BENDWAY WEIRS, A NEW STRUCTURAL SOLUTION TO NAVIGATION PROBLEMS EXPERIENCED ON THE MISSISSIPPI RIVER *

by

Robert D. DAVINROY, River Engineer
U.S. Army Corps of Engineers, St. Louis District, 210 Tucker Boulevard North, St. Louis Mo. 63101
(U.S.A.)

ABSTRACT

A problem of great magnitude exists in many of the bendways on the Mississippi River. A large number of point bars are encroaching into the navigation channel, causing tremendous delay times to the towing industry. Millions of cubic yards of material are being dredged each year at these point bars. Overbank scour holes on the outside of these bends are forming during high flows, destroying farmland. These sensitive problems have not been effectively addressed in the past. Examining the problem sources in the bendways can help to achieve a final structural design solution. The problem sources are a combination of morphology, hydraulics, and man-induced constraints.

The complexities of river mechanics in bendways have always perplexed river engineers. Three-dimensional flow through curved reaches introduces problems that cannot always be addressed by « traditional » training structures. A new « non-traditional » structural solution to bendway problems has been discovered which has been model tested and constructed in a prototype reach of the Mississippi River.

The structures are bendway weirs. They are level crested, totally submerged rock weirs that are directed upstream at an angle of 30 degrees to the perpendicular midbank flowline. Built in series, they widen the navigation channel through the bend and improve the downstream crossing. They also redirect detrimental high flow velocity patterns.

Bendway weirs will be used extensively in the future on the Mississippi River. The design principle may be used in straight reaches as well. The structures may also be scaled down and applied in many types of tributary and/or small stream bendways.

SOMMAIRE

Un problème de grande ampleur se rencontre fréquemment dans les courbes du système de navigation du Mississippi. Un grand nombre de seuils empiètent sur le chenal de navigation, causant des retards énormes dans l'industrie du transport par eau. Des millions de mètres cubes de matériau sont dragués chaque année sur ces seuils. Lors des crues, des fosses d'affouillement se forment derrière les rives et détruisent les terrains arables. Il n'a pas été remédié de façon efficace à ces problèmes délicats dans le passé. L'examen de l'origine du problème dans les courbes peut aider à apporter une solution de conception structurelle définitive. Le problème découle d'une combinaison de contraintes morphologiques, hydrauliques et induites par l'activité des hommes.

La complexité de la mécanique des fleuves dans les courbes a toujours rendu les ingénieurs perplexes. L'écoulement tridimensionnel dans les courbes comporte des aspects qui ne peuvent pas toujours être compensés par des aménagements « traditionnels ». Une nouvelle solution structurelle « non-traditionnelle » a été trouvée, testée sur modèle et construite dans une section-prototype du Mississippi.

Il s'agit de barrages de courbe, consistant en digues en enrochements à crête plane totalement immergées, orientées vers l'amont à un angle de 30 dégrés à la perpendiculaire du plan d'eau moyen. Construits en série, ces barrages conduisent à l'élargissement du chenal de navigation dans la courbe, ainsi qu'à l'amélioration de la section aval. Ils réorientent aussi la direction des courants de crue défavorables.

Dans l'avenir, les barrages de courbe seront utilisés abondamment sur le Mississippi. Leur principe de conception peut être appliqué aussi dans les sections droites du fleuve. A échelle réduite, ces structures peuvent être utilisées dans les courbes de divers types d'affluents et/ou de petits cours d'eau.

KEYWORDS

Navigation, point bars, delay times, overbank scour holes, river mechanics, three-dimensional flow, bendway weirs.

MOTS-CLEFS

Navigation, seuils de courbes, retards, fosses d'affouillement derrière les rives, mécanique des fleuves, écoulement tridimensionnel, barrages de courbe.

---

* This article has been awarded the Gustave Willems Prize for 1990.

INTRODUCTION

The United States, in its quest for the development of a permanent inland waterway navigation system on the Mississippi River, has overcome great obstacles in its efforts to ensure the safe and efficient transportation of waterborne commerce.

The main consideration in the development of a navigation system on a river as dynamic as the Mississippi is man's ability to transform the tremendous energy forces that are available into an accepted economical, environmental and social coexistence. With the vast amount of regulatory works installed throughout history, including the construction of locks and dams, dikes, revetments, etc., and the employment of dredging works, the Mississippi River has been, for the most part, successfully managed to ensure efficient channel depths from the Gulf of Mexico to Minneapolis, Minnesota, a total distance of 2,972 kilometers.

Yet, there are still energy forces in the river that are having massive economical, social and environmental consequences. These energy forces are located at bendways, the important geomorphic channel configurations of a river that are a result of Mother Nature's natural, sinusoidal response to water and sediment management in an alluvial floodplain.

Bendways are one of the last remaining sources of energy on the Mississippi River that have not been fully managed by man. They serve as necessary and natural flow management devices of the river, but they also lead to many negative impacts, including erosion of banklines, inadequate channel widths, excessive downstream channel crossing deposition, cutoff development, detrimental high flow velocity patterns, destruction of farmland and levees, and the loss of wildlife habitat. All of these problems directly impact the economy and the environment.

The bendway weir is a new structural design solution developed to minimize or alleviate the problems generated in bendways on the Mississippi River. They are cost-effective submerged rock structures. When properly designed and constructed, they can effectively manage the water and sediments through a bendway while still maintaining the integrity of the natural sinusoidal channel pattern. The direct physical attributes of bendway weir design include : a widening of the existing narrow navigational channel, a deepening and corresponding improvement of the downstream crossing channel, stabilization of the existing bankline, and redirection of otherwise detrimental high flow velocity patterns. Also, bendway weirs are low-elevation structures. They are totally submerged underwater, thereby maintaining the natural beauty of the scenic waterway.

Physical model tests to develop and evaluate the design of these new structures have been extensively conducted on a movable bed model of a selected prototype reach.

Construction of the first bendway weir has been completed on the Mississippi River, and post construction field monitoring has indicated favorable velocity and bed sediment trends have been established in the river channel.

It is the goal of this article to first discuss the problems that exist in bendways on the Mississippi River; secondly, to outline the sources of these problems; thirdly, to discuss the research and development of a structural solution gained by model testing; and finally, to describe the actual construction and field monitoring that has been completed in the river.

BENDWAY PROBLEMS

The negative impacts of bendways are discussed to make one aware of the magnitude and extent of the problems currently being experienced on the Mississippi River.

1. NARROW BENDWAY WIDTHS

Many of the bendways in the open river system below St. Louis, Mo., create a major problem to the navigation industry. The problem is inadequate navigation channel widths. The navigation channel becomes so narrow through a bend that a downbound barge tow has to expend a tremendous amount of time and energy using skilled flanking techniques to safely navigate through the bend. It is not uncommon for a tow to take up to three hours to transit through a troublesome bend. This undesirable channel condition usually takes place after a high water event on the river followed by a corresponding fast recession of the hydrograph. The end result is a narrowing of the navigation channel. Fig. 1 illustrates excessive narrowing of the navigation channel at Dogtooth Bend (located 256 kilometers below St. Louis). While a downbound tow is flanking through the bend, any upbound tow has to wait until the downbound tow is safely through the bendway. Depending on how much downbound traffic exists on a particular day, the wait could be as long as 12 hours. When one considers the number of bends and the volume of traffic that exist over the entire length of the waterway, it becomes obvious that these traffic delay times create massive costs to the towing industry and ultimately to the consumer. In 1988, an investigation was made to assess the cost of delay times impacted to the navigation industry. Examination of daily navigation logs of a particular towing company led to a determination of the average delay time per trip due to narrow bends. Also, the hourly towing cost and average daily traffic volumes were calculated. Based on this information, the impact cost of delay time due to bends in 1988 was estimated to be approximately $ 24 million. In 1988 there were no high flow events on the Mississippi, so there was no excessive narrowing of the navigation channel. A year with a fast falling, high flow hydrograph would add considerably to the above estimated cost.

Another impact cost to the navigation industry is the number of accidents that occur at these bends due to groundings. From 1985 to 1988, in the reach of the river from St. Louis to Cairo, Ill., there were an average of 20 groundings per year that occurred in bends. A large majority

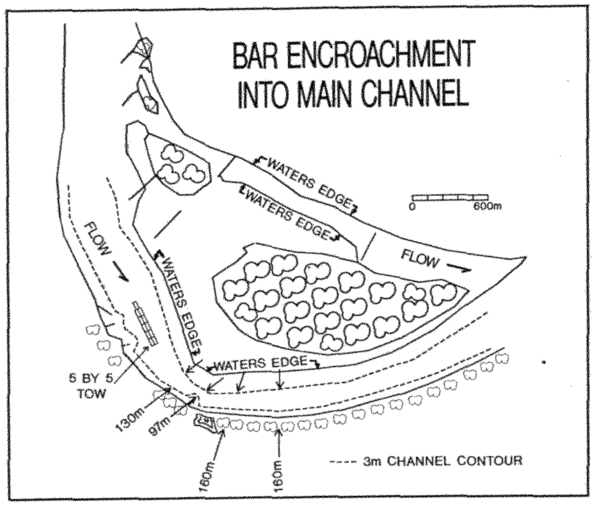


Fig. 1 - Excessive narrowing of navigation channel at Dogtooth Bend

of these events were the result of barges running aground on the point bars. Each time a barge grounding occurred in a bend, the following circumstances usually took place :

a. The integrity of the navigation channel was threatened because the actions necessary to remove the tow were often injurious to the channel.

b. The bendway became a bottleneck until the grounded vessel was removed, adding further to delay times.

c. The safety of the crews on-board both the grounded vessel and the vessels passing the accident was threatened.

