TECHNICAL PAPER

OPTIMAL DESIGN CRITERIA OF BENDWAY WEIRS FROM NUMERICAL SIMULATIONS AND PHYSICAL MODEL STUDIES

BY:

Pierre Y. Julien and Josh R. Duncan

DATE:

March 17, 2003

Colorado State University
Civil Engineering

TABLE OF CONTENTS

INTRODUCTION

The objective of this study is to provide a synthesis of the pertinent design criteria for submerged bendway weirs. The technical paper is an extension of previous research conducted by the National Center for Computational Hydroscience and Engineering (NCCHE) at the University of Mississippi on the hydrodynamic effects on flow characteristics and effectiveness of submerged bendway weirs for improving navigation in navigable waterways. This article provides the following:

- Background information on bendway weirs in alluvial river systems;
- NCCHE numerical simulations of channel flow with submerged bendway weirs and prototype studies at Victoria Bend on the Mississippi River;
- NCCHE numerical simulations of submerged weirs and comparisons with physical model data;
- Analysis of design criteria developed from the numerical models, laboratory model tests and prototype model tests. Design parameters include weir height and length, orientation angle, weir spacing, weir side-slope, weir roughness; and
- Determination of first generation design criteria for bendway weirs.

CHARACTERISTICS OF BENDWAY WEIRS

Bendway weirs are submerged linear rock structures, permeable or impermeable, usually positioned in series near the thalweg of river bends. Bendway weirs are different from spur dikes, jetties, or groins, and were developed for the improvement of navigable waterways.

Bendway weirs typically reduce the magnitude of secondary flows in channel bends. This effect enhances navigation, alleviates bend migration, and reduces bank erosion. To optimize the benefits of bendway weirs, several structures are normally placed in series along the river thalweg near the concave bank. Resistance of the weir establishes a high-pressure zone in front of the weir near the center of the weir, while a low pressure develops behind the weir, near the tip. These zones redirect the high-energy flow away from the concave bank while creating a low-velocity recirculation zone, or eddy pool. Since bendway weirs are positioned normal to the downstream direction, the flow streamlines redirect toward the center of the channel minimizing bank erosion and assisting in navigation. Figure 2.1 illustrates the flow near a submerged weir.

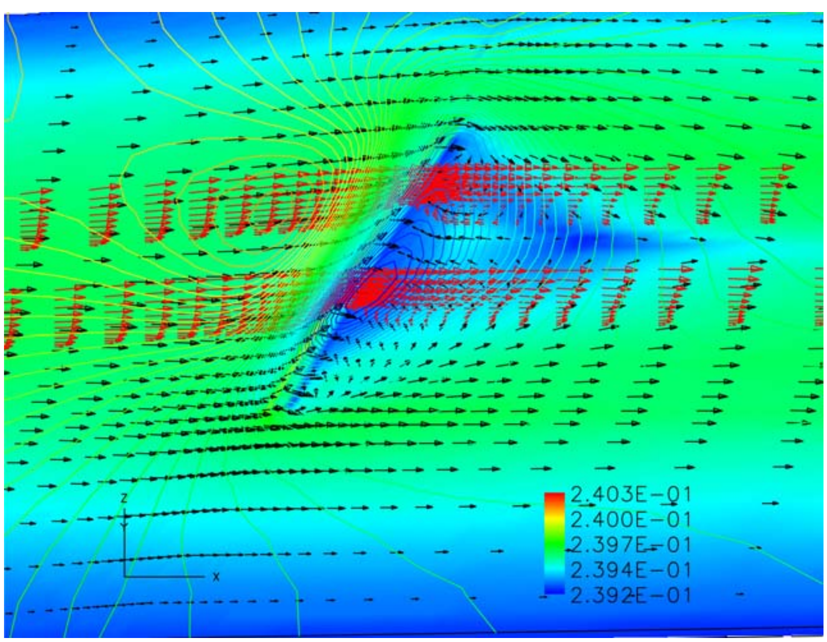

FIGURE 2.1: Oblique View of Flow around a Submerged Weir (Jia et al. 2002)

A submerged weir also suppresses the flow near the center of the weir due to the high-pressure zone. Due to the suppression of flow, the flow accelerates over the weir and decelerates downstream. Further downstream of the weir, the influences of the weir decrease causing the flow to gradually recover downstream.

A submerged weir also alters the secondary current by creating two counter direction zones. The pattern and strength of these secondary currents varies with flow conditions but the intensity of secondary current induced by the weir decreases and then gradually recovers further downstream. The presence of the weir illustrates a positive influence by altering the normally strong and persistent secondary currents by breaking this current into two divisions.

Properly designed bendway weirs have substantial benefits for navigation and alluvial systems. Derrick (1998) stated after monitoring several bendway weirs placed in Harland Creek, that

> "A single correctly positioned weir can have advantageous effects out of proportion to what would normally be expected."

Derrick continues to illustrate how an incorrectly designed weir can deteriorate the system it is trying to improve.

Design criteria of bendway weirs are few, if any exists. To develop successful criteria, the parameters that can drastically affect the design and efficiency of bendway weirs must be defined and studied. The weir angle, α, is defined as the angle between the weir orientation in the bendway and the axis normal to the direction of flow. The length of the bendway weir, L, is defined from the tip of the weir to where it intersects the slope of the outer bank. Typically, the shape of the weir is defined as an inverted trapezoid; the top of the weir is flat with sloped edges. The bendway weir height is the height of the structure. Figure 2.1 illustrates the plan view and profile view of the bendway weir.

