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Fluvial Processes and Passive Rehabilitation of the Lisbon Bottom Side-Channel Chute, Lower Missouri River

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Multiple large floods in 1993-1997 on the Lower Missouri River carved a side-channel chute through the river bottom at Lisbon, Missouri. Although similar in some respects to engineered side-channel chutes designed for habitat rehabilitation projects, the Lisbon Bottom chute has been unique in that it was allowed to evolve for more than four years with minimal stabilization. During the wet years, 1996-1999, the chute was subjected to abnormally high discharges and passed as much as 20% of the total discharge of the Missouri River. Relatively unrestrained fluvial processes during this time created a wide channel with highly diverse habitats. The upper one-half of the chute established a shallow, braided channel morphology similar to the pre-managed Missouri River. The lower half established a dynamically migrating, single-thread channel, and an incipient flood plain. Compared to the adjacent navigation channel, the chute established substantial areas of shallow, slow-velocity aquatic habitat that is considered to be in short supply in the present-day Lower Missouri River. The short-term biological benefits have been mixed: the chute has fewer waterbird and benthic macroinvertebrate taxa than adjacent riverine habitats, but greater numbers of fish species compared to the navigation channel.

1. INTRODUCTION

1.1. Large-River Rehabilitation

Stream restoration is defined as the re-establishment of the structure and function of the riverine ecosystem, with the goal of achieving a condition as close as possible to pre-disturbance conditions [*Federal Interagency Stream Restoration Working Group*, 1998]. In large, multi-purpose rivers the pre-disturbance goal is difficult to meet; such rivers are so altered that restoration, in a strict sense, is practically unachievable. In these cases, the concept of *rehabilitation* – recovery of some ecosystem functions by manipulating selected components of the riverine ecosystem [after *Federal Interagency Stream Restoration Working Group*, 1998]-- is a more applicable concept [*Gore and Shields*, 1995].

The lower Missouri River is a large, multiple-use system (Figure 1). The lower reaches of the Missouri drain 1,300,000 km^2 (525,000 mi^2), amounting to nearly 1/6 of the United States land area. A system of reservoirs in S. Dakota, N. Dakota, and Montana provide nearly 92,500 km^3 (75 million acre feet) of water storage and annually

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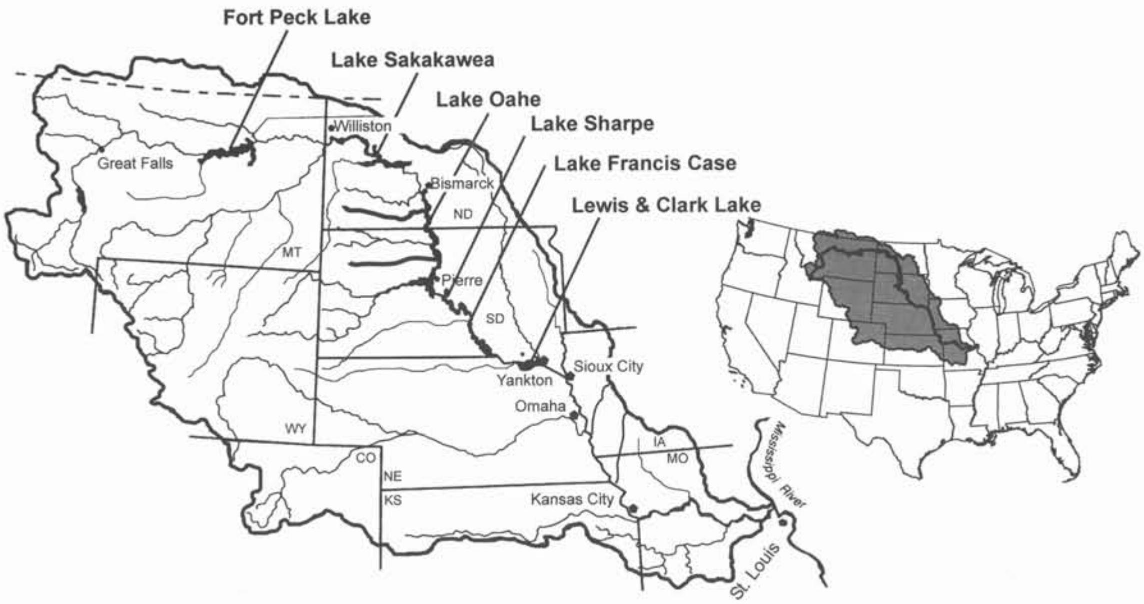


Figure 1. Missouri River basin and the Lower Missouri River. The Lower Missouri River extends downstream of Gavins Point Dam near Yankton, South Dakota, to the junction with the Mississippi River near St. Louis.

Table 1. Estimated major economic benefits of Missouri River system regulation

[Data from *U.S. Army Corps of Engineers*, 1998]

Management component	Estimated average annual benefits, $millions
Hydropower	$ 676
Water supply	541
Flood control	415
Recreation	85
Navigation	7
Total	$ 1,724

produce nearly 10 million kilowatt hours of hydroelectric power. The managed river system provides annual benefits estimated to be greater than $1.7 billion dollars (table 1).

However, management of the system for economic benefits also has been associated with substantial loss of habitats and native riverine biota [*Funk and Robinson,* 1974; *Hesse and Sheets*, 1993]. Clearing, snagging, and stabilization of the Missouri River began in the early 1800s, and have continued to the present. Most of the engineering works along the river are the direct result of the Missouri River Bank Stabilization and Navigation project, part of the Pick-Sloan Act of 1944 [*Ferrell*, 1993]. These structures have stabilized the riverbanks, and narrowed and focused the current to maintain a self-scouring channel with navigable depths of at least 2.7 m (9 feet) from St. Louis, Missouri, 1,170 km (730 mi) 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 (Figure 2). Furthermore, reservoir regulation has decreased flow variability and seasonality since the mid 1950's (Figure 3).

Recognition of the scope of habitat loss has increased interest on rehabilitating parts of the Missouri River [*Latka et al..,* 1993; *U.S. Government*, 1986]. Approaches and designs differ widely, but they can be described generally as resulting from three sets of questions:

- What are the rehabilitation objectives? Designs will vary greatly depending on whether the choice is – for example -- to (a) recover some semblance of naturally dynamic ecosystem functions, (b) create specific habitats for recreational species, or (c) create specific habitats for threatened and endangered species.
- Should rehabilitation focus on altering system hydrology, through reservoir release policies, or on altering riverine geomorphology? Hydrology determines how much water comes down the river, when, and for how long. Geomorphology, however, determines how that water is allowed to be distributed in space and create aquatic habitats. On intensively engineered rivers, hydrologic alterations alone may not be sufficient to produce more available habitat.
- Should rehabilitation employ passive or intensive approaches? Passive approaches allow the river to create

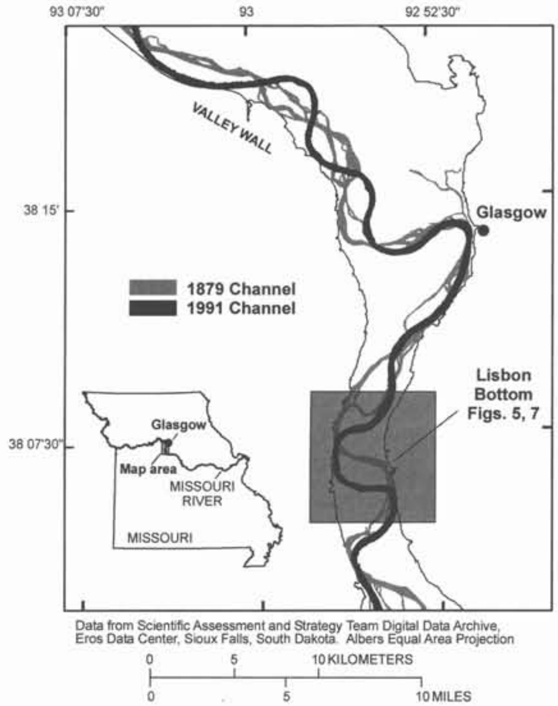


Figure 2. Channel positions of the Missouri River near Glasgow, Missouri, 1879 and 1991. Flow regulation and navigation structures have changed the river from a braided system with transient sand islands and multiple shifting, shallow channels to a meandering stream with stable banks, greater average depths, higher average velocities, and many fewer connections between the channel and flood-plain habitats.

dynamic habitats, presumably at least cost, but result in less control over the characteristics and timing of habitats. Intensive approaches – for example, diking wetlands and pumping water to create optimum waterfowl habitat – result in stable, controlled habitats, generally at greater cost.

Answers to these three questions require an informed, quantitative understanding of the ecological benefits of the alternatives. This paper addresses ecological benefits that can be achieved through alteration of riverine geomorphology using passive approaches.

It is generally accepted that physical habitat determines a template for aquatic ecosystem functions, but realization of the potential is highly dependent on other ecological processes [*Plafkin et al..*, 1989; *Schlosser*, 1987]. Unlike many biotic characteristics, however, physical habitat is directly amenable to management through reservoir regulation or channel engineering. Therefore, current management efforts on many large rivers emphasize physical habitat creation and maintenance.