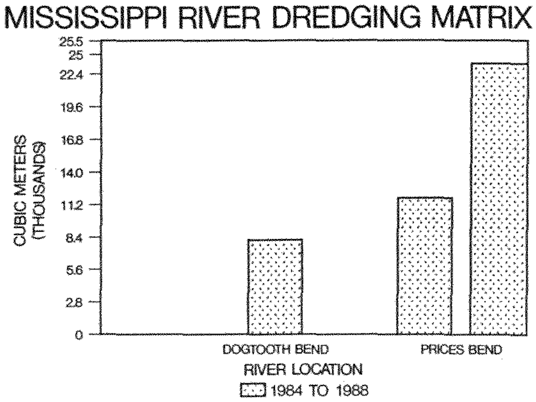


Fig. 2 - Dredging matrix showing amount of material removed at two bends on the Mississippi River

Additionally, the United States spends millions of dollars each year dredging the point bars at these troublesome bends. Fig. 2 is an example of the quantity of dredged material removed at two bends in the Mississippi. The frequency of this dredging occurs on an interval dependent upon the behavior of the hydrograph and the availability of dredges. Dredging of point bars serves as a short, temporary cure to the sympton, but it is not a permanent cure to the problem.

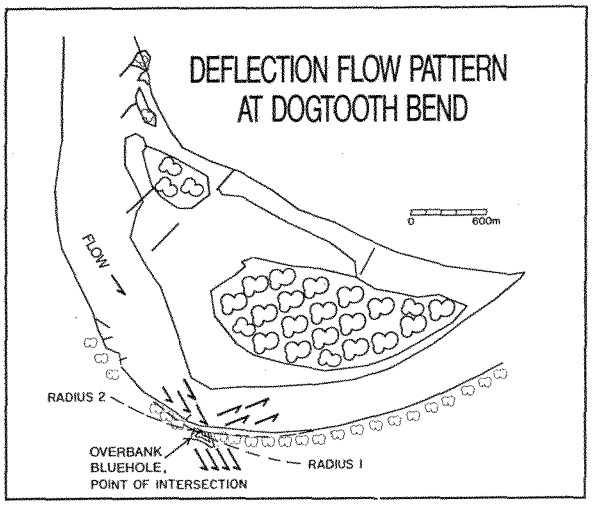


Fig. 3 - Illustration of deflection flow patterns at Dogtooth Bend

2. OVERBANK DEFLECTION FLOW

At bankfull conditions in some bends, a phenomenon occurs which leads to excessive overbank scour. The phenomenon is deflection flow, the detrimental velocity pattern developed as a result of a stabilized, multiple radii bankline alignment. The deflection occurs at the intersection point of two different outside bank radii. Instead of the velocities flowing in a curved, uniform pattern around the bend, they actually deflect off the high bank at the point of intersection. The problem is exaggerated when treeline protection on the riverbank is removed or nonexistent, as is the case at Dogtooth Bend on the Mississippi River. Figure 3 illustrates the deflection flow patterns at Dogtooth Bend. An overbank scour hole (commonly referred to as a bluehole) has formed behind the bank, and with time, a crossover channel could develop over the floodplain at this point.

BENDWAY PROBLEM SOURCES

A straightforward discussion into the problem sources of bendways can lead to a better understanding of what is required for a systematic design approach. The sources listed here are in order of importance.

1. MEANDERING PROCESS AND CAPTURED ALIGNMENT

Fig. 4 is a morphological depiction of the meander belts of the Mississippi River between Thebes Gap and its confluence with the Ohio River. Before the intervention of man, the floodplain consisted of alluvial deposits which contained primarily marshlands, swamps and prairies. Except for various geologic controls like Thebes Gap (shown in the upper left of the photo in Fig. 4), the river meandered across the floodplain unrestrained. Then, as man took advantage of the fertile soil and began cultivation, the need for protection against erosion dictated the installation of bank stabilization. In the 1920's, the early revetment works in the bendways were initiated. These works were built with hand-placed cobblestone, and eventually evolved into the present day revetment practices. Gradually, the once continually meandering river was becoming harnessed. The early economic demands for stabilization influenced the engineers to stabilize the natural existing alignments of the bends. Unfortunately, many of the bends were in transition, containing multiple radii, and the resulting captured alignment of the bend was not conducive to a favorable navigation channel.

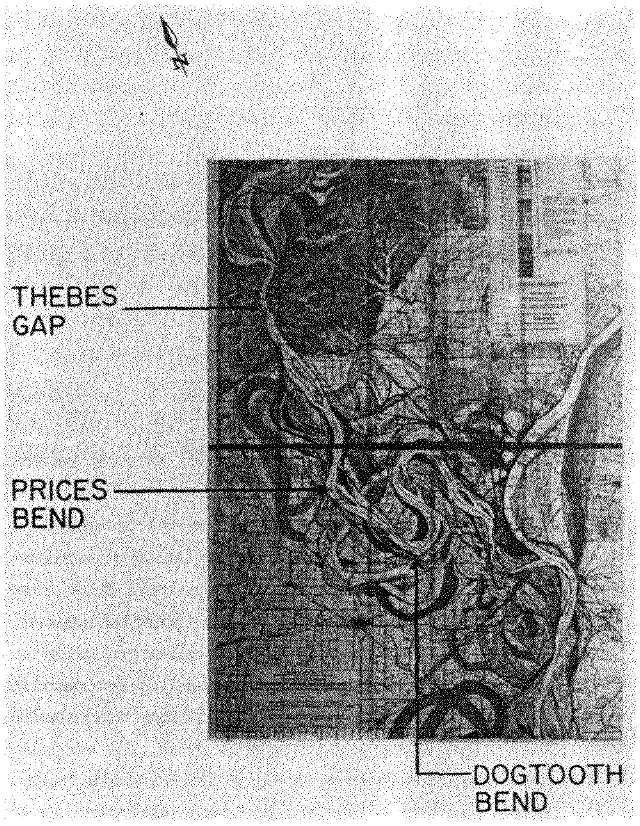


Fig. 4 - Historic Mississippi River meander belts, Thebes Gap to the confluence with the Ohio River

2. CHANNEL AND POINT BAR MIGRATION

The stationary revetted bankline and resulting captured alignment of a bendway causes problems that were not totally understood by the early engineers. Channel and point bar migration conditions have been totally changed. Fig. 5 illustrates channel and point bar migration for a theoretical unstabilized bend vs. an actual stabilized bend on the Mississippi River. Boxes 1A and 1B typify original bendway conditions. At Dogtooth Bend, revetment has been placed on the right descending bank. 2A shows the theoretical outward migration of the channel and point bar in an alluvial floodplain. The left and right descending banks migrate outward from the base of the point. The right bank migrates by erosion and bank caving, while the left bank migrates by deposition. In 2B, the right bank does not migrate outward from the point base because of the revetment. Instead, by conservation of energy and the centrifugal bend force, the river diverts its restricted horizontal energy into vertical energy, resulting in a deepening of the channel. The left bank continues to migrate by deposition, thus, the point bar actually encroaches into the channel, conversely narrowing the navigation channel. 3A shows that, during highbank flows, a cutoff occurs at the narrow neck formed a comparatively short distance from the base of the point. This cutoff is a result of headcutting and scour. The cutoff, or chute, is not well aligned with the channel upstream and downstream. This poor alignment and the extreme slope through the chute forces the principal currents to adhere toward the side of the chute against the base of the point, in the case of 3A, the left bank of the chute. As a result, the chute scours to correct the poor alignment, and with time, eventually evolves into the main channel, while the old bendway evolves into an oxbow lake (4A). In 3B, the chute has formed and the point bar continues to encroach into the main navigation channel by deposition. Eventually, the bendway becomes the chute, while the cutoff chute becomes the main channel (4B).

Field monitoring conducted on the Mississippi River, including surveys, discharge measurements, and visual observations have verified that many of the side chutes are enlarging and many of the main channels are decreasing in size.

