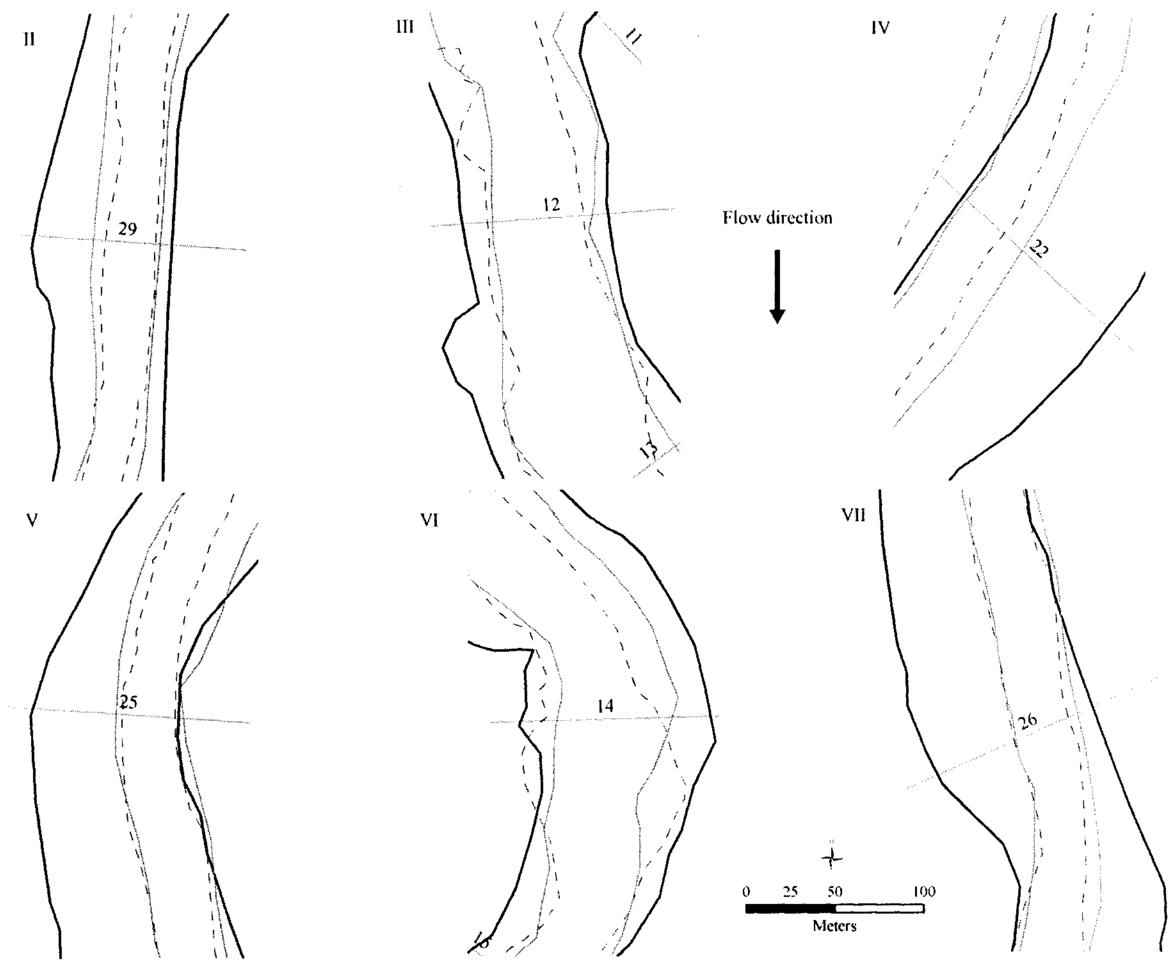

Figure 7. Overhead view of Type II–VII aggradation/degradation lines at the Upper Hamburg Bend side channel in 1996 (gray), 1999 (dashed), and 2010 (black).