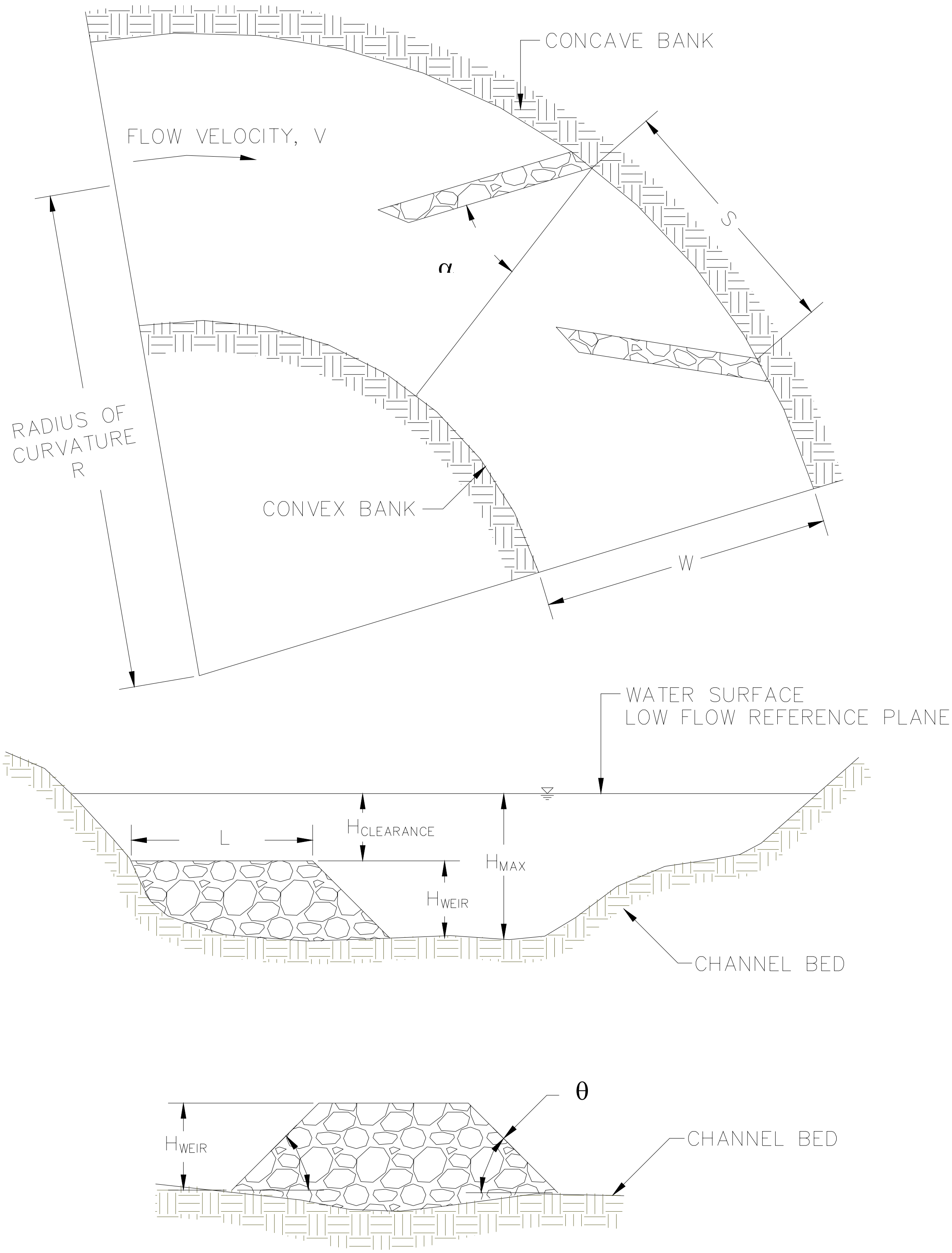

FIGURE 2.2: Plan and Cross-Sectional Views of Bendway Weirs

PROTOTYPE STUDIES AT VICTORIA BEND

3.1 INTRODUCTION

Navigation along the Mississippi River is of vital importance in the United States Army Corps of Engineers. To increase navigation safety and bank stability along the Mississippi River, experimental bendway weirs were placed and tested along some meander bends. Prior to construction and installation of several of these bendway weirs, the application of physical models, numerical studies, and an optimal design criterion of bendway weirs on the flow regime and velocity fields were minimal. Therefore, in the case of this channel reach, the Victoria bendway weir construction deteriorated the ease of navigation and the flow regime in this bend along the Mississippi River and tow pilots complained about navigation difficulties.

Due to the deterioration of navigation within the bend, NCCHE conducted a numerical study of the channel flow with submerged bendway weirs in the Victoria Bendway. This specific channel reach was also chosen for the study due to the sufficient amount of data existing pre- and post-construction of the weirs, such as bed elevation, velocity, and stage measurements. This abundance of data allowed for numerical model validation and verification. From the study, simulation of the flow fields with and without submerged weirs under the same flow conditions was evaluated to determine how and why bendway weirs affect the flow field and navigation.

3.2 LOCATION AND DESCRIPTION OF VICTORIA BEND

Victoria Bend is located along the lower Mississippi River, between Arkansas and Mississippi. The reach is located approximately 958 kilometers upstream of the Head-of-Passes (AHP) in the Gulf of Mexico. Upstream and downstream of Victoria Bend, a cutoff channel of the White River exists. Therefore, the flow through the cutoff bypasses Victoria Bend. Refer to Figure 3.1 for a plan view of the channel reach.