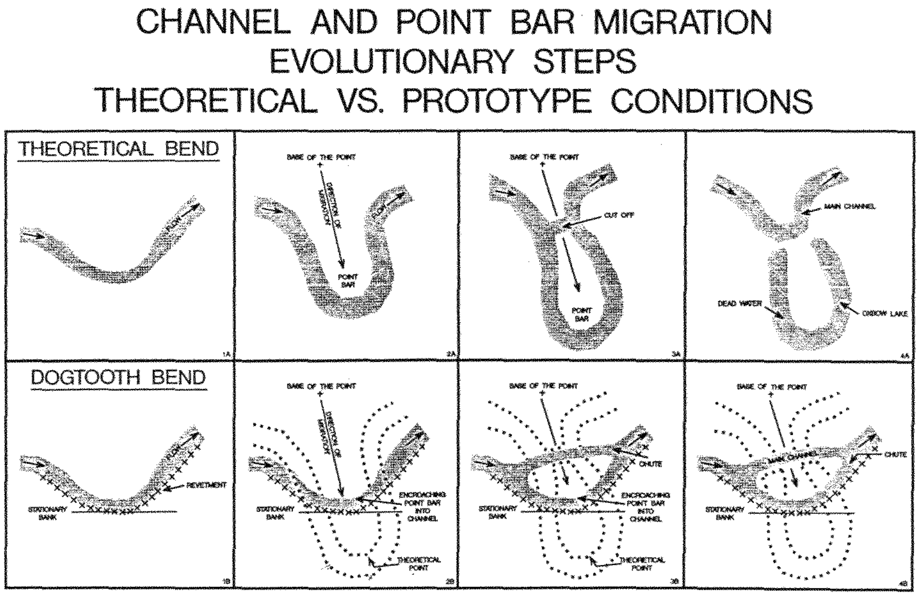

CHANNEL AND POINT BAR MIGRATION
EVOLUTIONARY STEPS
THEORETICAL VS. PROTOTYPE CONDITIONS

Fig. 5 - Channel and point bar formation, evolutionary steps, theoretical vs. prototype conditions

3. BENDWAY MECHANICS

The study of bendway mechanics involves complex, three-dimensional flow analyses. Fig. 6 depicts a three-dimensional bend flow element. Besides the normal and lateral velocity components which occur at a bend, transverse velocity components occur as well. This transverse velocity, or secondary flow, spirals about the channel cross-sectional axis. This spiraling effect is a direct result of the torque established from the centrifugal force action of the water flowing around the curve of the bend. Straight reach mechanics are much easier to manage than curved reach mechanics because the centrifugal force action is minimal. A channel cross section in a straight reach is made up of a series of manageable secondary cells. The simple conveyance equation applies, and the overall navigation depths and widths can usually be managed by « traditional » dike structures. However, in a bendway, the centrifugal force is so great that the conveyance equation does not apply, and « traditional » structures do not always work.

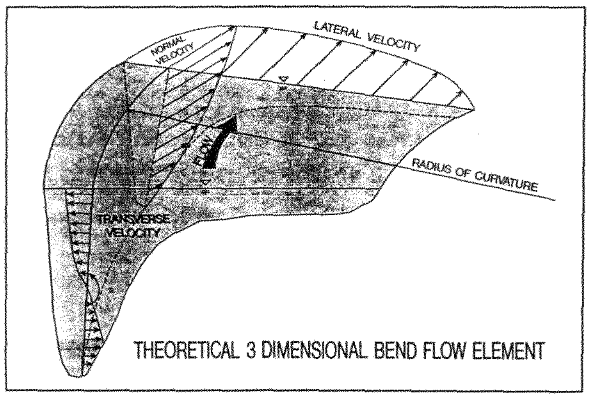


Fig. 6 - Three-dimensional bend flow

In a bend, two predominant secondary cells normally exist: the centrifugal force cell and the bankline friction cell. The cells spiral in opposite directions to each other. The bankline friction cell is of a very small magnitude in comparison to the centrifugal cell. The interface of the two cells forms the threadline of the flow in the channel (channel thalweg). If a structure could be placed in the bend that would increase the friction cell and decrease the centrifugal cell, then the threadline would be moved away from the outer bank and shifted toward the inner bar. This shift in the threadline would, in time, widen the navigation channel.

HYDRAULIC MODEL TESTS

1. STUDY REACH AND MODEL DESIGN CONSIDERATIONS

Fig. 7 shows an aerial view of a 31-kilometer study reach of the Mississippi River containing two problem bends, Prices and Dogtooth Bends. A model of the movable bed type was constructed of this reach. Granulated coal with a specific gravity of 1.3 and a median diameter of .635 cm was used as a bed medium. The horizontal scale was 1 : 400; the vertical, 1 : 100, for a 4 to 1 distortion ratio. Fig. 8 is a view of the model, looking downstream. The design hydrograph was determined by the author using historical records and mathematical model computations.

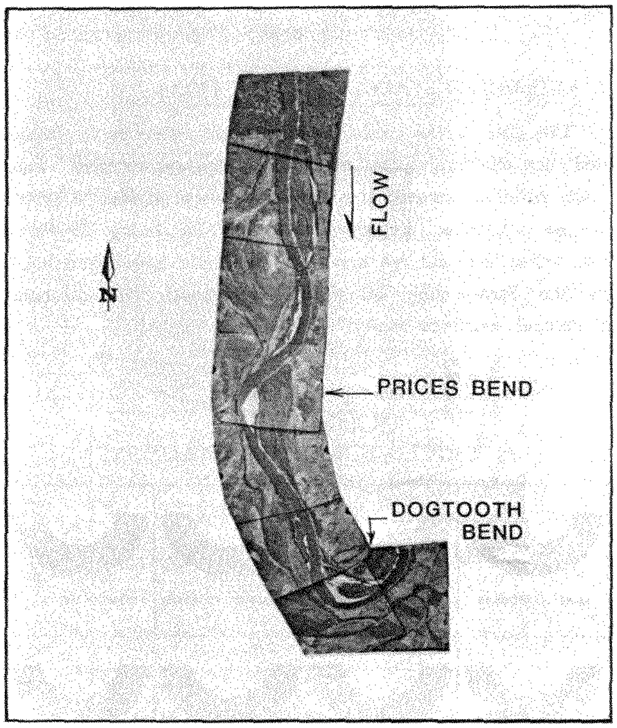


Fig. 7 - Aerial view of model study reach

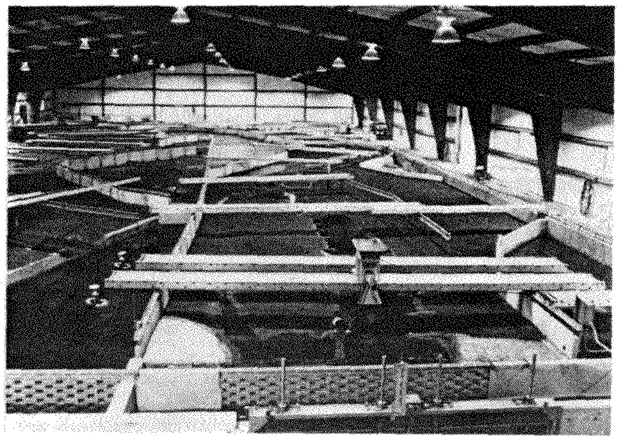


Fig. 8 - View of movable bed model

Successful verification of the model was achieved. Five consecutive design hydrographs were run to develop base test conditions. The base test is the comparative test which shows the tendencies of the river with existing conditions. Results of this test indicated that both of the bends had a tendency to narrow and deepen, and the depths of the crossing channel between the bends had a tendency to shoal.

On the Mississippi River, navigation channel design elevations are established in relation to the Low Water Reference Plane (LWRP). LWRP is a theoretical reference profile of the river based upon historical hydrologic data. A depth of 3 meters below the LWRP is the standard minimum design depth for the navigation channel. Survey contours developed on the model are thus referred to this LWRP datum, and the -3 m contour represents the design channel.

2. ATTEMPTED STRUCTURAL SOLUTIONS

The goal of the model tests was to arrive at a practical and cost-effective solution to the problem sources, hence many different structural alternatives were studied. A picture of the attempted structural solutions is shown in Fig. 9. Structures that did not benefit served as a lesson and helped in the formulation of new alternatives. The attempted structural solutions were :

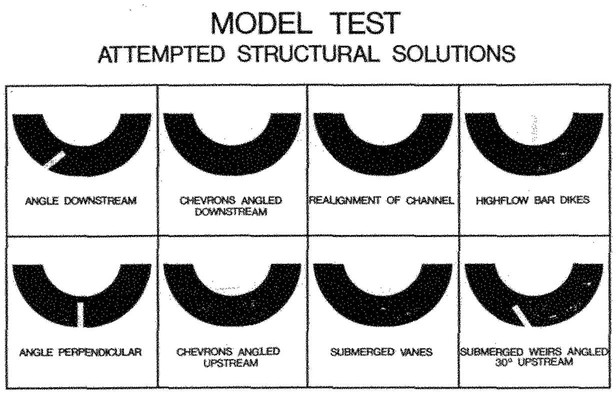


Fig. 9 - Attempted structural solutions in model study

a) DIKES LOCATED ON THE OUTSIDE OF THE BEND, ANGLED DOWNSTREAM

This plan had no effect on deflecting velocity toward the point bar; instead, velocities were actually deflected in toward the revetted bank, threatening the integrity and stability of the bank.

b) DIKES LOCATED ON THE OUTSIDE OF THE BEND, ANGLED PERPENDICULAR

This configuration had no effect on the existing channel, however, deflection flow patterns were minimized.

c) CHEVRONS ANGLED UPSTREAM AND DOWNSTREAM

The chevron (a flow dividing structure) had no effect on the point bar. They moved velocities in toward the outside bank, thereby threatening stability.

d) REALIGNMENT OF THE CHANNEL

Several different realignments of the channel were tested. Redevelopment of the upstream entrance channel had little effect on creating desired conditions in the bend. A constant radius alignment was also constructed through the bend and achieved some desirable results. However, major channel realignment is deemed cost-prohibitive.