Typically, aquatic habitat rehabilitation activities on the Lower Missouri River have been designed for two purposes: to provide specific flood-plain wetland habitats for recreational hunting, and to provide off-channel aquatic habitat for fishes and shorebirds. Design criteria for off-channel aquatic habitats generally have been based on the premise that rehabilitation should work to reverse the engineered simplification of the channel, to provide greater channel complexity (Figure 2). Hence, efforts have been focused on recreating side-channel chutes and increasing channel topwidth [*Harberg et al.,* 1993; *Latka et al.,* 1993; *Rothe*, 1995].

Considerable uncertainty exists about the ecological benefits of river rehabilitation projects and their long-term performance [*Federal Interagency Stream Restoration Working Group*, 1998]. The uncertainty is greater for large rivers than for small rivers because of inherent spatial and temporal complexities, the relative lack of empirical data, and shortcomings of predictive computational models or theoretical framework [*Burke* and *Robinson*, 1979; *Shields*, 1984; *Forrest* and *Ettema*, 1993; *Lubinski* and *Gutreuter*, 1993]. While there is a considerable foundation of understanding on how to build secondary channel structures [for example, *Harberg et al.,* 1993; *Klein et al.,* 1994; *Schropp*, 1995], there is very little understanding of their integrated ecological benefits or their long-term performance under highly variable hydrologic and sediment transport regimes [*Cals et al.,* 1998]. The study described here is intended to develop a stronger empirical basis for evaluating the benefits, costs, and performance of passive side-channel chute

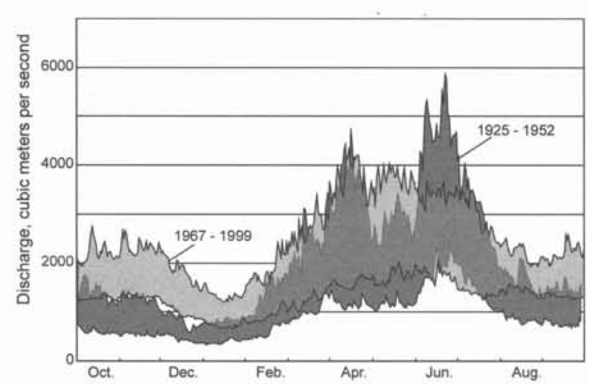


Figure 3. Duration hydrographs for the Missouri River at Boonville, Missouri. The shaded band of discharge values for preregulation (1925-52) and postregulation (1967-99) periods is the range of values between the 25 and 75 percentile of flows for each day of the year. Reservoir regulation has decreased variability of flows and shifted seasonality to maintain navigation in the lower river, April - November.

rehabilitation projects on large, multi-purpose river systems.

1.2. Purpose and Scope

This report documents evolution of physical habitat in a passively managed side-channel chute rehabilitation project on the Lower Missouri River. The chute was cut through Lisbon Bottom, the area of alluvial valley floor delineated by the valley wall and the Missouri River near the town of Lisbon, Missouri (Figures 4,5). This case study is intended to provide insights into fluvial processes and rates of habitat alteration in these heretofore poorly documented features. The relatively natural geomorphic evolution of this chute provides an opportunity to assess the quality and quantity of physical habitat that can be created on a large, multi-purpose river using least cost, passive approaches. Limited biological data cited in this report provide some insight into short-term biological responses in the chute.

Lisbon Bottom is in a high-sinuosity segment of the Lower Missouri River (Figures 4B, C). Results of this study should be applicable to geomorphically similar segments of the Lower Missouri River, and general conclusions may help inform rehabilitation projects on other large, highly managed rivers. The temporal scope of this report includes formation of a secondary side-channel chute and documentation of changes through a 4-year time interval during which human intervention was minimal. This must be considered a preliminary analysis because of the short time frame compared to adjustment rates of large rivers. Moreover, in June 2000 a hydraulic control structure was completed at the head of the Lisbon Bottom chute in order to ensure an acceptable level of risk to river navigation, thereby defining new boundary conditions for the next stage of this experiment.

2. METHODS

Multiple physical datasets have been combined to monitor and evaluate evolution of the Lisbon Bottom chute. Remotely sensed multispectral data (Landsat Thematic Mapper - TM, SPOT imagery) and aerial photography provide a broad-scale understanding of changes in the chute and surrounding river corridor. Detailed maps of the chute have been compiled from field mapping using post-processed differential global positioning system methods (DGPS); typically, these maps achieve sub-meter x-y accuracy, a level that is sufficient for monitoring morphologic changes given the large (multi-meter) annual changes in the chute boundaries.

Physical habitat in the chute was assessed using an integrated assessment system contained on a 5.8 m, shallow-draft boat. The system and methods are explained in detail in *Jacobson and Laustrup* [2000]. This system includes real-time, sub-meter DGPS for georeferencing, a high-resolution, 208-kHz echosounder, a bed-material classification system, and an acoustic Doppler current profiler (ADCP). The bed-material classification system uses the waveforms of the echosounder returns to calculate hardness and roughness parameters for the bed [for example, *Rukavina*, 1997]. In turn, these parameter values are classified into bed material based on calibration datasets obtained from independent identification of bottom materials. ADCP data were collected using a 600 kHz, broadband instrument; identical configurations were used in the chute and navigation channel. ADCP methods generally followed those of *Morlock* [1996]. The data were used to map habitats within the chute and adjacent navigation channel, and to compare habitats quantitatively.

Assessment of rehabilitation projects typically involves comparison to a reference condition to determine if the project has significantly improved habitat or biological characteristics. Historical reference conditions for Lower Missouri River physical habitats can be inferred from maps from 1879 [*Missouri River Commission*, 1879], and 1920 [*War Department*, 1920]. The historical reference condition documented in these maps present a well-defined goal for rehabilitation projects, although the goal is limited in that it displays only selected measures of habitat (land cover, planform, bathymetric transects) and only a few snapshots in time. Moreover, historical channel-morphology data do not resolve the effects of hydrologic characteristics – in particular, seasonality -- that have been altered by upstream reservoir regulation. Hence, historical channel geometry provides only one dimension of a reference condition. Notably, pre-management biological data are insufficient to provide an historical biological reference condition.

Reference conditions also can be defined by the present-day conditions in adjacent, non-rehabilitated parts of the river. Comparison to this spatial reference condition defines whether the project has improved ecological characteristics measurably compared to the managed river. The status quo reference condition is especially useful when historical data are insufficient to define a reference, or too different from achievable conditions to provide a meaningful goal. For this study, physical and biological spatial reference conditions are defined in the adjacent navigation channel of the Missouri River.

3. HISTORICAL CONTEXT OF THE LISBON BOTTOM CHUTE

The historical record of channel changes at Lisbon Bottom illustrates the natural processes of erosion and deposi-

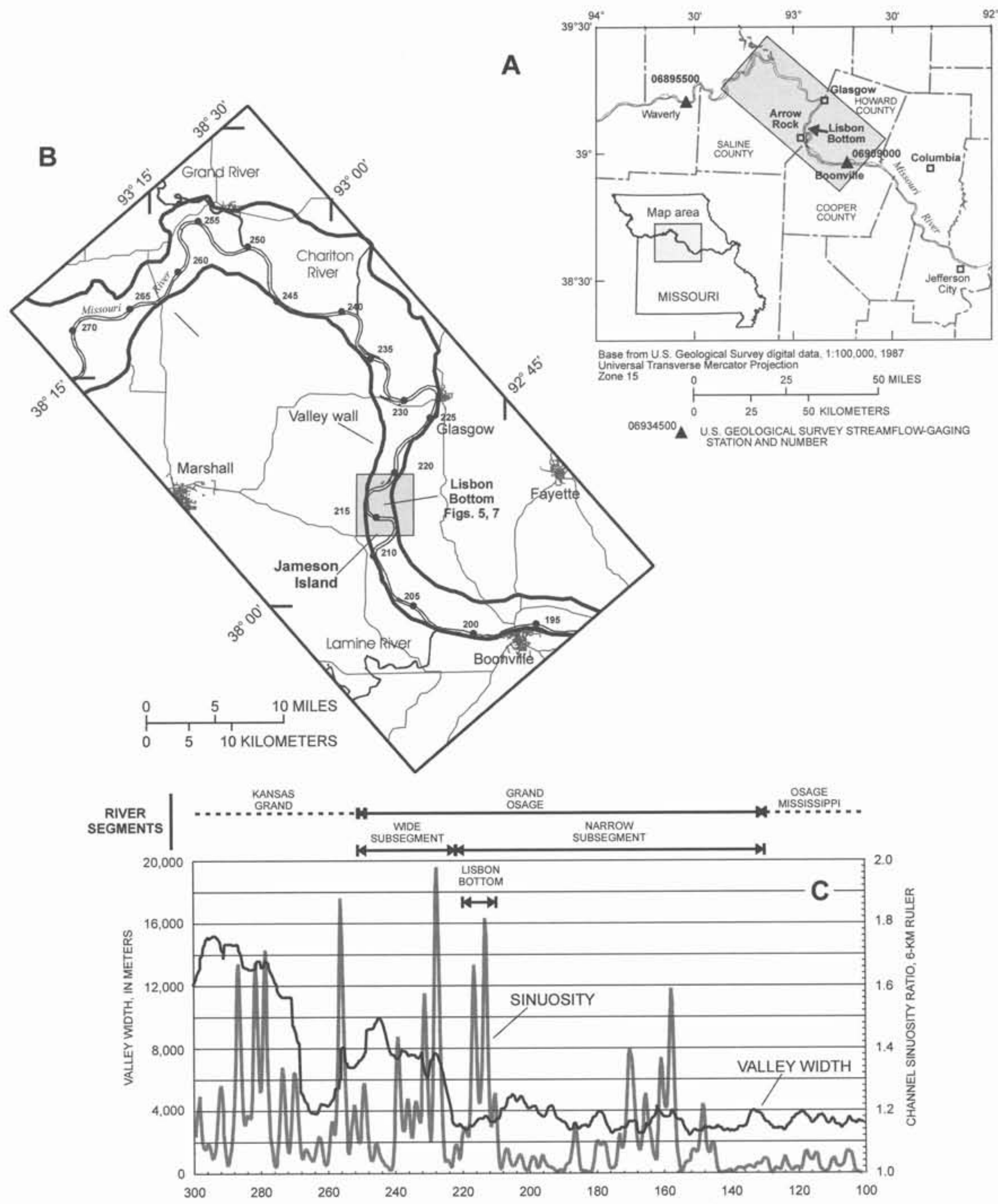


Figure 4. (A) General location map, Lower Missouri River (LMR). (B) Detailed location map showing part of the LMR valley and Lisbon Bottom location. (C) Graph of channel sinuosity (channel length per 6 km straight-line distance), valley width, and river segmentation, part of the LMR valley.