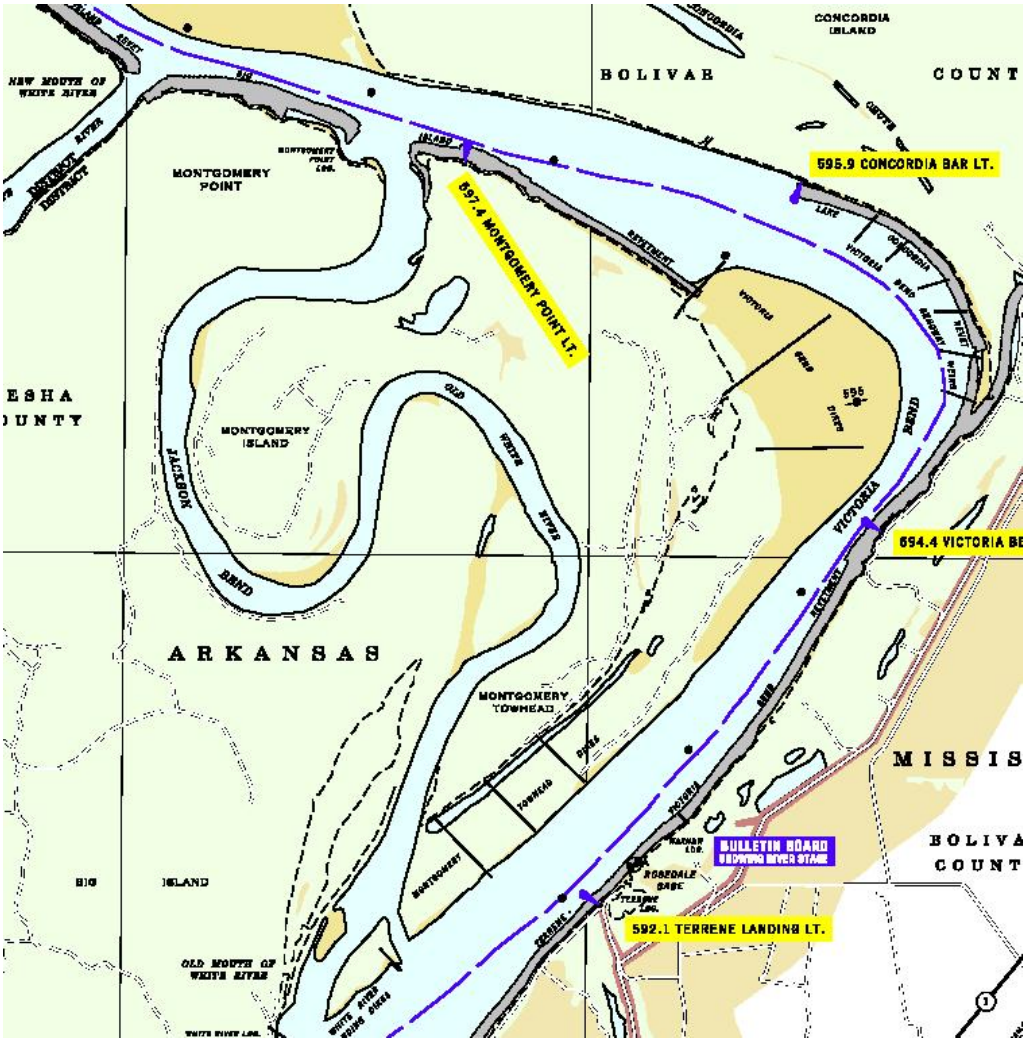

FIGURE 3.1 – Plan View of the Victoria Bend (Jia and Wang, 2000)

Victoria Bend is a sharp meander bend with a radius of curvature of approximately 1280 meters, a ratio of the radius of curvature to the channel width ranging from 1 to 3 depending on the water stage, and a 108° direction change. The centrifugal forces cause the flow toward the concave bank, creating higher velocities on the outer bank and slower velocities on the inner portion of the bank. In addition, the pressure gradient opposing centrifugal acceleration creates a secondary flow in the radial direction. The helical motion decreases as it progresses towards the convex (inner) bank at the bed of the channel, and increases towards the outer bank, closer to the water surface (Federal Highway Administration, 1990). The high stream velocity and helical flow toward the concave bank contributes to outer bank erosion and tends to thrust navigating barges toward the outer bank. In addition, the lower stream velocity toward the convex bank tends to create point bars.

Many hydraulic structures exist along the Victoria Bend. Three long spur dikes were built on the point bar of the Victoria Bend. The desired effect of these dikes is to converge the flow to the main channel and protect the point bar from erosion. In addition, discharge in the main channel would be enhanced for navigation purposes. In 1995, six submerged bendway weirs were constructed along the concave bank oriented upstream with an angle from 69 to 76 degree between the weir and the bend longitudinal line as defined by the Waterway Simulation Technology, Inc. (1999).

Prior to construction of the bendway weirs, surveys indicate bottom depths ranging from approximately 13 to 18 meters. The weir heights constructed in 1995 ranged from 7 to 13 meters, with an average depth of approximately 11 meters above the weirs. Post surveys indicated deposition at the upstream reach of weirs and scouring throughout the remaining weirs, where bed elevations in the scour holes were as low as approximately 3 meters to the original bed level.

3.2 PHYSICAL MODEL OF THE VICTORIA BEND

To analyze the hydrodynamic flow through the Victoria Bend, two-dimensional and three-dimensional numerical models were utilized. This previous study determined which two-dimensional and three-dimensional numerical models were appropriate to conduct the study. The two- and three- dimensional models used for this study were developed at the Center for Computational Hydroscience and Engineering at the University of Mississippi (CCHE2D and

CCHE3D) with funding provided by the Agricultural Research Service. Both the CCHE2D and CCHE3D are finite element hydrodynamic and sediment transport models that have been fully verified and validated in the past.

The CCHE2D model solves the unsteady, depth-integrated horizontal 2D momentum and continuity equations. The purpose of utilizing the CCHE2D model was to calibrate the model, find an appropriate resistance coefficient, and evaluate the flow characteristics throughout the bend. The CCHE3D model solves the unsteady, 3D momentum equations, continuity and free surface kinematic equations. The purpose of utilizing the CCHE3D model was to investigate the near-field flow, such as the transverse helical secondary flow, and the change in flow angle.

The entire channel reach was divided into two segments, a long channel extending from the upstream bend to downstream of the Victoria Bend and a short channel extending of the Victoria Bend. The advantage of the long channel was the simulations of the upstream and downstream boundaries were far away from the Victoria Bend. The disadvantage was the complication of the White River cutoff and higher computation effort. However, the division permitted the CCHE2D model to evaluate the boundary conditions of the entire reach and the resistance coefficient of the long channel at a lower computational cost than the CCHE3D model. This advantage thus ensured the best possible boundary conditions of the short channel at a lower cost in the CCHE3D model. Please refer to Figure 3.2 for the bed elevation and plan view of the long channel and Figure 3.3 for the short channel.

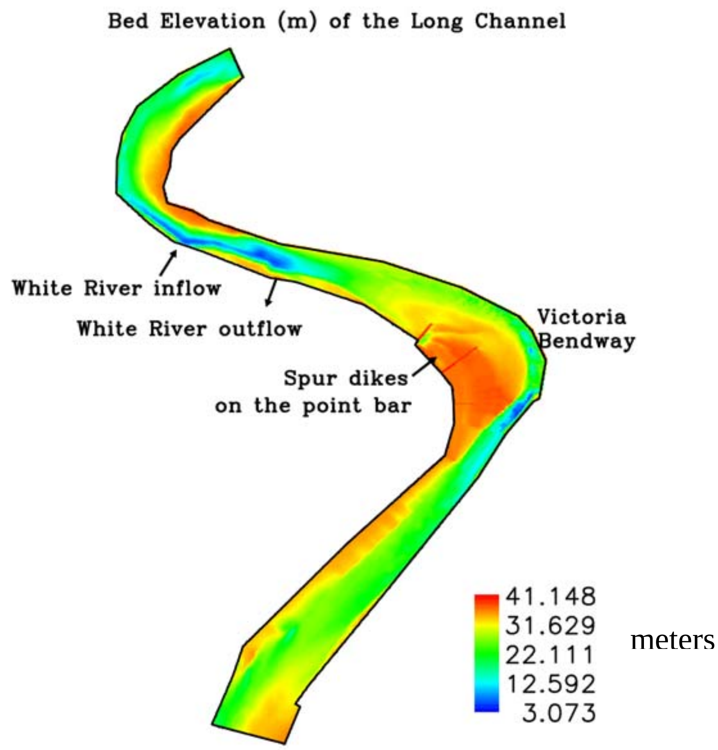

FIGURE 3.2: Plan View and Bed Elevation of the Long Channel (Jia and Wang, 2000)