e) SUBMERGED VANES

Submerged vanes developed by the University of Iowa were tested. Although they caused a small quantity of deposition to occur on the outside of the bend, they had little effect on attacking the point bar. More research and development on submerged vanes in navigation channels should be conducted in the future.

f) HIGHFLOW BAR DIKES

Dikes located on the point bar itself were tested. They had no effect on widening the channel, but they did seem to inhibit the tendency for cutoff development in the side chute.

g) SUBMERGED WEIRS ANGLED 30 DEGREES UPSTREAM

This plan showed very desirable results, as discussed further in this article. Evolution of this concept plan was as follows :

3. EVOLUTION OF BENDWAY WEIR DESIGN CONCEPT

The design concept for bendway weirs evolved from a previous model study on dike configurations in near straight reaches of the Mississippi River. In the study « Hydraulic Design of River Training Structures in Crossings » (WES 1989), various angles, both upstream and downstream were evaluated. There appeared to be some promise to upstream-angled dikes in straight reaches. The only skepticism that remained was if the concept could work in a bend, since the structures would have to be submerged in order for traffic to be able to pass through the bend. Results of this model study indicated that a dike angled upstream 45 degrees to the perpendicular flowline proved to be undesirable because the scour generated on the upstream face of the structure was so great that the stability of the entire structure was jeopardized. Dikes angled 20 degrees upstream to the perpendicular flowline generated so little scour action that the benefits were minimal. With this information, the bendway weir was developed with a compromised, upstream angle of 30 degrees to the perpendicular flowline. This angle proved to be extremely efficient.

4. BENDWAY WEIR MODEL TEST RESULTS

A total of 20 bendway weirs were placed in the two bends of the model study reach. Each weir was attached to the existing outside bankline and angled upstream 30 degrees to a line drawn perpendicular to the midbank flowline. The structures were constructed level crested with a top elevation of 5.49 meters below the LWRP.

Fig. 10 shows the survey comparisons for the model test results of the most upstream bend in the model study reach, Prices Bend. The base test represents the « before » conditions of the channel. The calculated radius of curvature for this bend is 2.4 kilometers. Notice should be given to the existing perpendicular short weirs that exist in the prototype. These weirs have little or no effect on the channel. They were constructed in the 1960s to stabilize the toe of the bendway bankline. After the installation of 9 bendway weirs, the channel through the bend widened an average of 130 meters. Figs. 11 and 12 show the « before » and « after » cross-sectional plots at range X-X on the plan view. Fig. 13 shows the comparison overlay of the two plots. Approximately 12 meters of deposition occurred on the outside of the bend at this section.

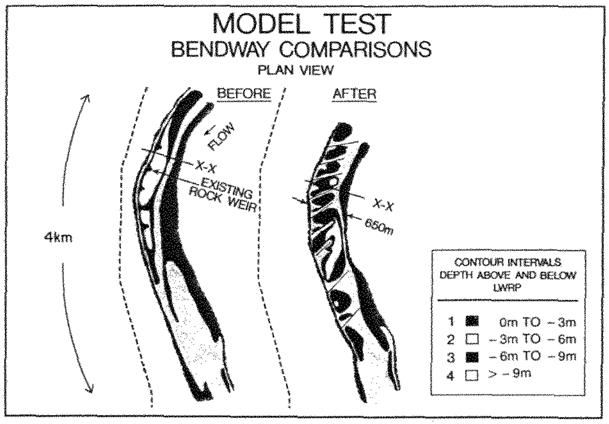


Fig. 10 - Model survey comparisons of Prices Bend

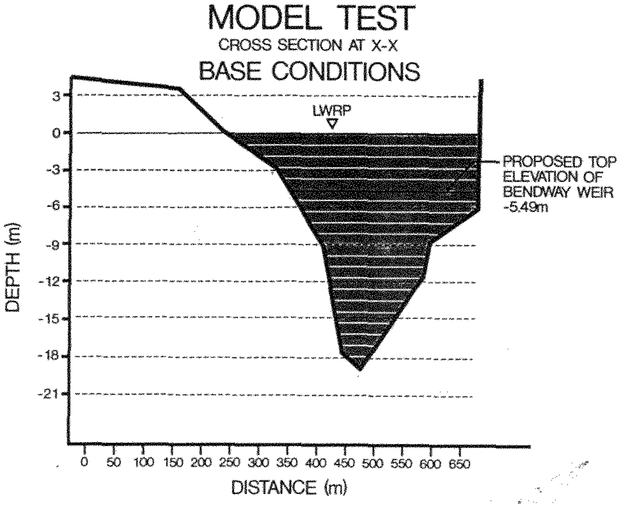


Fig. 11 - Cross-sectional plot of base test at X-X

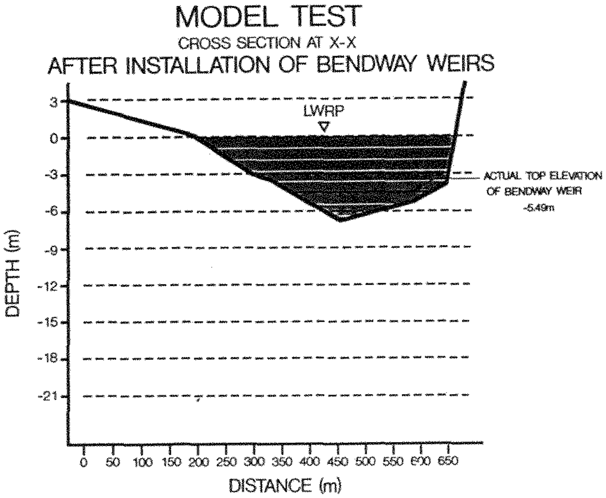


Fig. 12 - Cross-sectional plot of bendway weir plan at X-X

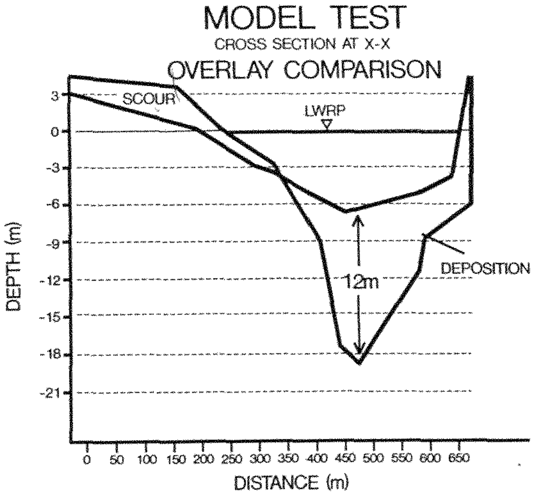


Fig. 13 - Overlay plot comparison at X-X

Fig. 14 shows the comparison survey of the next downstream bend, Dogtooth Bend, with an average radius of 1.8 kilometers. After the installation of 11 bendway weirs, the channel widened out an average of 85 meters. Figs. 15, 16 and 17 show the before, after, and the overlay cross-sectional plots at range H-H of the model. Approximately 15 meters of deposition occurred at the outside of the bend at this section.

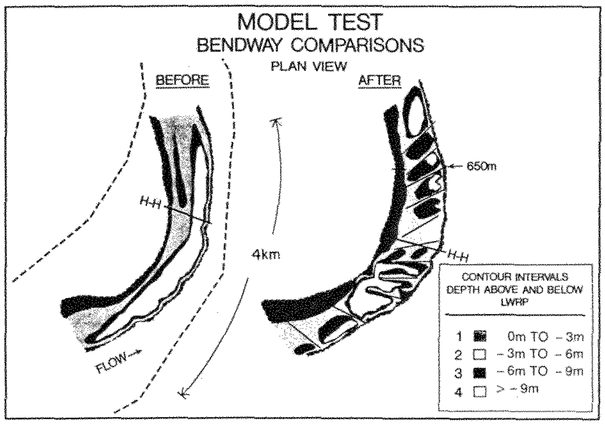
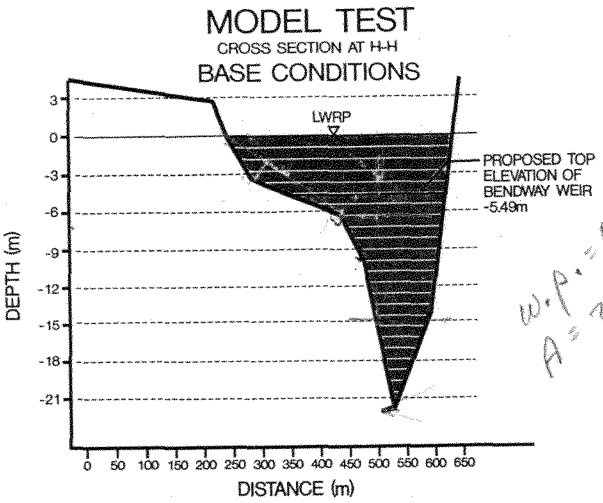
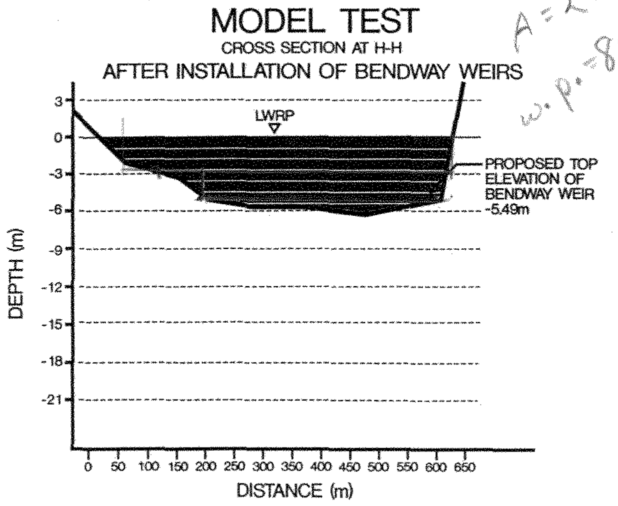