tion, and indicates the magnitude of change imposed by river management. Historical maps of channel positions in 1879 show that the Grand-Osage segment was characterized by a wide channel and numerous braided reaches with sand bars and islands (Figure 2). *Schmudde* [1963] estimated that under natural conditions the river was 2-3 times wider than after channel stabilization. Channel migration under natural conditions was sufficient to rework as much

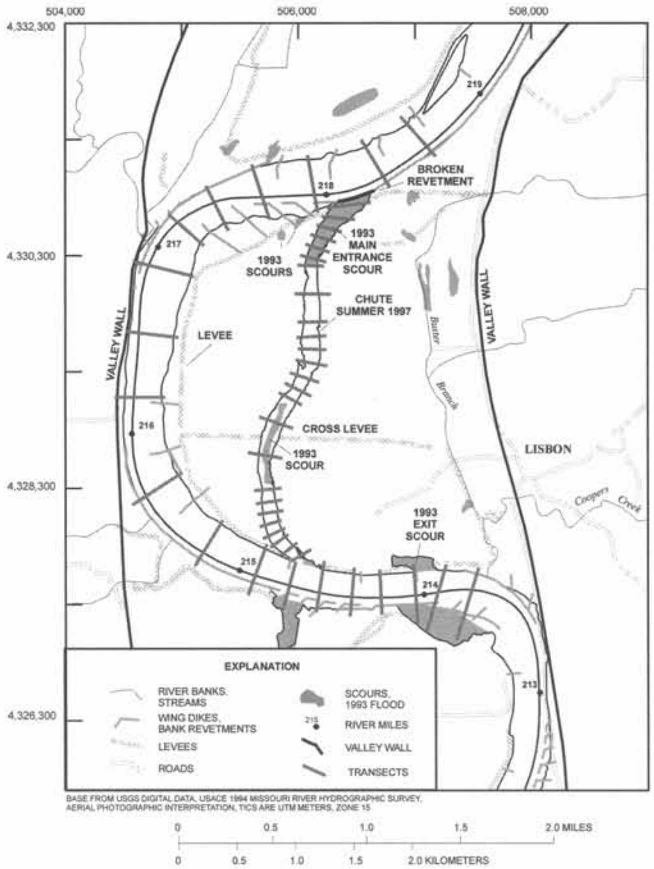


Figure 5. Map of the Lisbon Bottom area, levees, bank revetments, wing dikes, scours created by the 1993 flood, and the chute (as mapped in Summer 1997).

as 1/3 of the flood plain of the Missouri River in approximately 50 years [*Schmudde*, 1963].

Engineering alterations to improve navigability of the Missouri River began as early as the 1830's. Snagging (clearing of woody debris) and channel clearing to improve navigability for keelboats and steamboats were systematic and intensive from 1885-1910 [*Galat et al.,* 1996]. On 1879 project maps [*Missouri River Commission*, 1879], Lisbon Bottom land cover is depicted as dense willows, sandbars, and a few small fields. During the interval 1879-1920, the mainstem channel of the Missouri River moved approximately 1570 m (5,150 ft) across the downstream one third of Lisbon Bottom (Figure 2), leaving the town of Lisbon without river access.

Intensive channel structuring began after authorization of the Navigation and Bank Stability Project by the Flood Control Act of 1944 [*Galat et al.,* 1996]. In general, alterations followed a sequence of clearing of woody debris, construction of wing dikes to narrow the channel, construction of bank revetments to stabilize banks, and construction of levees to prevent inundation of urban, industrial, and agricultural lands [*Ferrell*, 1993; *Ferrell*, 1996; *Galat et al.,* 1996]. Navigation maps from 1954 [*U.S. Army Corps of Engineers*, 1954] show the channel has been largely confined to its present (June 2000) form and position. No levees were mapped along the main channel at Lisbon Bottom in 1954; a former landowner recollected that levees along the channel were not built until the mid-1980s [*Bill Lay*, pers. commun., 1997]. By 1993, Lisbon Bottom was completely leveed along the left bank downstream as far as Coopers Creek (Figure 5). In April of 1993 the levee was inspected and qualified for the U.S. Army Corps of Engineers maintenance program. The levee was built to a height that would protect Lisbon Bottom up to a stage of 9.75 m (32.0 ft) on the Glasgow gage, or approximately 186.2 m (611 ft) above sea level at river mile 218. Based on extrapolation from the streamgage at Boonville this is equivalent to protection from flood stages of 2-5 year recurrence interval. Revetments, wing dikes, and levees as they existed in 1997 are shown in figure 5.

4. THE FLOOD OF 1993

The flood of 1993 broke the Lisbon Bottom levee in multiple places. The exact processes by which the levee broke are unknown. Similar levees along the Missouri River broke by a variety of mechanisms, including overtopping and erosion, liquefaction by seepage water, and lateral erosion from the channel side [*Schalk* and *Jacobson*, 1997]. During the flood of 1993, the peak daily mean flow at Boonville was 20,400 cms (cubic meters per second; 721,000 cfs [cubic feet per second]) on July 30 (Figure 6). This exceeded the estimated 500-year flow at Boonville of 19,810 cms (700,000 cfs) [*U.S. Army Corps of Engineers*, 1994].

The 1993 flood left one large scour at the upstream margin of Lisbon Bottom and three smaller levee breaks and scours (Figures 5, 7). Also, the flow breached the cross levee in numerous places, and at least five exit scours developed along the downstream margin. Bathymetric maps of the main entrance scour (Figure 5) documented 7 m maximum depth in 1994 [*Galat* and others; 1997]. None of the levee breaks were repaired after the 1993 flood, so subsequent floods of smaller magnitude were allowed to flow through the levees (Figure 6).

Lisbon Bottom has been flooded multiple times since July 30, 1993. Sixteen discrete floods in excess of 5,600 cms (198,000 cfs) occurred from August 1993 to March 2000 (Figure 6). This discharge is estimated to be the 2-year flood for this segment of the Lower Missouri River

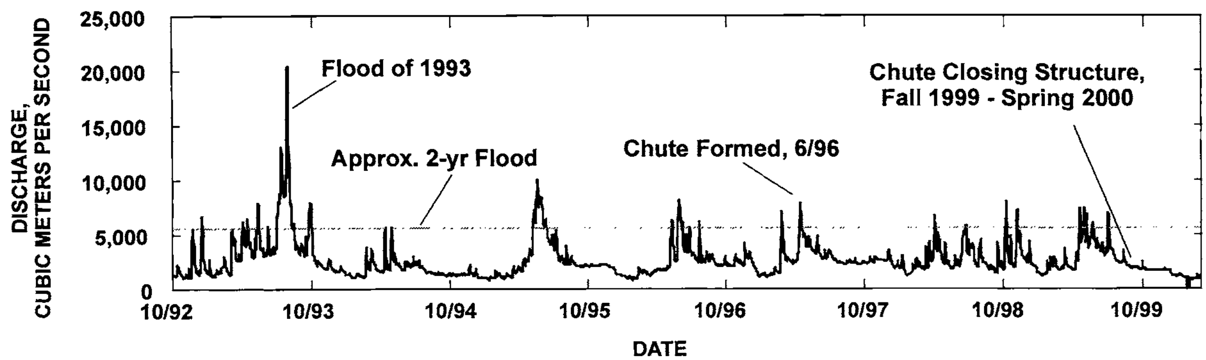


Figure 6. Hydrograph from the Missouri River at Boonville, Missouri, October 1993, to March 2000. The approximate discharge for the 2-year flood is indicated (U.S. Army Corps of Engineers, written communication, 1997).

[*U.S. Army Corps of Engineers, Kansas City District*, written communication, 1997] and would be approximately bankfull in the absence of engineered levees.

The largest daily mean discharge recorded at Boonville, Missouri, between September 1993 and January 1998 was 10,020 cms (354,000 cfs) in May 1995. This flood inundated at least 80% of Lisbon Bottom and resulted in substantial reworking of sand deposits emplaced by the 1993 flood, but it did not change the basic architecture of the scours. The most geomorphically effective flood occurred during late May-June 1996 with a peak flow of approximately 8,200 cms (290,000 cfs). This flood was sufficiently erosive to connect the upstream entrance scour with the non-connected scour at the interior levee and a small exit scour near RM 214.7, thereby creating the chute shown in Figure 5.