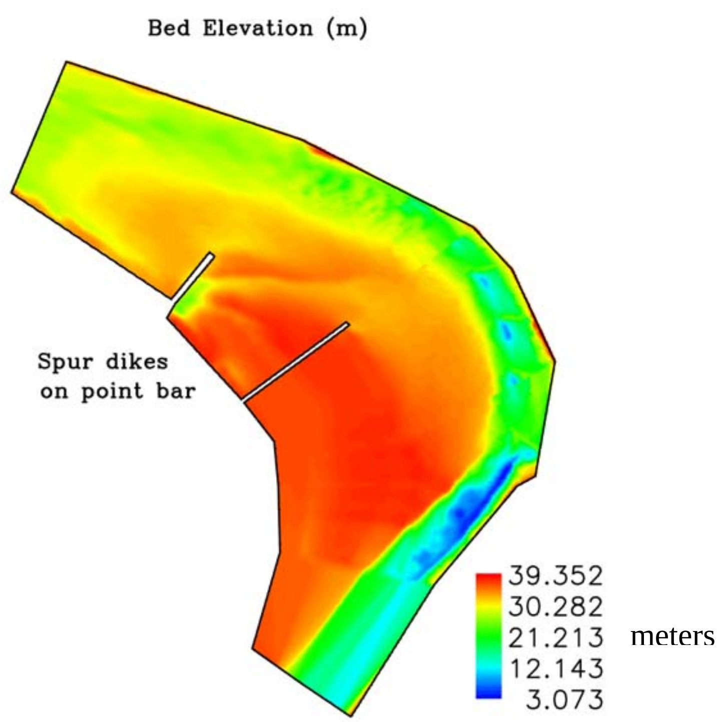

FIGURE 3.3: Plan View and Bed Elevation of the Short Channel (Jia and Wang, 2000)

To examine the effects of the bendway weirs, significant field data was used to validate the model. The data was obtained in June 1998 and included a high-resolution multi-beam sweep survey to define the bendway bathymetry, velocity data from an Acoustic Doppler Current Profile (ADCP), and water surface elevations from six gauges.

3.3 Model Design

The model design consisted of six individual phases. First, the mesh generation for both the long and short channel was created. The second phase was calibration using the CCHE2D model to examine the resistance coefficient, Manning's n, and in order to determine the roughness height equivalent. After calibration, simulations using both the CCHE2D and CCHE3D models were conducted along the channel reach for cases simulating the channel with and without weirs. Next, verification of the model with measured data was used to authenticate the simulation solutions. Finally, since validation occurred, comparison of scenarios with and without weirs was conducted and conclusions were then determined.

The bathymetry data for 1998 was used to generate the long and short channel meshes. The long channel mesh size was 123 (transversal) by 622 (longitudinal). The short channel mesh was obtained from the long channel and was 123 (transversal) by 322 (longitudinal) by 11 (vertical). Note that the long channel was two dimensional for the CCHE2D model and the short channel was three dimensional for the CCHE3D model. These mesh grid adequately defined the weir elevation and geometry as well as to determine the flow patterns.

Before conducting any analysis, a model simulation was conducted on the long channel with weirs using CCHE2D and water surface elevations. The purpose of this simulation was to calibrate the resistance coefficient and thus compute the roughness height equivalent to the calibrated roughness coefficient. The calibration was based on trial and error, and determined the Manning coefficient n = 0.047. This Manning coefficient accounts for bed resistance, however, since the three dimensional model utilizes a wall function as a boundary condition, the roughness coefficient was altered to a roughness height by Strickler's function:

$$n = \frac{d^{1/6}}{A} \tag{3.1}$$

Where: d = equivalent roughness height
n = Manning's Coefficient
A = empirical constant (A = 19 according to Chien and Wan 1999)

Three simulations of the Victoria Bend were conducted: (1) a simulation of the long channel without weirs using CCHE2D; (2) a simulation of the short channel with weirs using CCHE3D; and (3) a simulation of the short channel without weirs using CCHE3D. Approximately 16 kilometer of river channel were modeled with an upstream inflow boundary condition of 12,610 cubic meters per second (m^3/s) and a downstream water surface elevation of approximately 39.6 m NGVD.

To validate the CCHE2D model, the depth-averaged two dimensional velocity predictions were compared with the ADCP depth-averaged velocity measurements. The comparison illustrated sound agreement between the experimental physical data and the numerical solution.

The CCHE3D model was validated with the measured velocity data obtained on June 11, 1998 and June 12, 1998 because the three dimensionality of the flow in the Victoria Bendway was vital to the navigation problem. Locations on top of the weir, behind the weir, and in the weak zone near the bank illustrated very strong secondary flow and the agreement between physical and simulated results were not as good as other locations. A more precise grid that would more accurately estimate the turbulence scheme could enhance the accuracy of these locations. However, over 300 comparison plots were generated to validate both models and overall, the models were in very good agreement with field measured data.

3.4 RESULTS OF BENDWAY WEIRS IN THE VICTORIA BEND USING NUMERICAL SOLUTIONS

After validation and verification of the CCHE2D and CCHE3D models, the effects with and without weirs in the Victoria Bend were also examined.

3.4.1 TWO- DIMENSIONAL MODELING OF BENDWAY WEIRS

To examine the general flow characteristics at Victoria Bend, the depth-averaged flow field was simulated with a discharge of 12,610 m^3/s. Figure 3.4 illustrates the computed velocity field at Victoria Bend using CCHE2D without submerged weirs.