Fig. 14 - Model survey comparisons of Dogtooth Bend



w.p. = 1100 m
A = 3600

Fig. 15 - Cross-sectional plot of base test at H-H



A = 2900
w.p. = 800 m

Fig. 16 - Cross-sectional plot of bendway weir plan at H-H

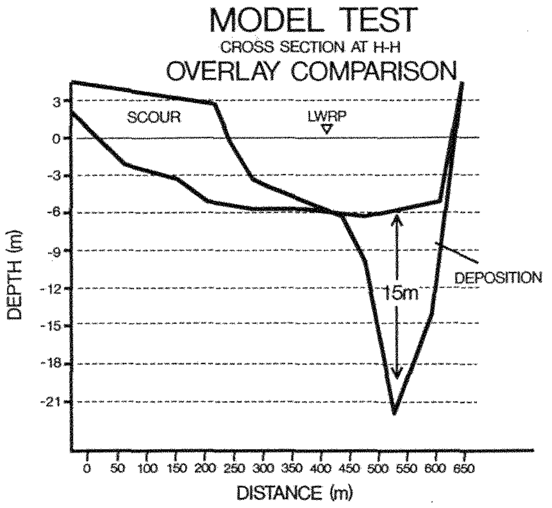


Fig. 17 - Overlay plot comparison at H-H

Fig. 18 shows the comparison survey of the channel crossing reach between the two bends. The comparison shows that after the installation of the weirs in the upstream bend (Prices), the channel widened and deepened considerably.

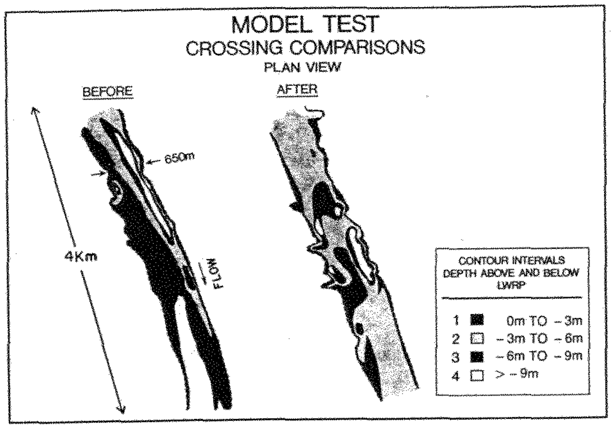


Fig. 18 - Model survey comparisons of crossing channel between Prices and Dogtooth Bends

Fig. 19 is a view of the bendway weirs in the model. These photos show the degree of deposition within each structure and the amount of scour located at the point bar. Evaluation of the functioning attributes of these structures were conducted during the course of the hydrograph. The following results were observed:

a) The 30-degree design angle proved optimum, as no unacceptable scour on the upstream face of the structures was experienced. The structural stability thus remained intact.
b) Detrimental deflection flow patterns were beneficially redirected, as verified by model confetti tests.

Numerous tests were conducted on various crest elevations for cost-efficiency. None of these alternatives were as efficient as the level crested weirs with a design elevation of -5.49 WRP.

NS OF MODEL TEST RESULTS

satisfactory results from the bendway weir plan, ulation of a flood hydrograph was run through the model as a final test to determine the overall response of the channel to both normal and high flow conditions. From surveys, confetti tests, and video tape review, the following conclusions were derived by the author:

The sinuosity and sediment management scheme is still maint d after installation of the weirs. Now, instead of th bar location serving as sediment storage during some storage is diverted to the opposite outside ank at a depth determined by the height of the us, at the low to midbank flows, the sediment e becomes redistributed in the bend to the advantage navigation, i.e., the bendway becomes wider and more

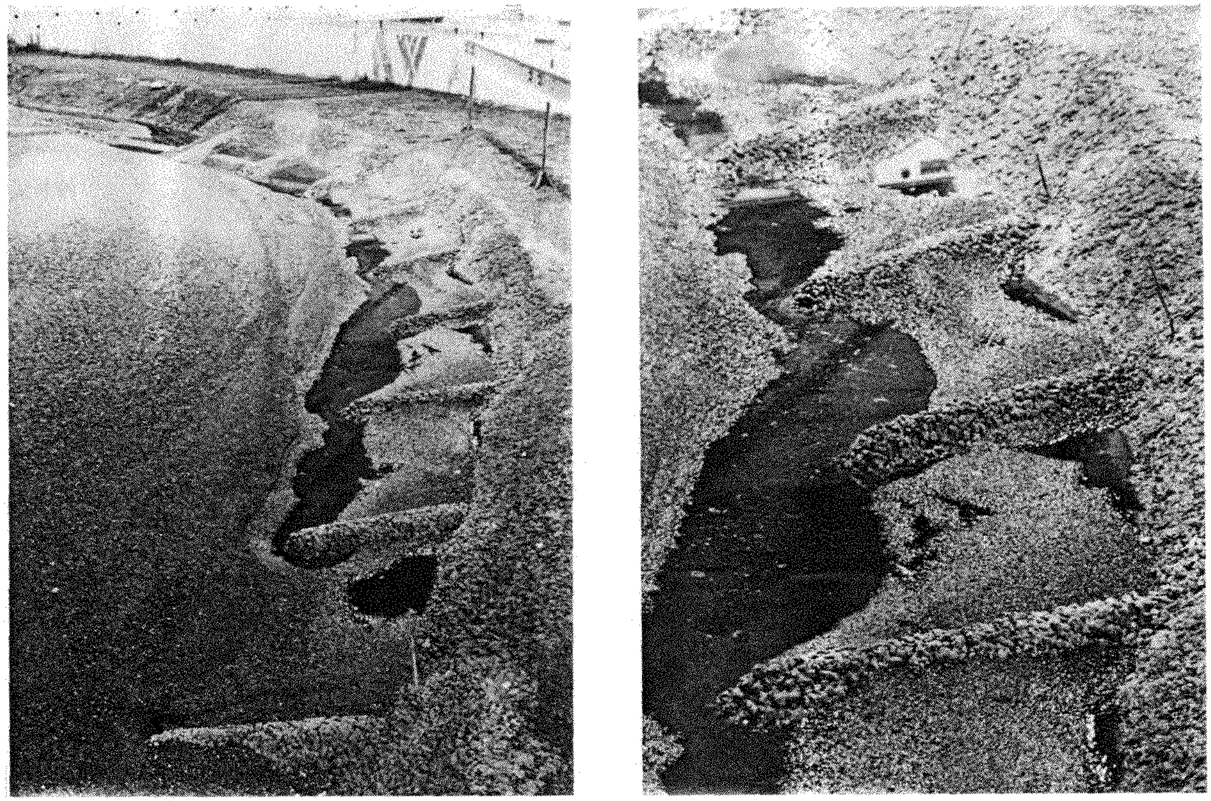


Fig. 19 - View of bendway weirs in model, looking downstream

shallow while still maintaining a navigable depth. The downstream crossing becomes drastically improved due to the temporary change in sediment transport geometry. At midbank to high flows, normal flow conveyance occurs and the storage sediments are transported downstream. As the hydrograph falls, the weir influence takes over again and the sediments fall out in storage to a manageable, desired configuration that is beneficial to navigation. Optimum sediment management is thus achieved in the bendway at all flow conditions.

Hydraulically, this new sediment management in the bend has been developed by the creation of a dominating friction cell counteracting against the natural centrifugal cell. The end result is a shift in the channel threadline at the low to medium flows.

CONSTRUCTION

Placement of the first bendway weir on the Mississippi River occurred in June 1989. The total time that was required for the construction of the weir consisted of only 4 days. The sequence of construction is summarized as follows:

1. Survey target points on both sides of the river were established. A 30-degree alignment centerline was established (the same angle as in the model tests), starting at the outside of the revetted bank and extending upstream across the channel toward the point bar. Also, an offset line 10 meters upstream and parallel to the centerline was established. This compensated for the drift forces against the sinking rock. This line was adjusted according to the particular changing velocities experienced over the length of construction. Drift velocities during construction never exceeded 1.5 m/sec due to backwater effects from the Ohio River.

GRADED STONE A

STONE WEIGHT POUNDS	CUMULATIVE PERCENT FINER BY WEIGHT
5,000	100
2,500	70 - 100
500	40 - 65
100	20 - 45
5	0 - 15
1	0 - 5

Not more than 5 percent by weight finer than 1/2-inch screen

Table 1 - Gradation requirements for Graded Stone A

2. Mobilization of a spud barge containing an 88B, 365-hp dragline with a .184-cu. m stone bucket was positioned over the offset line by the use of a 900-hp push boat. When proper alignment was reached, the spuds were lowered down into the riverbed. A rectangular spreader block template was attached to the spud barge and served as the position void for the placement of rock. Figs. 20 and 21 show the construction equipment setup.