5. GEOMORPHIC EVOLUTION AND PHYSICAL HABITAT IN THE LISBON BOTTOM CHUTE

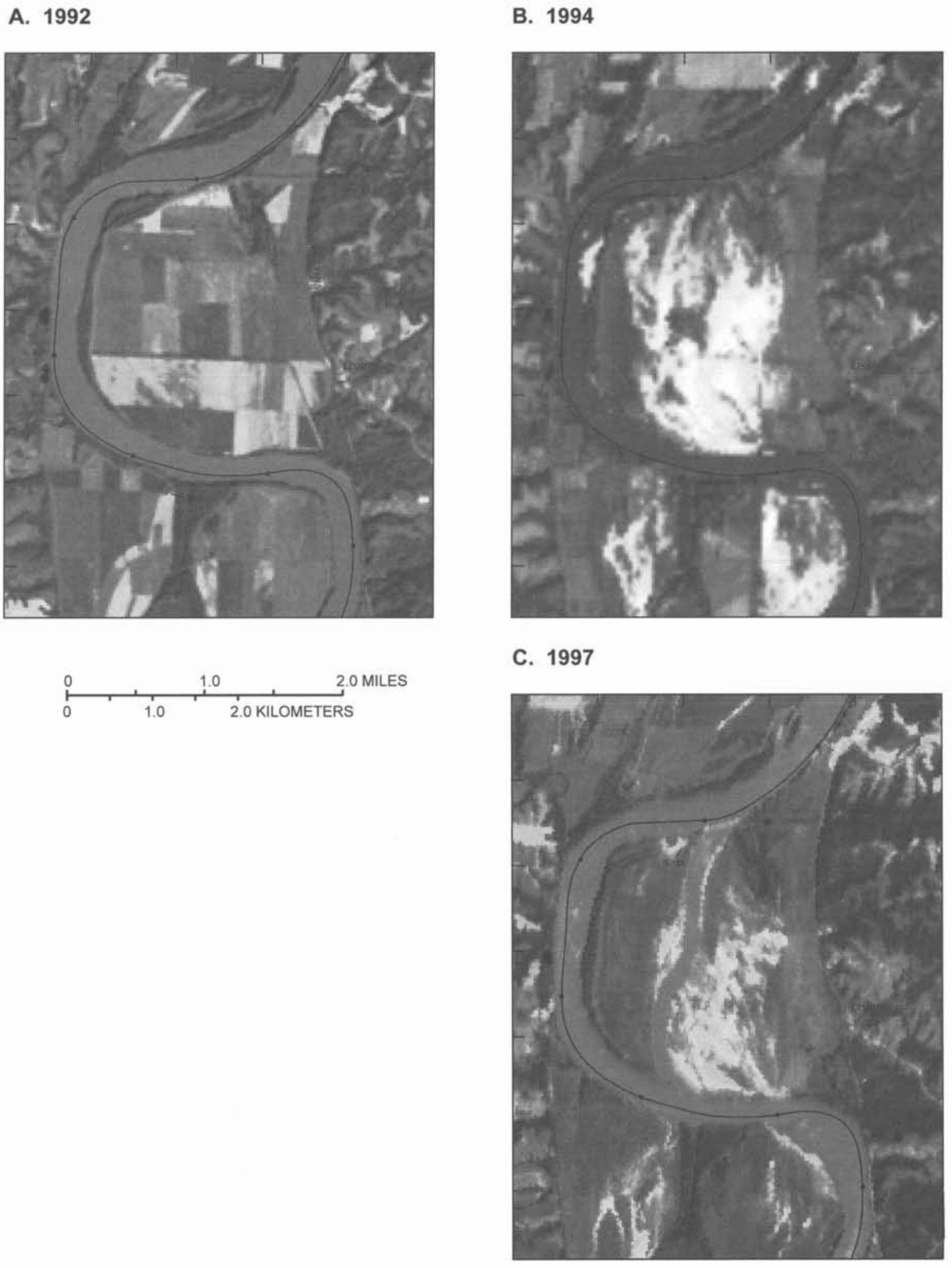
From May-June 1996 to October 1999, the chute evolved with minimal human intervention. During this time, it carried 2-20% of the discharge of the Missouri River, depending on total discharge and the state of repairs of the upstream revetment. In December 2, 1997, the chute was carrying approximately 20% of the total Missouri River discharge (736 cms of 3,560 cms); in May 1998, the chute was carrying 4.8% (85 cms of 1,750 cms); In September 1998, the chute carried 1.7% (28 cms of 1,657 cms).

Since formation in May-June 1996, the chute has incised into flood-plain deposits, widened, migrated laterally, and increased in complexity (Figure 8). Initially, the chute was narrow and bordered by high banks as much as 5 m above low-water levels. As the chute developed a thalweg in the lower half it began to migrate laterally, creating several prominent cutbanks (Figure 8). Consequently, the sinuosity increased and slope decreased (table 2). Initially, the chute slope was approximately equal to the slope of the flood plain, about twice that of the navigation channel. The notches in the revetment at the upstream end of the chute performed as a hydraulic control, and therefore determined the chute slope. The notches were periodically repaired to different specifications 1996 - 1999, resulting in non-systematic variation of the slope. In June 1999, the revetment was sealed in anticipation of construction of a notched hydraulic control structure.

The rate of widening of the chute (measured as average bankfull channel width) was initially rapid, but slowed markedly after June 1997 (Figure 9A). When it was formed in 1996, the chute was relatively straight and had a trapezoidal cross section. By January 1998, the chute had developed three distinct bends and complex channel structure (Figure 8). In the upstream half, the chute is characterized by mid-channel bars and a braided appearance (Figure 10A). The downstream half has developed point bars, an incipient flood plain within the high banks, and a meandering thalweg (Figure 10B).

To quantify and compare the resulting channel morphology with a historical reference, we assembled a dataset of channel cross sections from 1920 navigation charts of the Lower Missouri River [*War Department*, 1920], (Figure 11). Eleven side channels in the vicinity of Lisbon Bottom were selected, and width:depth ratios were calculated, using the average depth of the cross section. The bathymetry was originally mapped in July 1920, prior to systematic USGS discharge data, so the flow duration is unknown; however, the large areas of sand bars on these maps indicate a general low-flow condition.

Width:depth ratios for cross sections in the Lisbon Bottom chute change markedly with discharge. Because flows for all measurements were within the high banks, larger discharges tended to have smaller ratios. Notwithstanding


A. 1992
B. 1994
C. 1997
0
1.0
2.0 MILES
0
1.0
2.0 KILOMETERS

higher discharge in June 1999 compared to December 1997, width:depth ratios increased in the upper half of the chute, a trend consistent with channel widening. In September 1998, lateral and mid-channel bars were just beginning to emerge in the chute at approximately 2,300 cms in the main channel (measured at Boonville, Missouri). At this discharge, width:depth ratios in the chute were substantially larger. In the upper half of the chute, width:depth ratios were within the range of historical values, indicating a correspondence to the historical reference condition for channel geometry (transects 5-15, Figure 9B).

Velocities and depths in the chute and neighboring navigation channel were assessed at two discharges in December 1997 and May 1998 by ADCP survey (Figures, 5, 12). Distributions of depth and velocity show the broad variation of physical habitat that exists in the navigation channel, primarily resulting from wing dikes that cause constrictions and recirculating eddies. The chute has a relatively high percentage of shallow and slow water; the relative contribution of shallow, slow water increases with decreasing discharge.

Early in the evolution of the chute, the margins of the channel at the upstream one half were underlain by cohesive silty clay and clay beds. These units were the remains of the topstratum of the sedimentary sequence that the chute had cut through. As the chute widened and incised through the cohesive units, the bed material became coarser and dominated by sand. A systematic survey of the chute with a bed classification instrument in June 1999 indicated variation in bed material along the chute that was consistent with the transition from braided to meandering planform. The braided, upstream half was dominated by gravelly sand and sand, whereas the downstream half was characterized by a sand channel, sandy point bars, and mud margins (Figure 13). Gravelly sand substrate at the upstream end of the chute is considered an especially valued substrate because of the relative scarcity of this coarse substrate habitat in shallow, low-velocity areas of the Lower Missouri River (Figure 14). The median bed-material particle diameter on this part of the Lower Missouri River is typically fine to medium sand, in the range of 0.24 – 0.55 mm [*U.S. Army Corps of Engineers,* Unpub. data].

6. BIOLOGICAL RESPONSES TO HABITAT EVOLUTION

Biological responses to the evolving chute habitats vary by trophic level. Assessment of benthic invertebrate communities indicates that the relatively mobile, sandy substrate of the chute supports a community with relatively few taxa [*Poulton et al.,* 1999]: only 4 taxa of macroinvertebrates were collected in sandy substrates within the chute, as compared to 78 taxa associated with rock revetments in the main channel, and 59 taxa associated with mucky sediments in recirculating eddies downstream of wing dikes. Organic snags in the chute, however, had 30 taxa of macroinvertebrates [*Poulton et al.,* 1999] indicating that accumulation of large woody debris in the chute may be necessary to achieve high secondary productivity.