TABLE 1
UPPER HAMBURG BEND SIDE-CHANNEL TRANSECT LINE TYPE, CLASSIFICATION, DESCRIPTION, AND NUMBER CORRESPONDING TO EACH TYPE, BASED ON AS-BUILT SURVEY

Type	Classification	Description	Transect number
I	Entrance/exit structure	Entrance and exit structures built to design width and lined with rock	4, 5, 31
II	Run	Runs that developed slowly, generally not approaching design width until 2003	23, 24, 28, 29, 30
III	Run	Runs that developed rapidly, nearly reaching design width in first year	11, 12, 15
IV	Run	Runs that developed rapidly, generally exceeding design width by more than 50%	6, 7, 10, 20, 22
V	Bend	Bends that developed slowly, generally not exceeding design width until 2003	17, 21, 25
VI	Bend	Bends that developed rapidly, nearly reaching design width in first year, generally exceeding design width by more than 80%	8, 9, 14, 18
VII	Run	Runs that changed into bends, generally exceeding design width by more than 75%	13, 16, 19, 26, 27

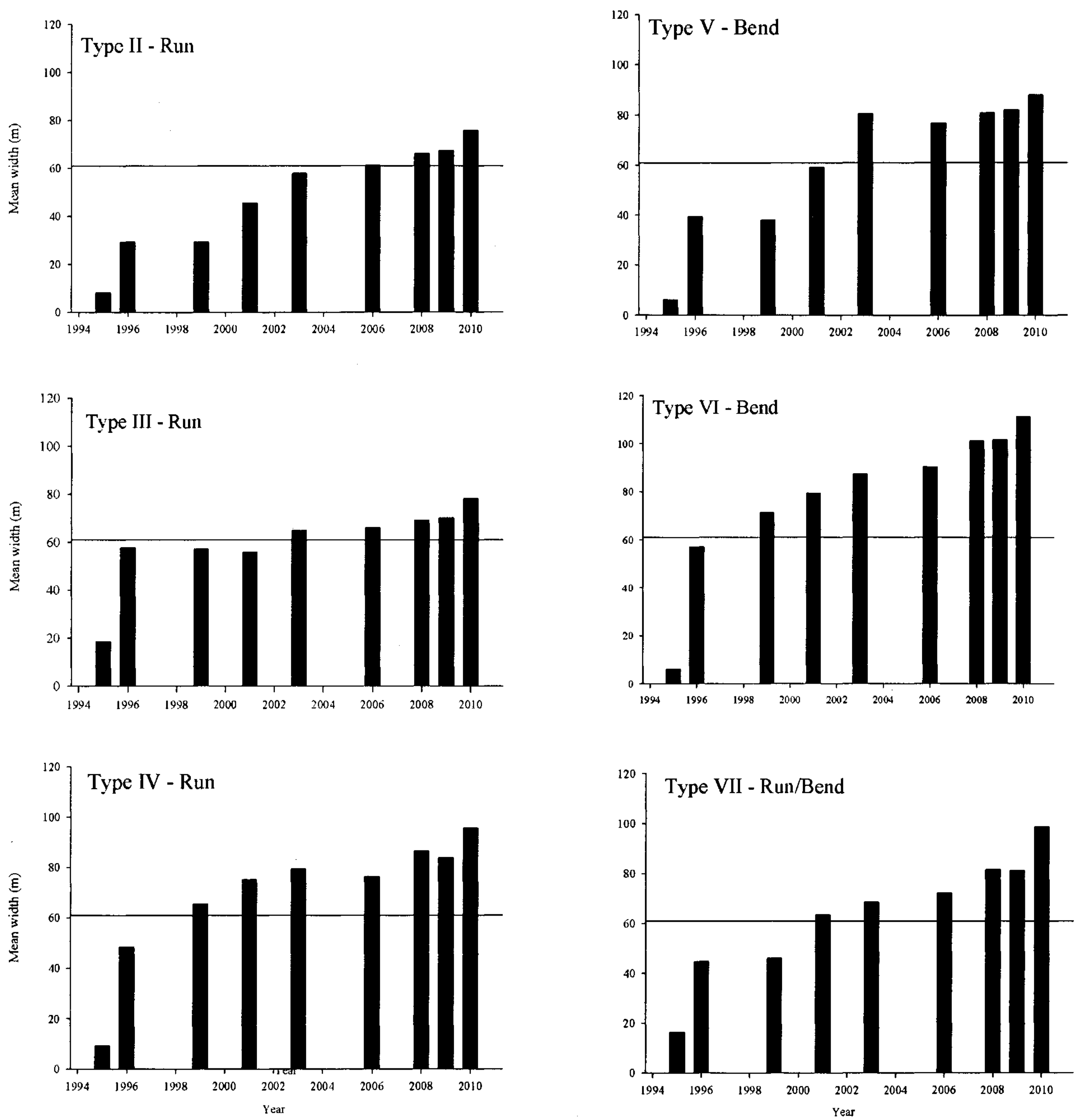