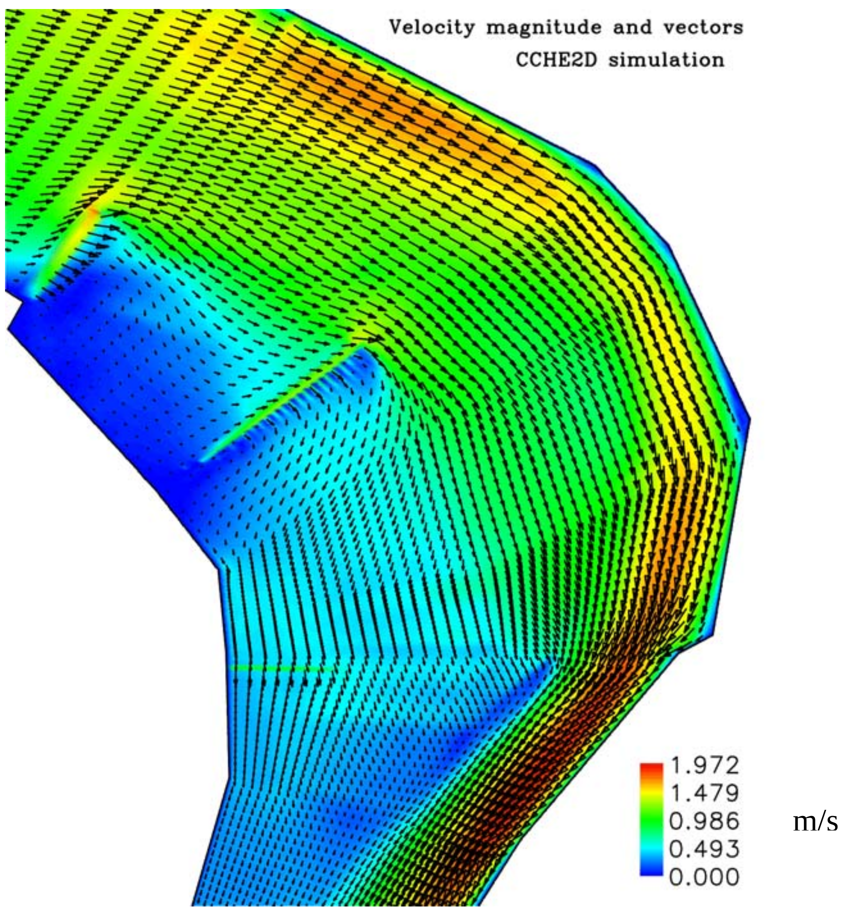

FIGURE 3.4: Flow Field in the Victoria Bend without Bendway Weirs using CCHE2D (Jia and Wang, 2000)

To compare the effects of bendway weirs in two dimensions, flow was simulated with submerged weirs. Figure 3.5 illustrates the flow field in the Victoria Bend with bendway weirs.

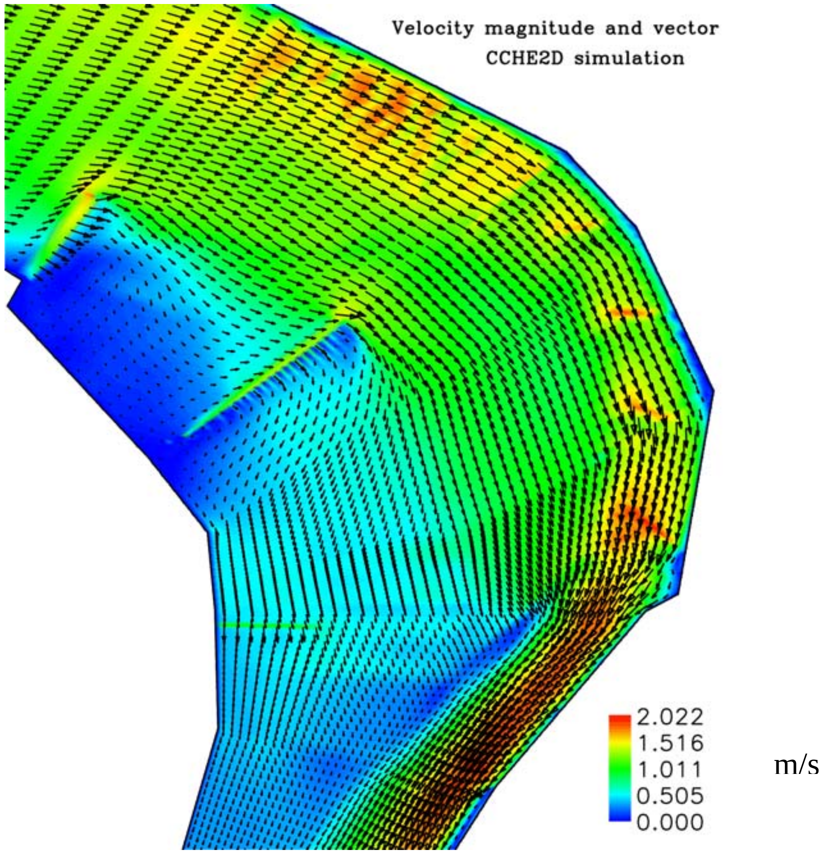

FIGURE 3.5: Flow Field in the Victoria Bend with Bendway Weirs using CCHE2D (Jia and Wang, 2000)

Figure 3.5 illustrates that the bendway weirs cause an acceleration of flow over the weirs due to the restriction of flow, and a deceleration of flow between weirs. In addition, the spur dikes on the point bar direct the convex bank flow toward the center of the channel.

When comparing Figure 3.4 and Figure 3.5, the maximum velocity is approximately the same; however, velocity discrepancies develop between the weirs. The velocity between weirs is lower due to the presence of bendway weirs. In addition, the velocities on top of weirs are higher than without.

3.4.2 Three-Dimensional Modeling of Bendway Weirs

Similar to the two-dimensional analyses, model simulations were performed for Victoria Bend with and without weirs. To effectively evaluate the three-dimensional flow, a 27-section mesh was generated along the main channel, where the longitudinal lines were along the main flow direction and the transverse lines were perpendicular to flow. This allowed for the longitudinal velocity and the secondary flow velocity to be evaluated by projecting the velocity components onto the established mesh lines.

The simulation determined the influence of weirs on the secondary current, or helical flow, the primary flow in the main channel, and the effect on flow direction. Figure 3.6 demonstrates the secondary helical flow in sections 7, 8, and 9 with the presence of weirs (left side of figure) and without (right side of figure). Each section was evaluated in that study but for simplicity, sections 7, 8, and 9 were specifically examined in this study.