The fish community of the chute has been shown to be quite diverse [*U.S. Fish and Wildlife Service,* 1999]. Collections in 1997-1999 found 64 species of fish in the chute, compared to 26 species in the adjacent navigation channel; 91 species of fish are known to inhabit the Lower Missouri River. Of the 64 species collected in the chute, one was the federally listed pallid sturgeon (*Scaphirhynchus albus*), and four others were species of concern (sicklefin chub (*Macrhybopsis meeki),* sturgeon chub (*Macrhybopsis gelida*), plains minnow (*Hybognathus placitus*), and blue sucker (*Cycleptus elongates*); U.S. *Fish and Wildlife Service,* [1999]). In contrast, waterbird taxa richness in the chute area decreased from 50 to 37 species in the 1.5 years after the chute was formed. This decrease was attributed to replacement of shallow, lentic habitats that existed in the original scour, with lotic habitats in the chute [*Helmers et al.,* 1999].

Vegetative succession on the margins of the chute has been minor because of the steep banks and unstable bars. Only in the Spring of 2000 were substantial areas of vegetation growth observed on incipient flood plain and lateral bars adjacent to the high banks. These communities are mainly grasses and forbs, but they have minor woody components represented by seedling cottonwood (*Populus deltoides*) and willows (*Salix spp.*). Cottonwood-willow com-

Figure 7. Images of Lisbon Bottom showing extensive changes to land cover from 1992 to 1997. Darker gray tones are indicative of vegetation cover. The bright white in (B) and (C) represents sand deposits. From October 1994 to August 1997, much of Lisbon Bottom became more vegetated, despite the floods of May 1995 and June 1996. (A) Pre-flood Thematic Mapper image September 24, 1992, Boonville discharge = 1,870 cms. (B) SPOT image October 11, 1994, Boonville discharge = 1,320 cms. (C) SPOT image, August 23, 1997, Boonville discharge = 2,580 cms. Images courtesy of Earth and Planetary Remote Sensing Laboratory, Washington University, St. Louis. Location is shown on Figure 5.

munities are expected to be persistent in frequently scoured sites like the chute bars [*Mazourek et al.,* 1999].

7. DISCUSSION – UNDERSTANDING GAINED AT LISBON BOTTOM

The chute at Lisbon Bottom is a unique experiment in rehabilitation of large-rivers, because of the extent to which fluvial processes are being allowed to create and maintain physical habitats. The relatively passive approach has allowed a high degree of connection between flows in the river, and flows in the chute and adjacent wetlands. The connection allows for transmission of flood pulses into the chute, with associated exchanges of nutrients, large woody debris, and sediment. Relatively unhindered flows have resulted in continued sediment transport in the chute and resultant dynamic habitats. Hydrologic connection and dynamic habitats generally are considered ecologically beneficial in large rivers [*Junk et al.,* 1989; *Gore* and *Shields*, 1995; *Galat et al.,* 1998; *Sparks et al.,* 1998].

The chute has widened and migrated laterally since formation in 1996. The upstream half of the chute has achieved a wide, shallow, braided channel, and appears to be evolving toward a historical reference condition. The downstream meandering portion has a well-defined thalweg and lateral bars that contribute additional diversity in depth, velocity, and substrate. The chute is presently (June 2000) providing depths, velocities, and substrate that are relatively lacking in the adjacent navigation channel.

The future stability and physical characteristics of the chute are a concern because of potential impacts on river navigation and biological characteristics of Lisbon Bottom. A decreasing rate of widening may indicate adjustment toward an equilibrium channel form. Increasing sinuosity, decreasing slope, and increasing hydraulic radius also may combine to increase frictional energy losses in the chute, and to promote channel stability.

Frictional energy losses and habitat characteristics will be determined largely by whether the chute evolves toward a braided or a meandering planform. Discrimination between braided and meandering channels is frequently described as a slope-discharge threshold [*Leopold and Wolman*, 1957], in which discharge is assessed as a bankfull value. Bankfull discharge is problematic to determine for the chute because it is not clear if channel geometry has adjusted to define bankfull dimensions. Nonetheless, a flood during June 2000 may have been a reasonable approximation of near bankfull flow. This flood produced flow of 200 cms (7,100 cfs) in the chute from 3,700 cms (133,000 cfs) total in the channel. The flow in the chute just reached the top of the depositional lateral bars that were beginning to be stabilized by vegetation; hence, this discharge appears to be close to the concept of bankfull, although it was considerably less than the estimated 2-year flow in the main channel (5,600 cms; U.S. Army Corps of Engineers, Kansas City District, Unpub. data). Figure 15 shows the range of slope and bankfull discharge that might

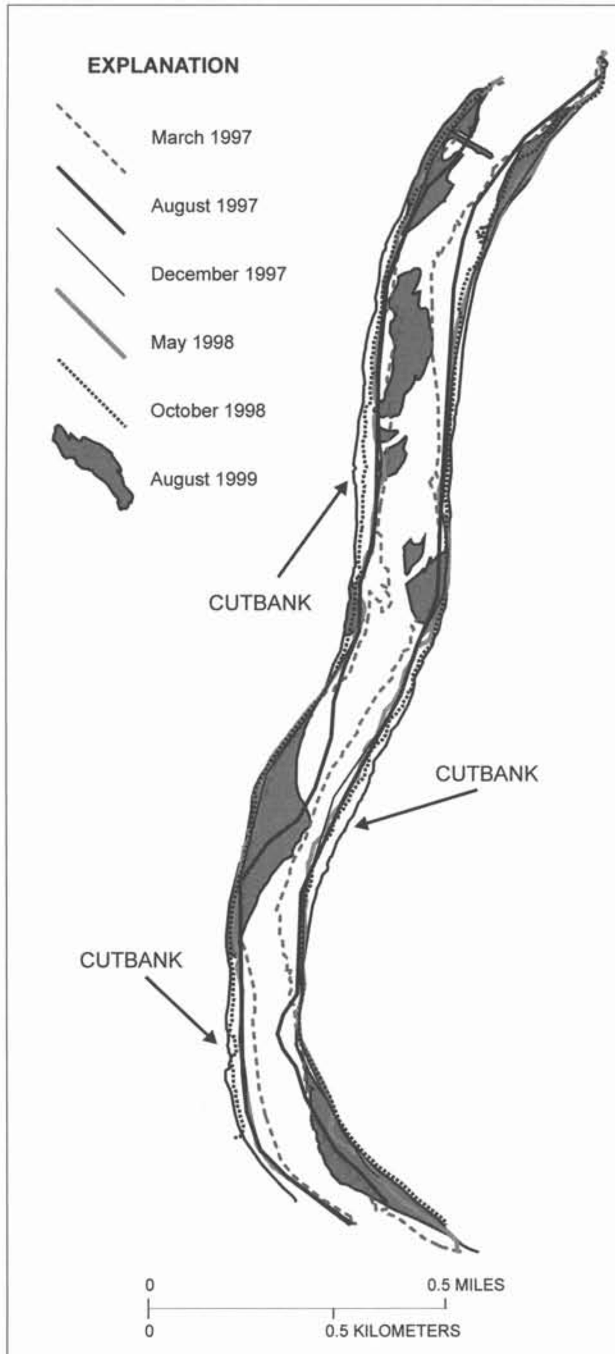


Figure 8. Maps of chute banklines from March 1997 to August 1999, and low-water bars August 1999.

Table 2. Evolution of slope and sinuosity in the Lisbon Bottom chute, 1996 - 2000

[Sinuosity is the ratio of length of the thalweg to straight-line distance; slope of the navigation channel is 0.00016]

	Jun-96	Mar-97	Oct-98	Jun-99	Jun-00
Chute Slope	0.00026	0.00024	0.00023	NA	0.00009
Chute Sinuosity	1.10	1.19	1.24	1.13	1.13
Ratio of Slopes, Chute: Navigation Channel	1.60	1.47	1.42	NA	0.56

NA: Data not applicable because of repairs to upstream revetment.

apply to the Lisbon Bottom chute using discharges from 200 cms to 560 cms (assuming 10% of main channel, 2-year flood in the chute), and with slopes ranging from the actual chute slope to the down-valley slope of the bottom land. These parameter values define an area almost entirely within the meandering portion of the [*Leopold and Wolman*, 1957] threshold relationship.

Another approach to evaluating channel pattern stability fields was proposed by *van den Berg* [1995] based on unit stream power and median bed material particle size. Computed values for unit stream power at bankfull stage in the chute range 6-35 N/m*s; with median bed-material size of 0.24 – 0.55 mm [*U.S. Army Corps of Engineers*, Unpub. data]; these values also plot well within the single-thread meandering field defined by *van den Berg* [1995].