Figure 8. Mean width from 1996 to 2010 and classification of transect types at Upper Hamburg Bend side channel.

The overall sinuosity of the site has not varied much since the 1996 topographic survey; however, the upper and lower reaches have evolved differently. Sinuosity in the upper portion of the side channel decreased from 1.17 to 1.13 between 1999 and 2010, as a result of channel realignment due to rock control structures. The lower portion of the side channel saw an increase in sinuosity from 1.12 to 1.18 between 1999 and 2010, as the bends started to move laterally and downstream through cut-and-fill alluviation. It was observed that large woody debris has been deposited in the downstream portions of the side channel, especially on eroded outside bends. Large point bars have formed on the insides of these bends. Deep scour holes are associated with the entrance

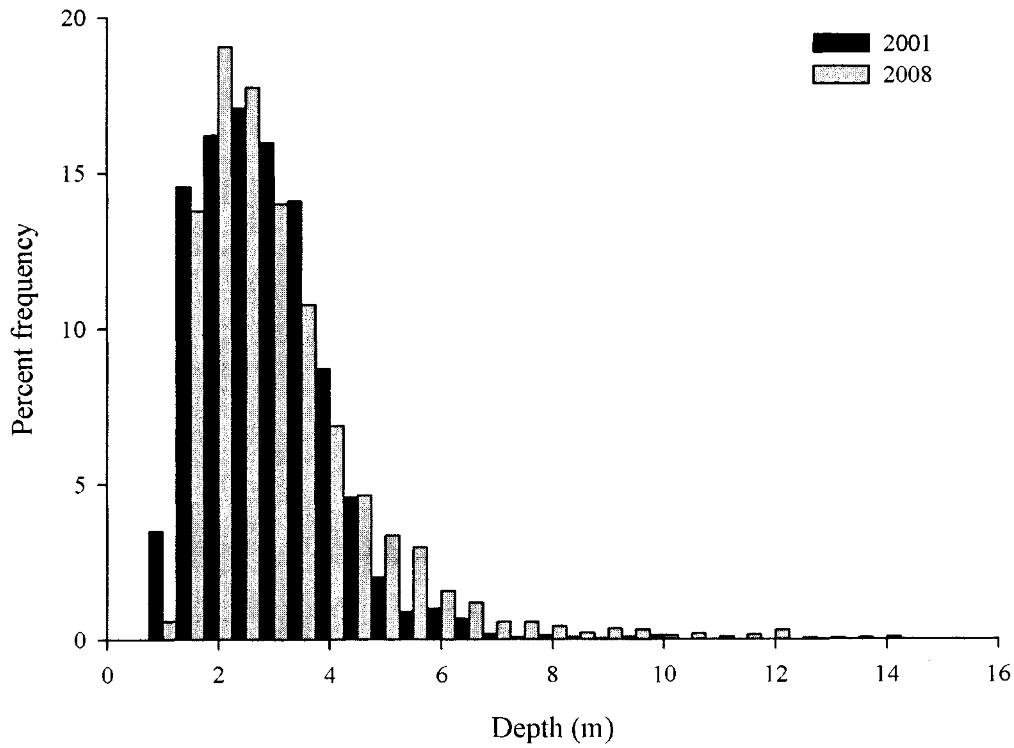

Figure 9. Depth frequency distributions for the August 2001 and July 2008 ADCP surveys of the Upper Hamburg Bend side channel (2001 data from Jacobson et al. 2004).