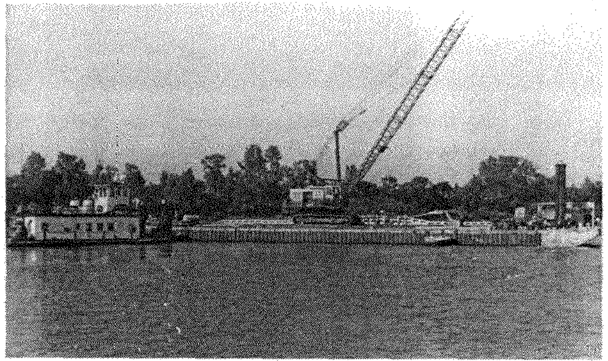


Fig. 20 - View of construction equipment

3. A rock barge containing graded stone A was pushed parallel to the template. Table 1 gives a summary of the gradation requirements for graded stone A.
4. The stone was then dragged into the void created by the template (Fig. 22) and skillfully dumped as massive units

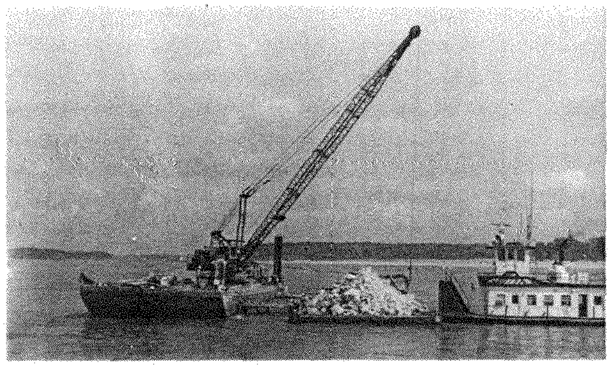


Fig. 21 - View of construction setup with rock barge positioned against spreader box template.

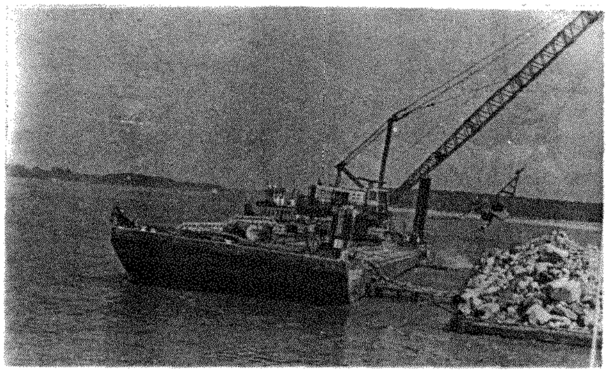


Fig. 22 - View of stone being placed in river, looking from the outside bank toward the point bar