In a re-examination of the braided-meandering transition, *Carson* [1984] argued that the fundamental prerequisite for braiding was high bed-material load, rather than a threshold combination of slope and discharge. In this analysis, slope is considered a dependent variable adjusted to discharge and sediment availability. It would follow that the factors that ultimately control sediment transport into the chute will be critical to determining future channel planform

Sediment load also may define, over the long term, whether the chute fills in with sediment, is maintained as a secondary channel, or will tend toward pirating the main channel of the Missouri River. In an analysis of river avulsion processes, *Slingerland and Smith* [1998] showed that stability of a side-channel chute depended on the ratio of the chute slope to the main channel slope, the ratio of the height of the lip of the chute to flow depth in the main channel, and particle size of the moving bed layer in the main channel. These factors determine the balance between sediment flux through the chute and sediment flux down the main channel. For medium-sand-sized bed-material in the range typical for this part of the Missouri, and a ratio of chute slope to main channel slope of 1.4 – 1.6 (table 2), the *Slingerland and Smith* [1998] analysis is relatively insensitive to the lip geometry and would predict a sustainable side-channel chute ("equilibrium crevasse") rather than sedimentation or avulsion. A somewhat finer particle size (0.1 mm), however, would result in sedimentation of the chute because greater sediment concentration in the water column in the main channel would allow greater transport into the chute. Although prediction from the *Slingerland and Smith* [1998] analysis would not be justified without

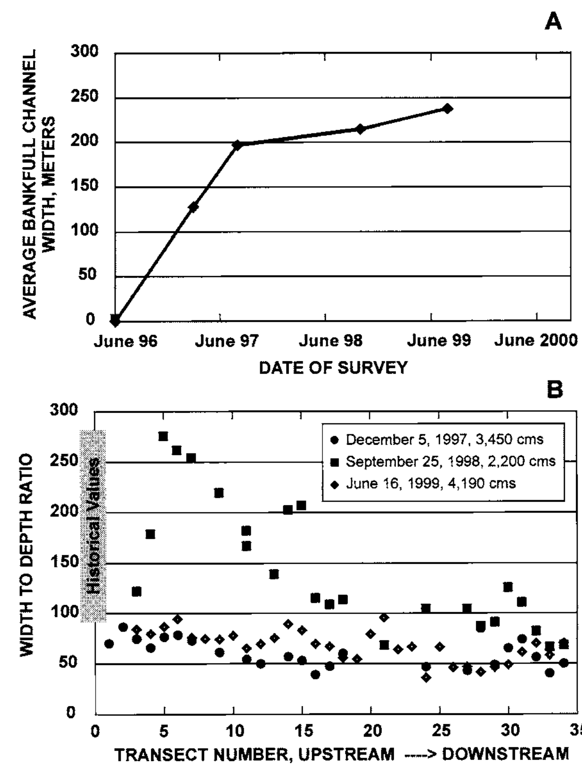


Figure 9. (A) Average chute channel width plotted over time. This channel width is a bankfull channel width mapped from DGPS surveys of the high bank line. (B) Width:depth ratios calculated from bathymetric data from monitoring transects, upstream to downstream in chute. Discharge at Boonville, Missouri, on December 5, 1997 was 3,450 cms; on September 25, 1998, 2,200 cms; on June 16, 1999, 4,190 cms. The range of historical values is from 1920 bathymetric data for side-channel chutes in vicinity of Lisbon Bottom.

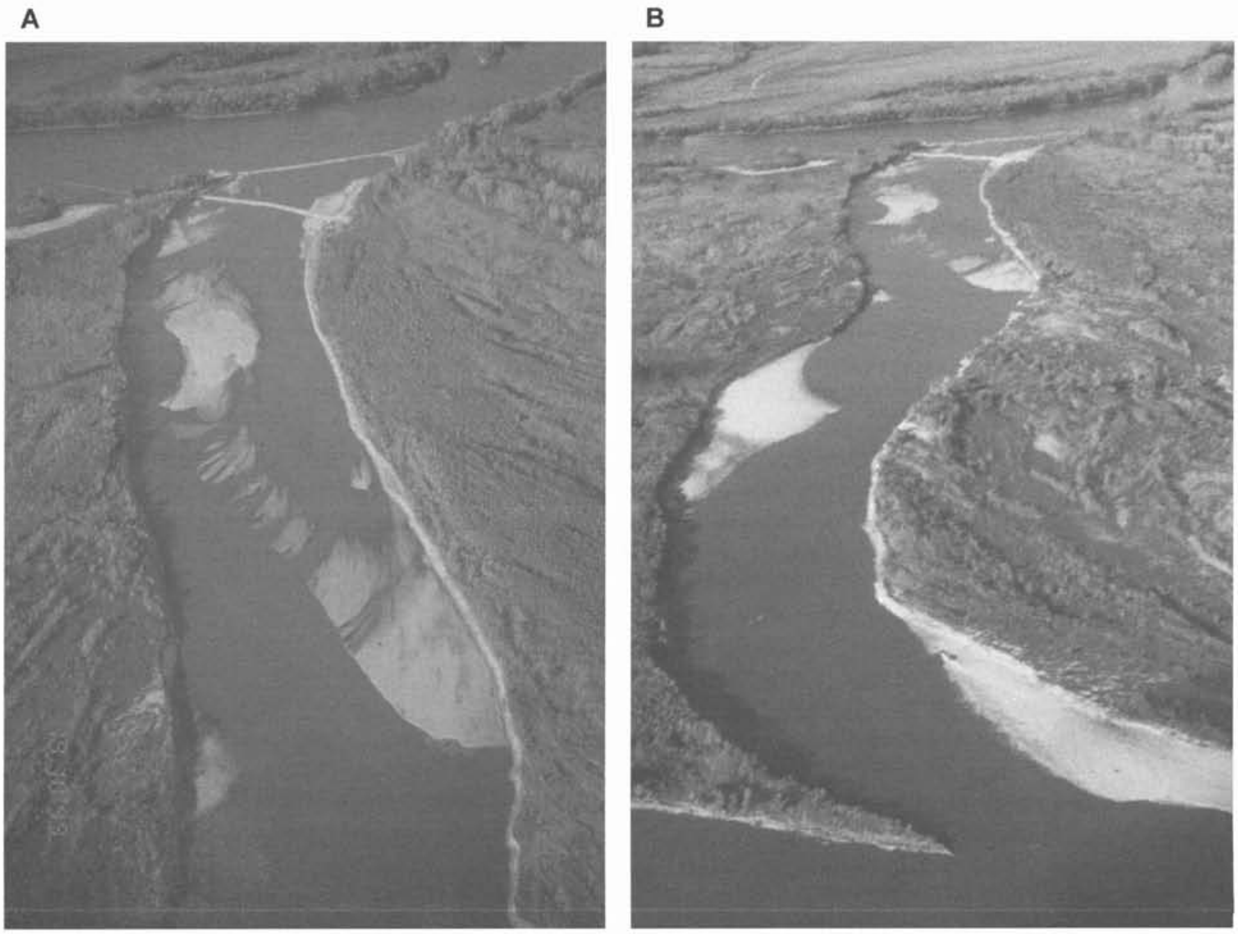


Figure 10. Low-altitude, oblique aerial photographs of the Lisbon Bottom Chute, October 1999. (A) Upper, braided one-half of the chute, looking upstream toward revetment and hydraulic inlet structure (under construction). (B) Lower, meandering one-half of the chute, looking upstream; the navigation channel appears in the foreground and background.

much greater attention to details of model formulation and validation for this site, the analysis supports the idea that long-term evolution of the chute will be dependent on the interplay of sediment load, sediment particle-size distribution, and chute geometry.

Plan-form geometry is an additional potential factor in ultimate chute stability. In a review of 20 channel cutoffs in the southeastern U.S., *Shields and Abt* [1989] found that the rate of channel filling in old, cutoff channels increased with increasing cumulative discharge in the cutoffs, increasing sediment concentration in the main channel, and decreasing sine of the angle between the main channel and the cutoff channels. The smaller the planform angle of approach, the greater potential for sediment transport into the cutoff channel. With an approach angle of about 50°, the Lisbon Bottom chute geometry would not be expected to produce extremely fast or slow filling rates.

Designers of secondary channels on the Rhine River in the Netherlands have concluded that secondary channel systems are inherently unstable over the long term, and will tend either to fill up with sediment or pirate the main channel [*Bareneveld et al.,* 1994; *Schropp*, 1995]. Designs for secondary channels on the Rhine aim to keep all sediment from entering the secondary channel to prevent sedimentation, although it is recognized that low sediment transport in the secondary channel increases the chance that harmful aggradation will occur in the main channel and may lead to excessive incision of the secondary channel [*Schropp*, 1995]. *Barenevel et al*. [1994] argue that careful modeling of discharge and sediment transport can help design a balance of channel dimensions and water/sediment distribution. However, such designs are believed to achieve a secondary channel that would be in equilibrium for no more than several years, after which dredging of the secondary channel would be necessary. The disagreement between the Rhine design experience and the theoretical analysis of *Slingerland and Smith* [1998] indicates the need for empirical documentation of field-scale experiments.