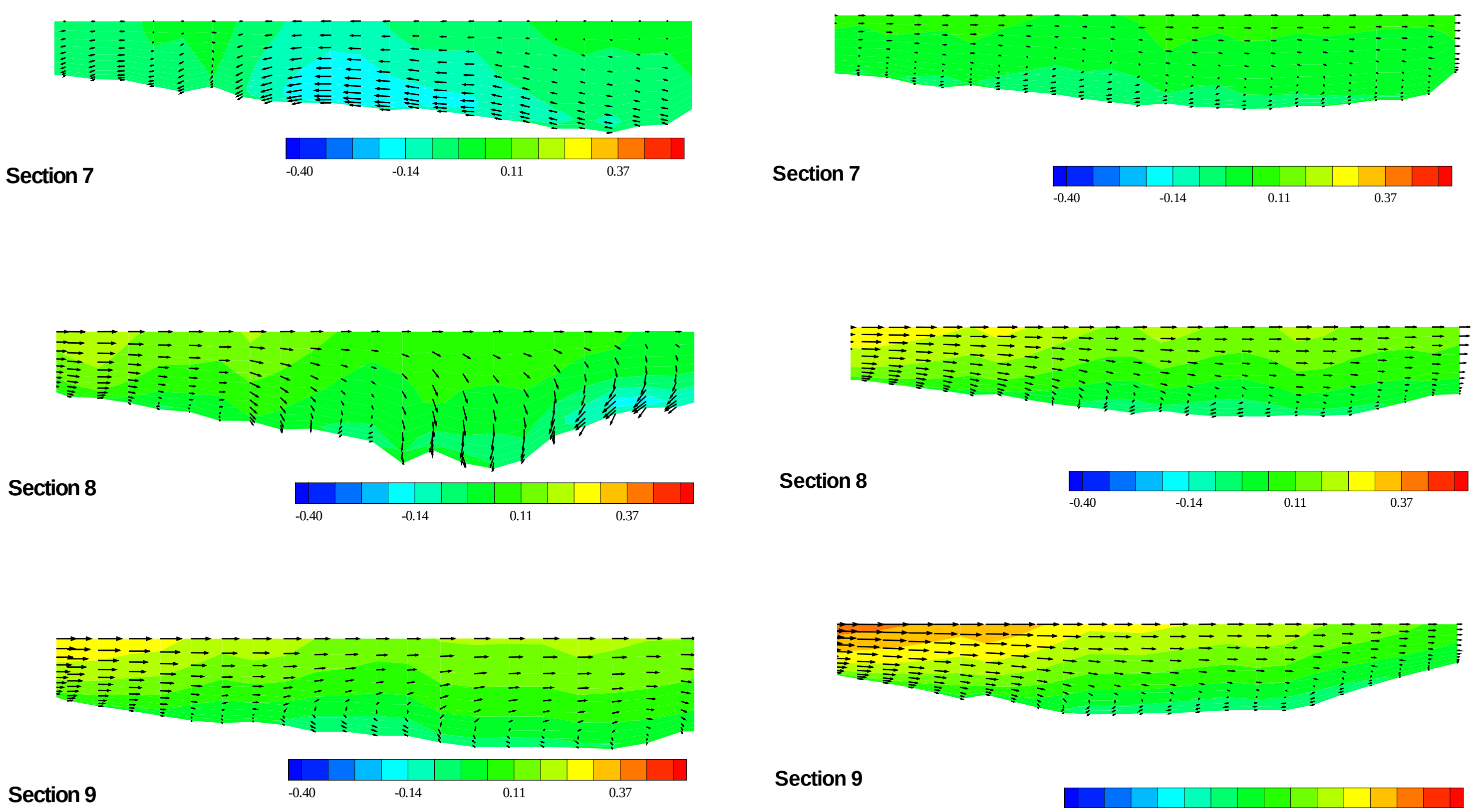

FIGURE 3.6: Secondary Flow in the Victoria Bend with (left side) and without (right side) Bendway Weirs (Jia and Wang, 2000)

As seen in Figure 3.6, the presence of bendway weirs altered the helical current and reduced the magnitude along the length of the weir. The secondary flow field was divided into two cells; flow before and behind the weirs. The surface velocities on top of the weirs illustrated the acceleration and deceleration of flow caused by the weirs. For comparison, the secondary flow patterns were much smoother and consistent without weirs. As a result, the presence of weirs disturbed the existing strong and continual secondary flow without weirs.

The primary flow at Victoria Bend was altered by the presence of bendway weirs. The structure reduced the longitudinal flow velocity due to the constriction of flow in the channel. As previously stated, the flow decelerates between weirs and accelerates as the flow passes over the top of the weir.

The final analysis conducted was the influence of bendway weirs on the flow direction of the free surface. This analysis shows the positive influence of bendway weirs to alter the flow in a direction perpendicular to the downstream weir face and away from the concave bank. The surface flow angle is defined as:

$$\theta = \arctan\left(\frac{u_{transversal}}{u_{longitudinal}}\right) \qquad (3.2)$$

Where: θ = surface flow angle
$u_{transversal}$ = velocity component perpendicular to the main flow direction
$u_{longitudinal}$ = velocity component in the main flow direction

By analyzing the magnitude and duration of the flow angle change, the effectiveness of bendway weirs on improving navigation conditions was quantified. As theta (θ) increases, the surface flow is increasingly deflected towards the concave bank. Three simulations resulted: (1) change in flow angle for the bendway with and without weirs; (2) the change in flow angle at different depths for the bendway with and without weirs; and (3) the change in flow angle for the bendway with weirs with a smooth bed and the existing bed with scour holes.

The change in flow angles is defined by:

$$\Delta\theta = \theta_{with\ weirs} - \theta_{without\ weirs} \tag{3.3}$$

Where: $\Delta\theta$ = change in flow angle
$\theta_{with\ weirs}$ = flow angle with the presence of weirs
$\theta_{without\ weirs}$ = flow angle without weirs

The importance of defining this relationship was to analyze the influence of bendway weirs. Figure 3.7 illustrates the change in flow angle with and without bendway weirs. A positive change in angle (in green) indicates the flow was directed toward the concave bank while a negative angle (in blue) indicates flow towards the convex bank. Therefore, a zone with a negative angle change indicates a favorable zone that promotes navigation.