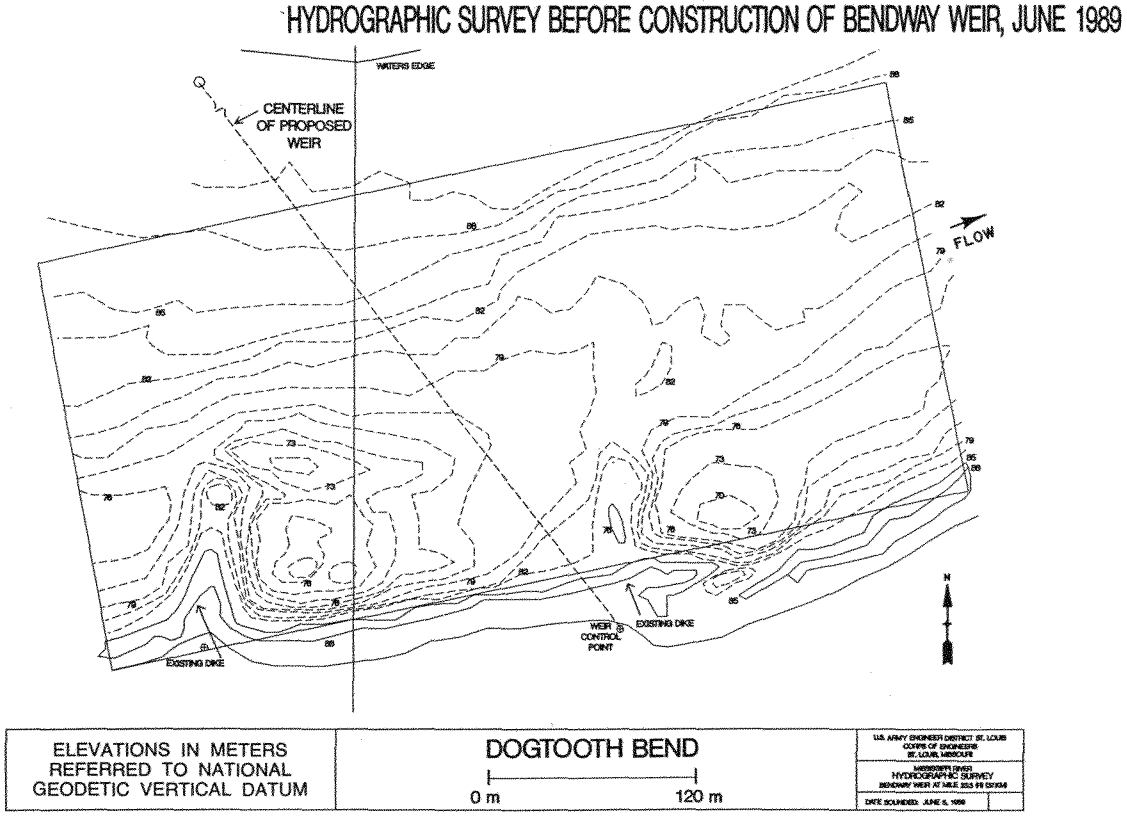


Fig. 23 - Hydrographic survey of Mississippi River, pre-construction

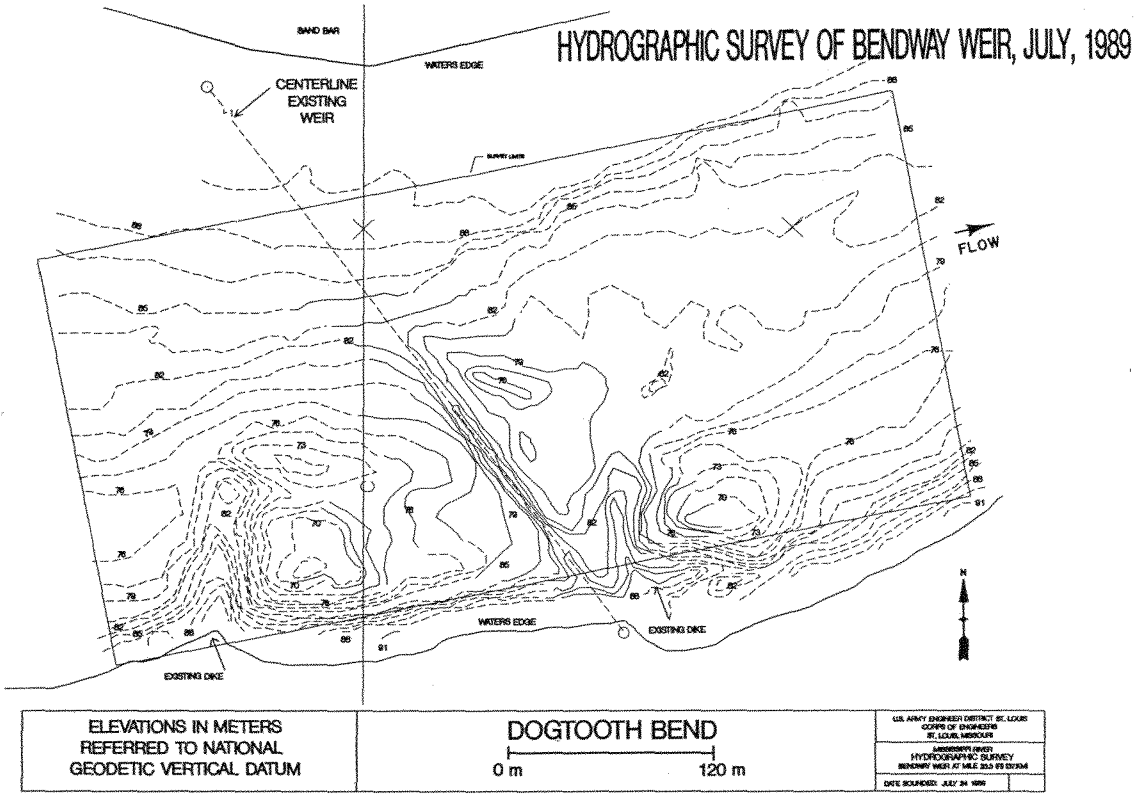


Fig. 24 - Hydrographic survey of Mississippi River, after construction

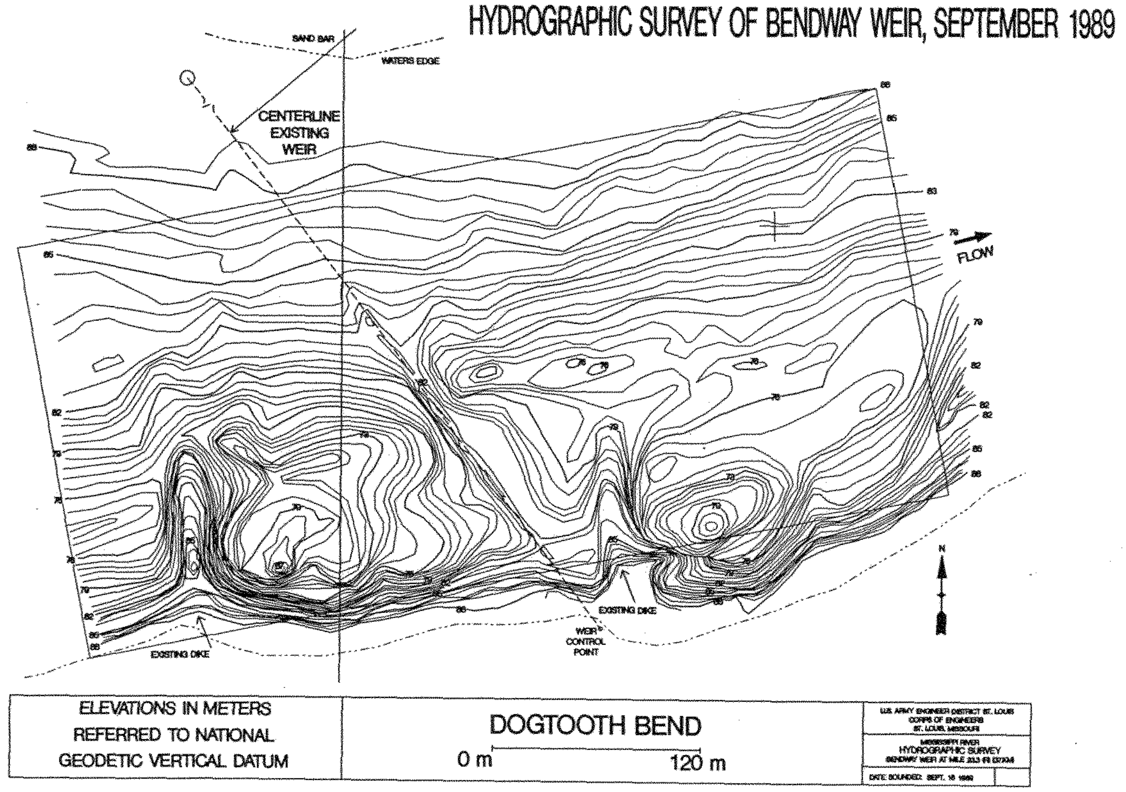


Fig. 25 - Hydrographic survey of Mississippi River, after construction

containing proper gradation. Because of the offset line, the stone drifted on the desired centerline alignment.

5. Intensive, computerized soundings were performed during the construction to check the alignment and elevation of the structure.
6. The entire mobilization process had to be repeated frequently in order to allow navigation traffic to pass through the bend.

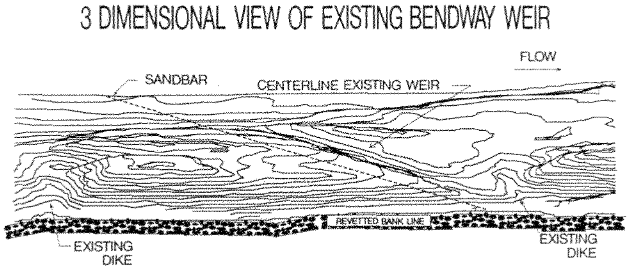


Fig. 26 - Three-dimensional contour generated from hydrographic survey, after construction

PROTOTYPE MONITORING

Intensive prototype monitoring was conducted before, during, and after construction of the bendway weir. The monitoring included :

1. DETAILED BED SOUNDINGS

Figs. 23, 24 and 25 show detailed hydrographic surveys established from sounding data. As seen in Fig. 25, a scour hole approximately 3 m in depth developed 120 meters out into the channel, downstream of the center of the weir. This is very encouraging and desirable, as it verifies a tendency for thalweg shift as replicated in the model. Fig. 26 is a three-dimensional contour plot generated from the after construction hydrographic surveys.

2. SONAR PICTURE

Fig. 27 is a bottom image of the weir and channel bed. This was generated using an Image Side Scan Sonar. The image defines the bed scour tendencies experienced downstream of the weir, as well as deposition tendencies on the outside of the bank.

3. VELOCITY CROSS SECTIONS

Fig. 28 shows the established data collection range, A-A, that was used to collect velocity data both before and after placement of the weir. A velocity isovel plot was generated from a velocity grid. Fig. 29 is the plot before weir placement, and Fig. 30 is the plot of data collected one month after construction. A definite trend of an overall flow shift toward the middle of the channel can be seen.