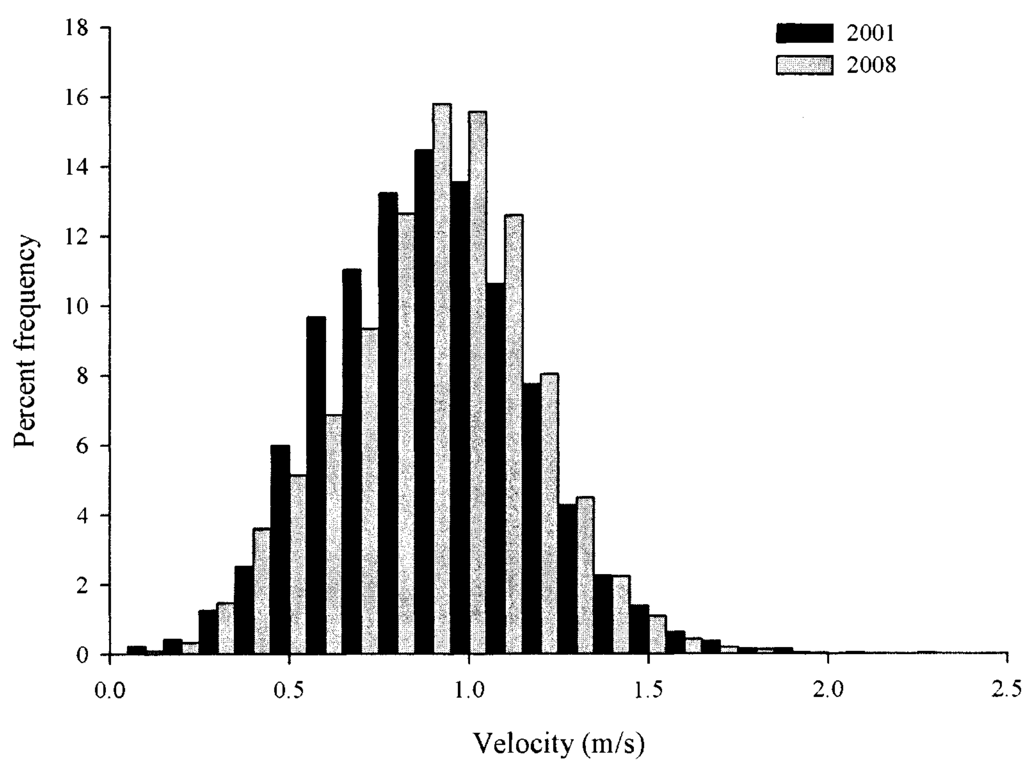

Figure 10. Velocity frequency distributions for the August 2001 and July 2008 ADCP surveys of the Upper Hamburg Bend side channel (2001 data from Jacobson et al. 2004).

and exit structures of the side channel as well as behind the remnants of old pile dikes.

DISCUSSION

The question of the chute widening by alluvial processes was partially answered on the day the side channel was opened in May 1996, when the second author had to abandon an ongoing topographic survey and retreat from a rapidly eroding bankline near agg/deg line 12. Change at the site began immediately and has continued ever since. Flood flows appear to have been the driving force behind most channel development at the site, the exception being the development that occurred during the drought from 2001 to 2003. Even after the first 10 years, with floods occurring in nearly half of those years, there was substantial change in the side channel as a result of the floods in 2007, 2008, and 2010 (Fig. 3). The large changes in 2010 can be attributed to the flood being of sufficient magnitude that it overtopped several of the rock control structures, resulting in significant channel widening on what was the landward side of these structures.

The mean width of the side channel has steadily increased (Fig. 5), although individual agg/deg lines have been documented to narrow between surveys, due to accretion. The length of the side channel has remained relatively constant, although the length is limited by the size of the site and the control structures. Changes have not been uniform across the site but have been affected by a variety of factors, including channel alignment, the presence of rock control structures, and in some cases the locations of agg/deg lines used in the analysis. Aggradation/degradation lines classified as both runs and bends tended to widen rapidly in the upstream and middle portions of the side channel and more slowly in the downstream portion (Table 1; Fig. 8). Conversely, the greatest lateral movement occurred on the lower 60% of the site, which is characterized by bends, and runs that became bends, with highly erodible outside banks and fewer rock control structures. Most lateral movement occurred during the same time periods of high and low water when the greatest channel widening occurred. Normalized lateral movement was greater than observed by Shields et al. (2000) on the upper Missouri River in Montana (0.6% post-dam to 1.7% pre-dam using centerline measurements).