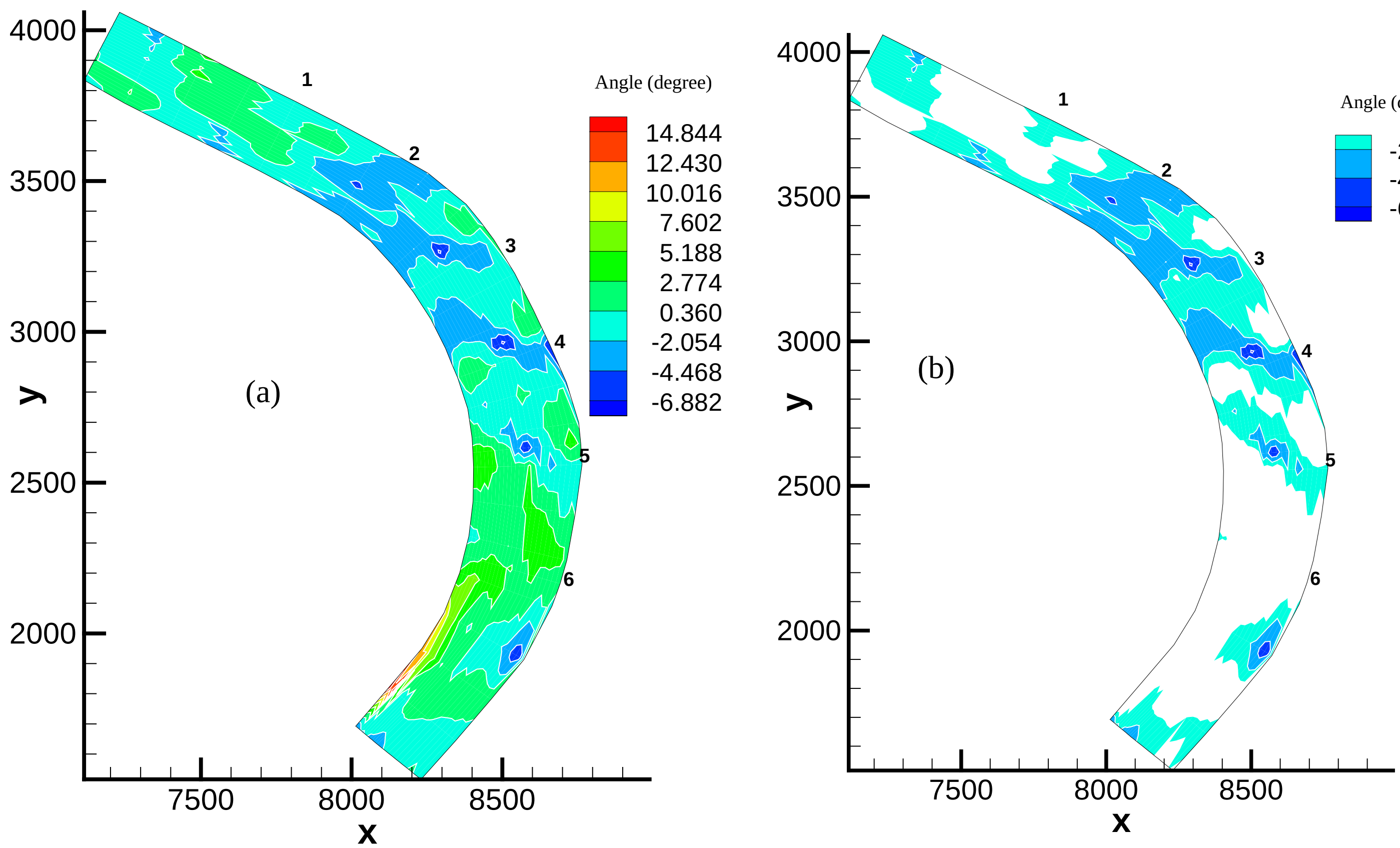

FIGURE 3.7: (a) Change in Flow Angle (Δθ) at Victoria Bend and (b) Areas of Improved Flow Angle (Jia and Wang, 2000)

In addition to Figure 3.7a, Figure 3.7b illustrates the areas with improved flow conditions (negative angle value in blue). In Figure 3.7b, the areas where flow conditions did not improve, in green, were replaced with white color. From Figure 3.7b, over 50% of the total area was improved due to submerged weirs.

The next simulation examined the flow angle at varying flow depths. The results indicate the change in flow angle was relatively constant with depth. The final simulation examined the flow angle with bed change. After installation of the bendway weirs, scour holes developed below each weir. The bed was smoothed in the model and flow angle was compared between the bed elevation with scour holes and the smoothed bed. The results illustrated that the bed changes that occurred after weir construction had minimal effect on the performance of the weirs and flow characteristics in the bend.

3.5 Conclusions of Bendway Weirs at Victoria Bend

Modeling submerged weirs at Victoria Bend revealed several important changes in flow characteristics near submerged weirs. The two-dimensional model, CCHE2D, demonstrated the general flow characteristics through the bendway. The model also permitted validation and verification with physical field data.

The three-dimensional model, CCHE3D, illustrated the primary flow velocities in the main channel with acceleration over the weirs and deceleration between them. The primary flow with weirs was generally lower than without weirs and varied gradually along the channel. The model results also demonstrated that submerged weirs divide the secondary helical flow into two cells; flow before the weirs and after the weir. The magnitude of the helical flow was reduced and the weirs disturbed the existing strong and continual secondary flow without weirs. Submerged weirs improved the flow realignment in the bendway by reducing the flow angle from the concave bank and altering the main flow in an improved direction for navigation. The flow realignment was relatively constant with depth. Finally, the model indicated that scour and bed deposition that occurred after construction had minimal effects on the efficiency of weirs to improve flow realignment.

BACKGROUND OF PHYSICAL MODEL TESTS AND NUMERICAL ANALYSIS

4.1 INTRODUCTION

A physical model analysis was conducted to further examine the influence of submerged weirs on bendway hydrodynamics. The objective was to thoroughly examine the relationship of flow characteristics with submerged weir geometry and channel geometry. The study was a continuation of the previous numerical study of six submerged weirs in the Victoria Bendway, Mississippi River. Similar to the previous investigation, a three-dimensional numerical model for free surface turbulent flows, CCHE3D, was utilized to examine the flow characteristics of both single and multiple weirs in experimental and prototype bendway channels with varying properties. Both field and physical model data were used for validation of the numerical model and to evaluate the numerical model with the physical model.