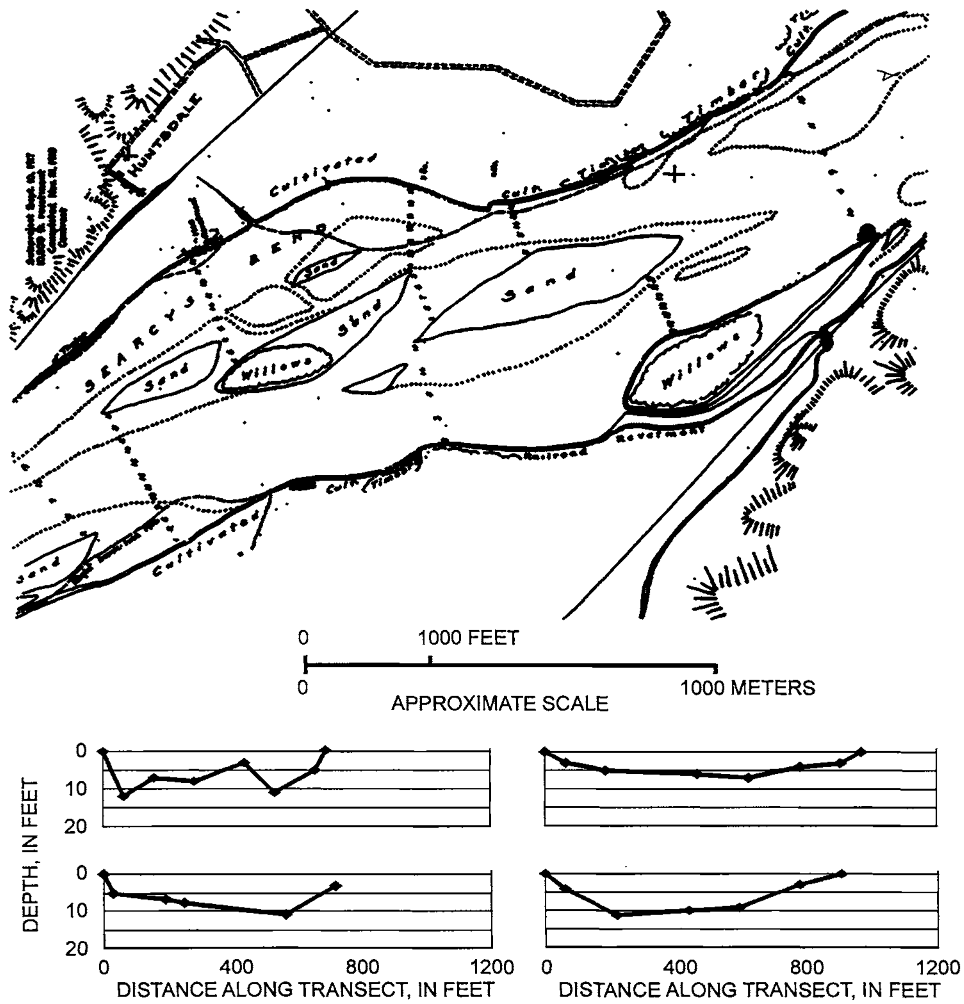


Figure 11. Excerpt from Lower Missouri River navigation charts from 1920 [*War Department,* 1920], showing an example of data used for determining bathymetry for historic side-channel chutes, and four examples of 1920 side-channel chute cross sections.

Although the evolution of the Lisbon Bottom chute was minimally affected by management in 1996-1999, its future will be more controlled. In June 1999, a grade-control structure was installed across the chute approximately 450 m upstream from the downstream end. The design for the grade control structure called for rocks to be keyed into the banks and emplaced into a trench in the channel bed, so it would not affect flow or impede boat and fish passage [*U.S. Army Corps of Engineers,* 1998]. Beginning in autumn 1999 and extending through May 2000, a notched hydraulic control structure was constructed approximately 270 m downstream from the revetment at the upstream end of the chute (Figure 10A). This structure and the revetment (Figures 5, 10A) are notched to allow flow through the structure 95% of the time. The hydraulic structure also was designed to allow an increasing percentage of total flow with increasing discharge, in an attempt to ensure that habitat forming flows continued in the chute. In June 2000, discharges in the chute were 3-6% of the total river discharge when the river was flowing 2,000-3,300 cms, compared to as much as 20% before the structure was in place. Hence, future evolution of the Lisbon Bottom chute may be very different from that which occurred in 1996-1999. Notwithstanding that the water and sediment fluxes into the chute, and bed degradation are now controlled, the Lisbon Bottom chute is unique in the Lower Missouri River in that it retains over 2.5 km of unstructured, naturally evolving side-channel habitats.

Channel widening and migration of the Lisbon Bottom chute in 1996-1999 occurred during a period characterized by abnormally high flows, including eight floods in excess of 2-year recurrence (Figure 6). These high and relatively

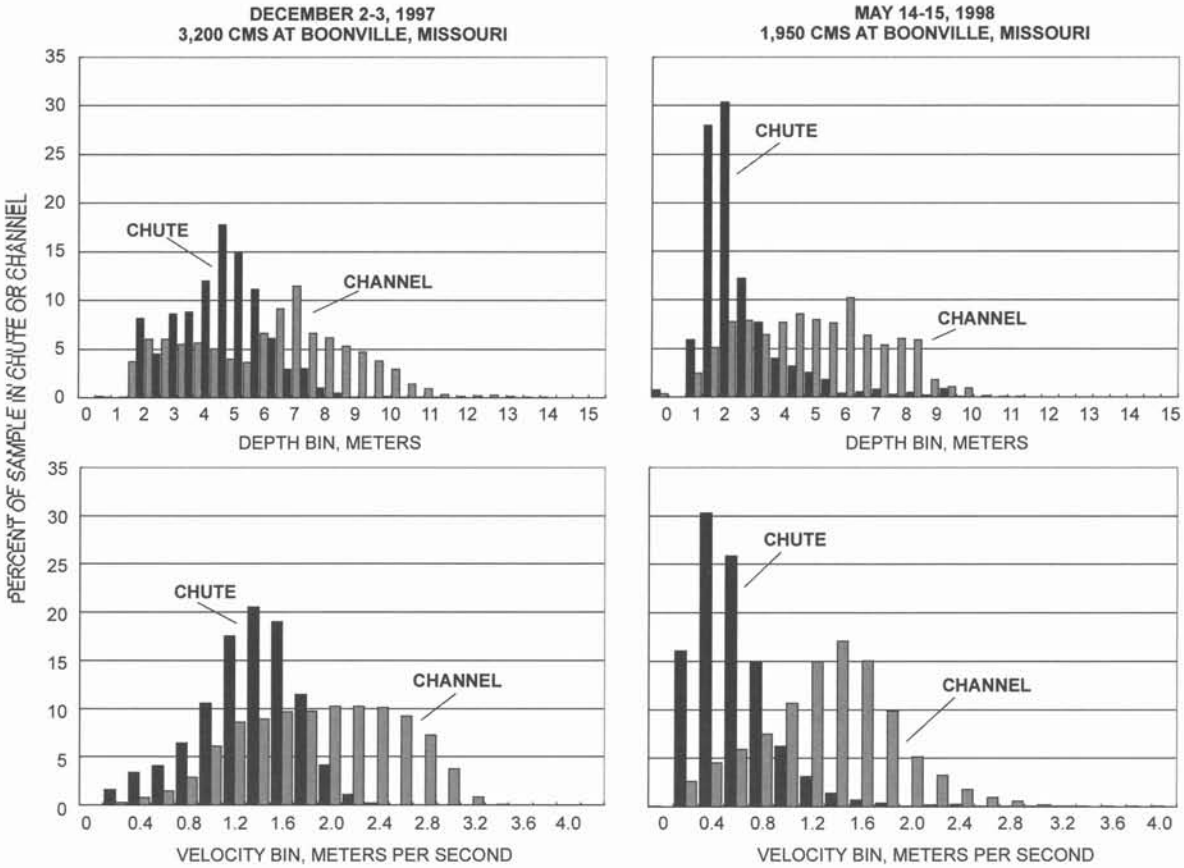


Figure 12. Histograms of samples of depths and velocities in the Lisbon Bottom Chute and Missouri River navigation channel, for two discharges, expressed as percent of sample in each area. Velocity data were collected with a 600 kHz acoustic Doppler current profiler using identical setups in the chute and navigation channel. Velocity data are total point magnitudes throughout the water column. Sample sizes range from 2,100 to 14,250 points.

unrestrained discharges allowed fluvial processes to shape the chute, and to form bars and incipient flood plain within the high banks. These new depositional surfaces (Figure 8) provide a range of elevations that can be inundated by a range of discharges, thereby substantially increasing habitat diversity and aquatic-terrestrial connections. Relatively unrestrained fluvial processes in 1996-1999 created habitat that will be more biologically effective at future, controlled discharges than if the period of habitat formation had not been allowed. Engineered side-channel rehabilitation projects may benefit from designs that similarly allow time for unrestrained habitat-forming floods to create natural features before ultimate stabilization.

Passive rehabilitation projects like Lisbon Bottom generally are less costly than more engineered or intensive approaches. For example, the cost of design and construction of minimal stabilization of the 3.3 km Lisbon Bottom chute has been estimated at $800,000 whereas cost of an engineered 2.9 km side-channel chute near Overton, Missouri has been estimated at $2.4 million. The Overton chute includes upstream and downstream hydraulic control structures, multiple grade-control structures, and substantial riprapped bank revetment to protect an adjacent interstate highway *[U.S. Army Corps of Engineers*, unpub. design]. While the cost of a rehabilitation project is relatively simple to assess, a complete performance evaluation would need to include an integrated assessment of ecological benefits relative to construction and maintenance costs. Quantifying integrated ecological benefits of rehabilitation projects remains a particular challenge.