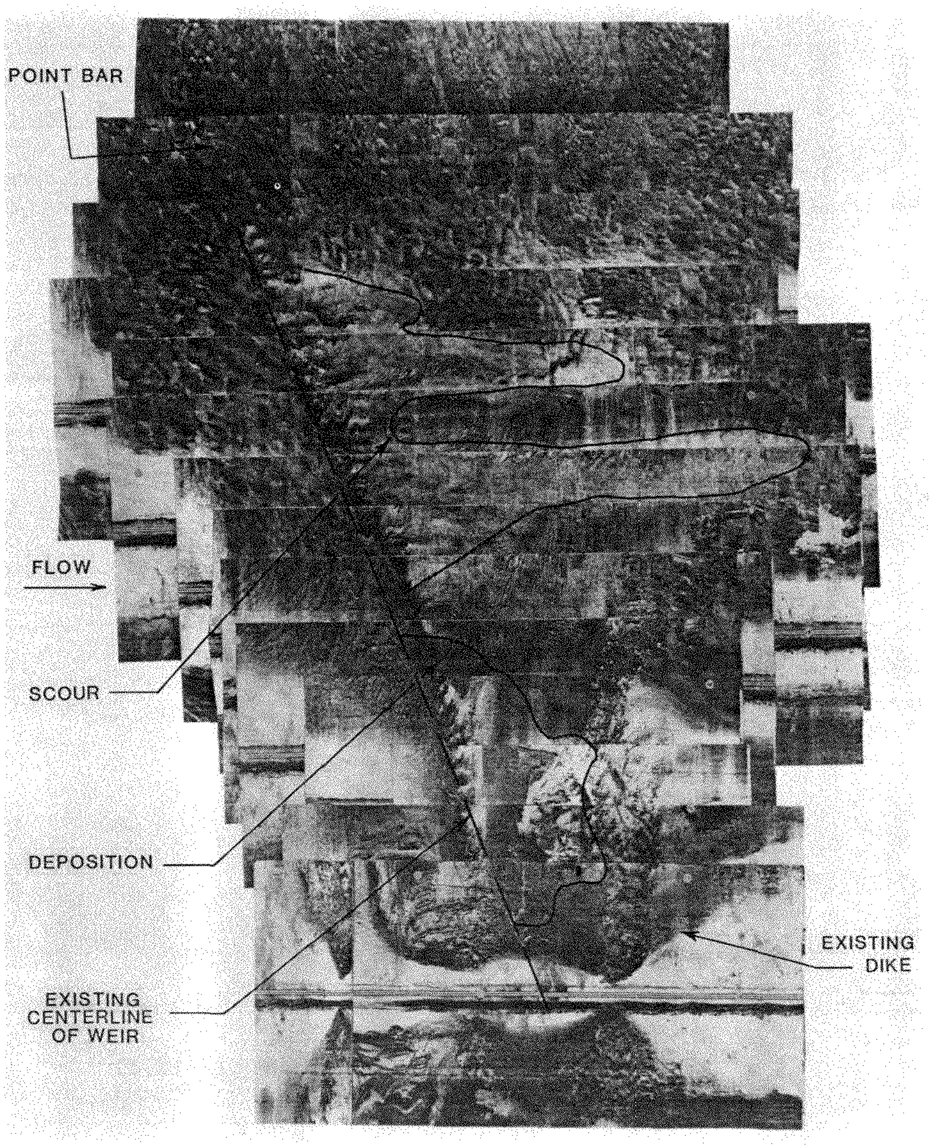


Fig. 27 - Image side scan sonar picture of weir and channel bottom

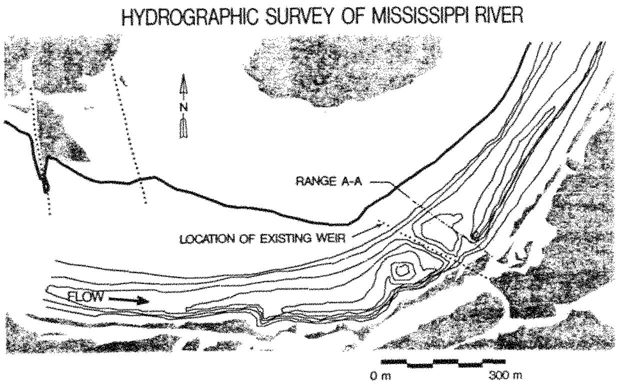


Fig. 28 - Location of data collection range A-A

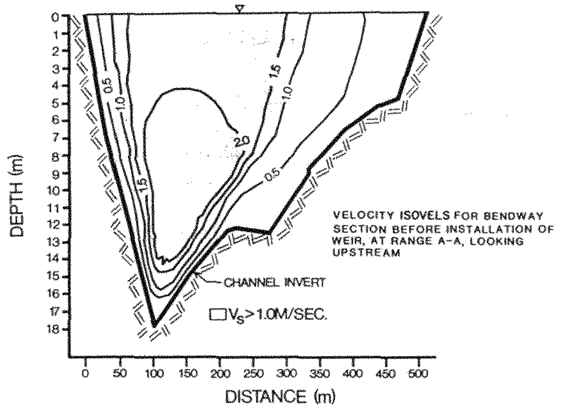


Fig. 29 - Velocity isovels at range A-A, pre-construction

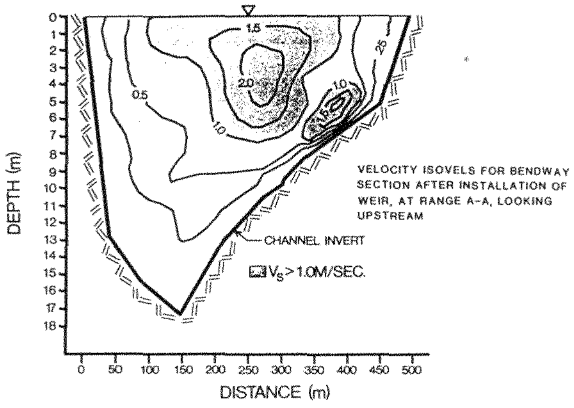


Fig. 30 - Velocity isovels at range A-A, after construction

4. DEPTH INTEGRATED SUSPENDED SEDIMENT SAMPLES

Suspended sediment samples were taken at a bend control section to investigate the sediment characteristics of a typical, unmodified bend (a bend that contained no structures). Fig. 31 is a plot of the sediment concentrations for this unmodified bend section. Fig. 32 is a concentration plot developed from samplings taken at range A-A, downstream of the bendway weir. By comparing these two plots, a definite shift can be seen in the passage of suspended sediments in the bendway weir section. The concentrations extend farther across the section toward the point bar, verifying a shift in flow characteristics toward the middle of the channel.

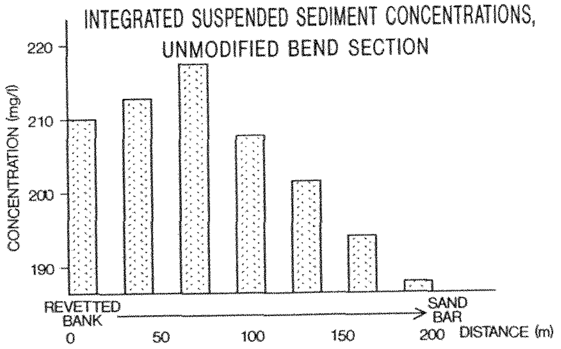


Fig. 31 - Integrated suspended sediment concentrations across unmodified bend section

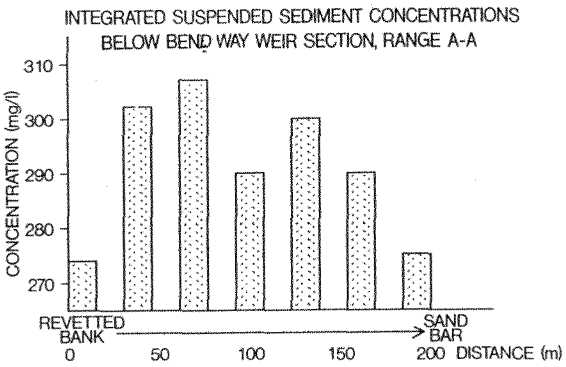


Fig. 32 - Integrated suspended sediment concentrations across bend section just downstream of weir, range A-A

FUTURE CONSTRUCTION AND MODEL TESTS

A contract will be awarded in 1990 to construct an additional 10 bendway weirs throughout Dogtooth Bend. The spacing and construction sequencing will duplicate what was found conclusive in the model. In general, the optimum spacing is approximately 175 meters between each structure. Tests are being conducted to develop a spacing criterion dependent on the radius of curvature of the bend.

CONCLUSIONS

The design and installation of bendway weirs in the Mississippi River is revolutionary. The centrifugal bend forces can now be managed to effectively influence the water and sediments of a bendway, including the downstream crossing. Sediment storage is redistributed in a favorable arrangement for the navigation channel while the natural sinuosity of the river is still maintained.

Construction of the first bendway weir proves that the model test design can be quickly and economically installed in the Mississippi River. If the drift velocities are taken into account, then successful placement of materials can be conducted with acceptable accuracy.

Field verification of model tests has occurred. The first prototype bendway weir has shown desirable velocity and sediment trends.

The long-term benefits from bendway weir design are on a magnitude that can only be evaluated over the course of time. Fuel consumption will be saved by the towing industry, and typical delay times on the open river system will be greatly reduced. Accidents as a result of groundings on point bars will become minimal. Banklines will become further stabilized, and detrimental deflection flow patterns will be minimized. Finally, the goal of maintaining a safe and dependable navigation channel can be advanced on the Mississippi River by the bendway weir concept.

The application of bendway weirs is not limited to bendways. The design may also be used in near straight reaches to realign the thalweg. Scaled-down versions of the structures can be utilized on some of the tributaries and smaller streams throughout the United States and the world abroad.

The aforementioned discussion represents the views of the author and are not necessarily the views of the Corps of Engineers.

REFERENCES

- DEPARTMENT OF THE ARMY, 1989. Hydraulic Design of River Training Structures in Crossings, (Unpublished), Waterways Experiment Station, Vicksburg, Mississippi.
- DEPARTMENT OF THE ARMY, 1989, Dogtooth Bend Movable Bed Model Study, (Unpublished), Waterways Experiment Station, Vicksburg, Mississippi.
- DEPARTMENT OF THE ARMY, 1981, Hec-2 Water Surface Profiles Users Manual, Hydrologic Engineering Center, Davis, California.
- DEPARTMENT OF THE ARMY, TIFFANY, J.B., 1969, State of Knowledge of Channel Stabilization In Major Alluvial Rivers, Committee on Channel Stabilization, Vicksburg, Mississippi.
- DEPARTMENT OF THE ARMY, TIFFANY, J.B., 1963. Review of Research on Channel Stabilization of the Mississippi River 1931-1962, Committee on Channel Stabilization, Vicksburg, Mississippi.
- DAVINROY, R.D., 1986. St. Louis Harbor Study, Missouri and Illinois, Potamological, Hydrologic and Hydraulic Design Memorandum, U.S. Army Corps of Engineers, St. Louis, Missouri.
- DAVINROY, R.D., 1985. Design of Submerged Vanes in a Movable Bed Model, Potamology Study (S-12), U.S. Army Corps of Engineers, St. Louis, Missouri.
- ODGAARD, A.J., and KENNEDY, J.F., 1982. Analysis of Sacramento River Bend Flows, and Development of a New Method for Bank Protection, IIHR Report No. 241, Iowa Institute of Hydraulic Research, The University of Iowa, Iowa City, Iowa.

ACKNOWLEDGEMENTS

Without the progressive attitudes and positive enthusiasm of the St. Louis District Corps of Engineers, the concept and construction of the bendway weir would not have been possible, and this article could not have been written. Acknowledgement goes to the management staff, including Colonel James E. Corbin, District Engineer, Mr. Jack R. Niemi, Deputy District Engineer for Project Management, Mr. Art Johnson, Chief, Engineering Division, Mr. James T. Lovelace, Chief, Hydrologic and Hydraulics Branch, and Mr. Claude N. Strauser, Chief, Potamology Section.

Recognition is also given to Mr. Tom Pokrefke, Mr. Dave Derrick, Mr. James Crutchfield, and Mr. Rusty Henderson, all of the Waterways Experiment Station, Hydraulics Laboratory, Vicksburg, Mississippi, for their superior work and insights given during the conduction of the movable bed model tests. Their research abilities are unsurpassed.

Acknowledgement is given to the people who made the field monitoring possible, including Mr. Carl Okenfuss, Mr. Dave O'Connell, Mr. Fred McLard, Mr. Roger Myhre, and Mr. Robert Mesko, all of the Engineering Division, and the men on board the M.V. Pathfinder.

The design and construction was not possible without the help of Mr. Steve Redington and Mr. Kenneth Anderson, of the Engineering Division, and Mr. William Busch, Mr. John Zimmerman, and Mr. David Mueller of the Construction Division.

Special thanks goes to Mr. Jack Rhodes, Mr. Russel Elliott, Mr. Ron Bockhorst, Mr. James Reed and Mr. Calvin Mooney for their outstanding support with the illustrations used in this article.

Finally, appreciation goes out to the contractors who cooperated and gave quality work, including Mr. Ray Armstrong of Kenneth Balk and Associates, Dr. Glendon T. Stevens of the University of Missouri at Rolla, Mr. Jay Youngman of J.T. Blankenship Engineers, Ms. Patricia C. Elliot of Kinetic Corporation, Mrs. Liz Anderson of The Enterprise-Courier, Inc., and the construction crew of Luhr Bros., Inc.