The lateral stability index, although variable, indicates that overall the site has become more stable over time (Fig. 6). Since 2006, despite floods in 2007, 2008, and 2010 (Fig. 3), LSI scores have remained high, ranging from 0.89 to 0.98, indicating little channel movement. Related to channel stability, a number of agg/deg lines located in the downstream portion of the side channel that were classified as runs became bends as adjacent bends migrated downstream. This downstream movement of bends was a naturally occurring process on the Missouri River, but it did not occur on the upper and middle reaches of the side channel because of greater control by rock structures.

As of 2010, the site was characterized by a wide, shallow upper section containing in-channel sandbars and a lower section with a meandering thalweg, point bars, and high cutbanks. This resembles the side channel created naturally by the 1993 Missouri River flood at Lisbon Bend near Glasgow, MO. Jacobson et al. (2001) describe the site as having an upper section defined by bars and braiding and a lower section defined by a meandering thalweg and high banks. The channel migration patterns observed at Upper Hamburg Bend were similar to those documented at Lisbon Bend. They also documented a similar pattern of decreasing lateral migration and widening at the Lisbon site over time. Based on these findings it appears that the engineered Upper Hamburg Bend site has followed a natural development process.

Engineers have constructed other side channels at various sites along the Missouri River in Nebraska, Iowa, and Missouri. These sites, constructed after the floods of the late 1990s, have developed much more slowly than Upper Hamburg Bend site, probably due to a lack of floods (Eder and Mestl 2009). The current water-management regime on the Missouri River dictates that releases from the upstream reservoirs seek to balance the multiple authorized uses of the system, including flood control, navigation, power generation, water supply, and recreation. The net result has been to decrease peak flows substantially (Galat and Lipkin 2000), which during most years may not provide sufficient discharge to contribute to side-channel development. Lack of high flows may also substantially slow the rate of channel development to a state of dynamic equilibrium.

Has the side channel at Upper Hamburg Bend increased the diversity of aquatic habitats available in this reach of the Missouri River? The side channel is shallower and slower than the adjacent main channel, but the available depths and velocities have continued to change. Because of the limitations of the boat-mounted survey equipment, neither survey covered water less than 0.8 m deep, which subsequently limits our understanding of the kind and quantity of changes in extremely shallow habitats. But the amount of area of the site that initially met the requirements for shallow-water habitat as defined by the Missouri River Biological Opinion (<1.5 m deep and velocities <0.6 m s^{-1}) decreased between 2001 and 2008. So, although the side channel has continued to widen since 2001, the side channel and its thalweg have become deeper and faster rather than shallower and slower. This is supported by an increase in the discharge of water through the side channel, from 97.4 $m^3 s^{-1}$ in 2001 to 153.6 $m^3 s^{-1}$ by 2008. Increases in the mean depth and velocity raise questions about the future morphology of the site. While the side channel is unlikely to fill in, it may continue to scour deeper and further reduce the area of shallow, slow water that it was intended to provide. It is important to note that engineers have taken measures to limit the amount of water entering the site in recent years, but water conditions have prevented surveys to assess how depth and velocity have changed due to these updates.

The pilot channel constructed at Upper Hamburg Bend was intended to restore aquatic habitat adjacent to the Missouri River by developing into a wide, shallow channel that would meander across the floodplain and restore access to the site by fish. The side channel has widened beyond design specifications and, instead of providing shallow-water habitat, has continued getting deeper and faster. Over time, depths and velocities in the side channel are becoming similar to those in the main channel of the Missouri River. We recommend modifying the structures to limit the amount of water flowing into the site, and where possible, remove or relax the rock control structures where not absolutely necessary to contain the side channel to the site, thereby allowing for additional lateral movement and downstream bend migration. By allowing bend migration to occur naturally within the side channel at Upper Hamburg Bend, the alluvial processes that defined the historic Missouri River and supported the native biological communities could be partially restored.

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