8. SUMMARY AND CONCLUSIONS

The chute at Lisbon Bottom on the Lower Missouri River has provided a unique opportunity to document the effects of fluvial processes in passive rehabilitation. The opportunity began with the flood of 1993, estimated to have a 500-year recurrence interval. This flood opened the flood plain to fluvial processes and allowed a much smaller flood to carve a natural side-channel chute. The chute

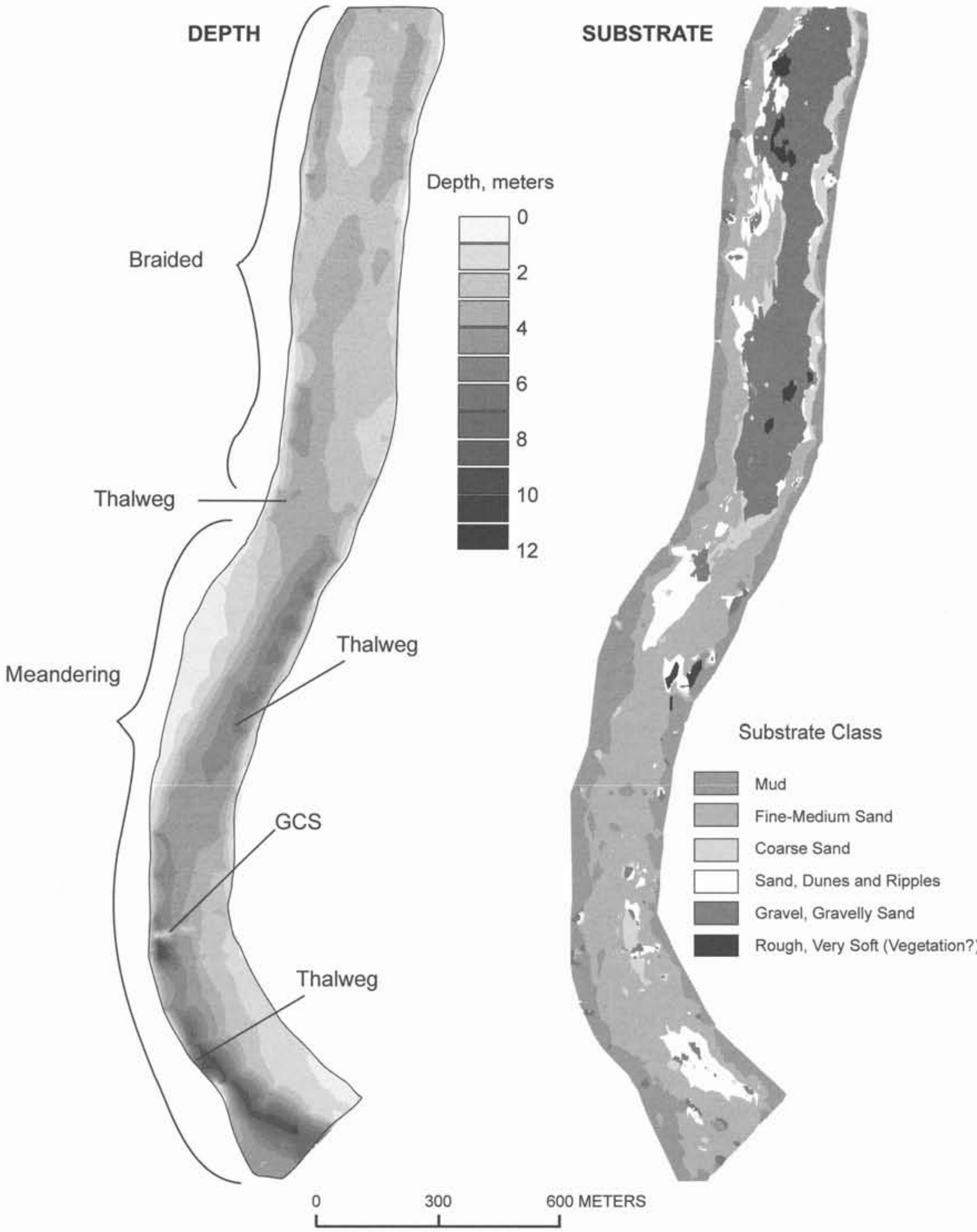


Figure 13. Depth and substrate maps of the Lisbon Bottom chute, June 1999. GCS - Grade Control Structure.

channel morphology has evolved toward an historical analog and is now providing diverse habitats that are in short supply in the engineered navigation channel. The short-term biological benefits have been mixed: the chute has fewer waterbird and benthic macroinvertebrate taxa than adjacent habitats, but greater numbers of fish species compared to the navigation channel.

Long-term biological responses of the chute will depend in part on the physical evolution of habitats, as well as other ecological interactions such as predator/prey rela-

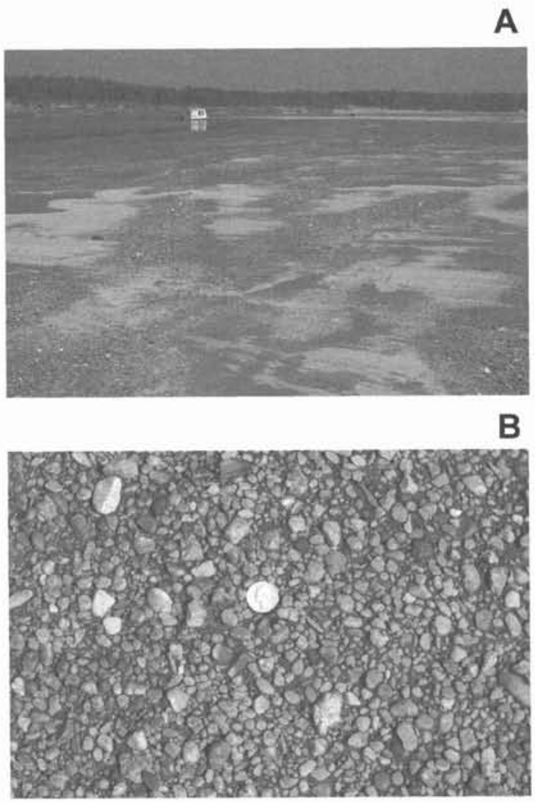


Figure 14. (A) Photograph of patches of sand and sandy gravel on upstream bar, Lisbon Bottom chute. (B) Close-up photograph of well-sorted medium to coarse gravel. Quarter shown in (B) is 24 mm across.

tions, effects of invasive species, altered nutrient fluxes, and changes in water quality. Although the chute is presently (June 2000) characterized by braided and meandering sections, the slope and discharge plot within the stability field for a meandering channel. In addition, loss of sediment supply from the main channel would be expected to encourage meandering rather than braiding in the future. Whether the chute is a persistent feature or will tend to fill with sediment is dependent primarily on factors that control relative fluxes of sediment into the chute and down the main channel. Theory and design experience disagree, however, in their predictions, indicating the need for continued monitoring.

In addition, we anticipate that future biological responses to habitat evolution will depend substantially on large woody debris dynamics and formation of the chute's own flood plain. Large woody debris is relatively rare in the chute as of June 2000. Accumulation and retention would provide fine-scale hydraulic complexity, cover for fish, and stable substrates for benthic macroinvertebrates. Accumulation will be dependent on how effective the chute is in gathering debris transported by the main channel and, as cottonwood-willow communities age, accumulation will depend in part on lateral erosion rates that deliver large woody debris directly to the chute. Retention of large woody debris will depend on discharges and velocities in the chute, and whether marginal areas of shallow depth and slow velocity develop to trap the debris.

When initially formed, the chute was incised within a flood plain so the bank heights were commensurate with a much larger river. The high banks effectively disconnected the chute from the adjacent flood plain, and decreased potential for exchange of nutrients, sediment, invertebrates, and fish. During 1996-1999 the chute migrated laterally and began to form bars and its own incipient flood plain. These fluvial features now provide a range of elevations that can be inundated by a range of discharges, thereby substantially increasing habitat diversity and aquatic-terrestrial connections. As the chute continues to migrate laterally and this flood plain develops, there will be greater opportunity for migration of species from channel to flood plain, for deposition of fine sediments in backwaters, and for retention of large woody debris. Macroinvertebrate production should also increase in the chute's vegetated flood plain. A key factor in habitat availability in the Lisbon Bottom chute was the four years of relatively high discharges and minimal management that allowed fluvial processes to begin the process of creating diverse habitat.

The future of the chute and its physical and biological characteristics are not predictable with confidence. The fluvial processes that create physical habitat can require long time intervals, and the ultimate characteristics of the chute may not be apparent for decades. Biotic responses to the physical habitat template can also require long time intervals as communities and populations adjust to physical habitat. Moreover, unpredictable sequences of hydrologic events or complex biotic interactions may alter trends and produce unexpected results. Continued monitoring and

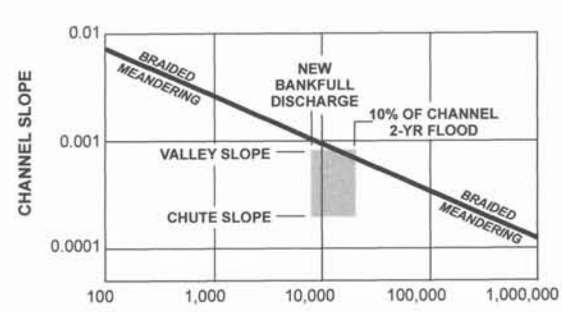


Figure 15. Stability threshold between braided and meandering stream pattern, based on *Leopold and Wolman* [1957]. Shaded area shows range of conditions for the Lisbon Bottom chute.

evaluation of the evolution of the Lisbon Bottom chute will be necessary to assess long-term ecological benefits of passive rehabilitation in this setting.

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