4.2 PHYSICAL MODEL

The physical model experiments for investigating the hydrodynamic effects of submerged weirs on river bends for navigation were conducted at the Waterways Experiment Station, US Army Corps of Engineers in Vicksburg, Mississippi. The physical model consisted of two meander bends, with a radius of curvature (R) of approximately 15.24 meters and uniform sand grain size (d_{50}) of 0.1 millimeters. Four steady flow conditions were used in the investigation, two mean flow velocities and two water stage depths.

4.3 MODEL DESIGN

To thoroughly analyze the effects of submerged weirs on the flow resulting in the development of an optimum design, several simulations with varying weir properties were investigated. The effects of submerged weirs on the flow field depend primarily on the flow angle, α (defined perpendicular to thalweg), length and height of the submerged weir. The shape of the submerged weir was defined as an inverted trapezoid; therefore, the top surface of the weir was flat and horizontal. For the analysis under the four steady flow conditions, the angles and lengths of the weirs studied were:

α = 0°, 10°, 20°, 30°, 40°, and 50°;

L = 1 m, 1.4 m, and 1.8 m.

The height of the submerged weir varied with respect to depth due to the variation of the flow conditions studied. Please refer to Section 2.0 for the definitions of the orientation of the weir angle and length of the weir. Utilizing the three weir lengths and six different orientations, a total of sixty three-dimensional simulations were conducted.

Similar to the previous investigation on the Victoria Bend, the study utilized both the CCHE2D and CCHE3D numerical models to simulate flow throughout the bend. As previously stated, the CCHE2D model solves the unsteady, depth-integrated horizontal 2D momentum and continuity equations. The purpose of utilizing the CCHE2D model was to determine the effective bed roughness for numerical simulations through calibration because the physical model bed was not perfectly smooth. The CCHE2D model not only accounts for bed surface resistance but also for bed form and curvature induced resistance. Since four different flow conditions were utilized, flow depth calibrations must be made for each study and resulted within a range from 2 to 8 mm.

A mesh capable of adequately examining the changes near the submerged weir must be utilized and developed. Therefore, the mesh generator, CCHE-MESH, was utilized to generate the computational meshes for the study. To examine the sensitivity of the mesh required to fully examine the hydrodynamic flow changes, a sensitivity test was applied using 20° angle long (1.8 m) weir.

The purpose of utilizing the CCHE3D model was to investigate the near-field and the change in flow angle. To increase the three-dimensional effectiveness, the channel under investigation was shortened to the first bendway. Figure 4.1 illustrates the two-dimensional and three-dimensional areas described above.

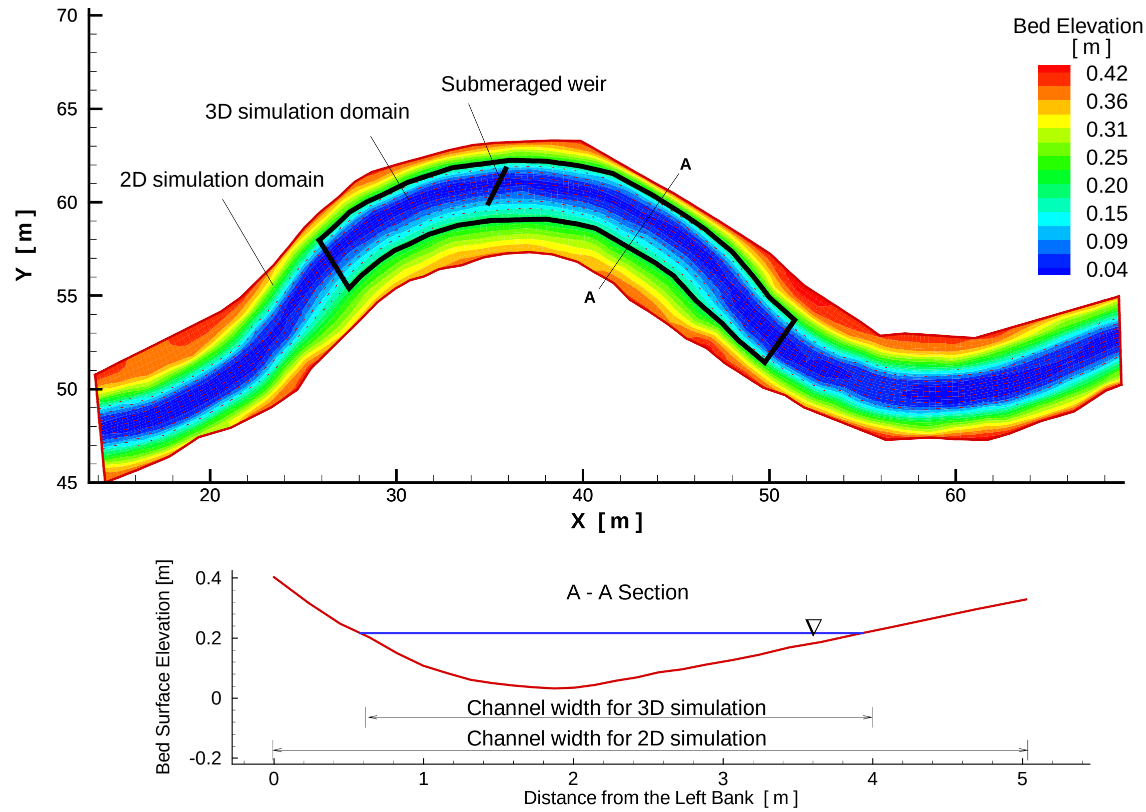

FIGURE 4.1: Plan View and Bed Elevation of the Experiment Channel (Jia et al., 2002)

Due to the comprehensive analysis needed for the changing angles and lengths of weirs, the mesh was configured to an appropriate level to analyze the affects on the flow. This resulted in fifty meshes being generated. The unit discharge and flow direction at the inlet were then interpolated to the new mesh to establish the same distributions for all simulations of the same flow condition.

4.4 Results of One Submerged Weir on Flow Characteristics

Similar to the previous study conducted on the Victoria Bend, the change in surface flow angle was analyzed to determine the positive influences of submerged weirs. As previously demonstrated, the surface flow angle was positively influenced by the submerged bendway weir, nonetheless, the magnitude and total area of favorable influence changed with varying parameters. Figure 4.2 illustrates the flow direction change at the surface with varying orientation and weir length, where a negative change in the surface angle means an improved angle for navigation. The figure illustrates that a longer weir and larger orientation angle establishes a wider and longer area of positive influence.

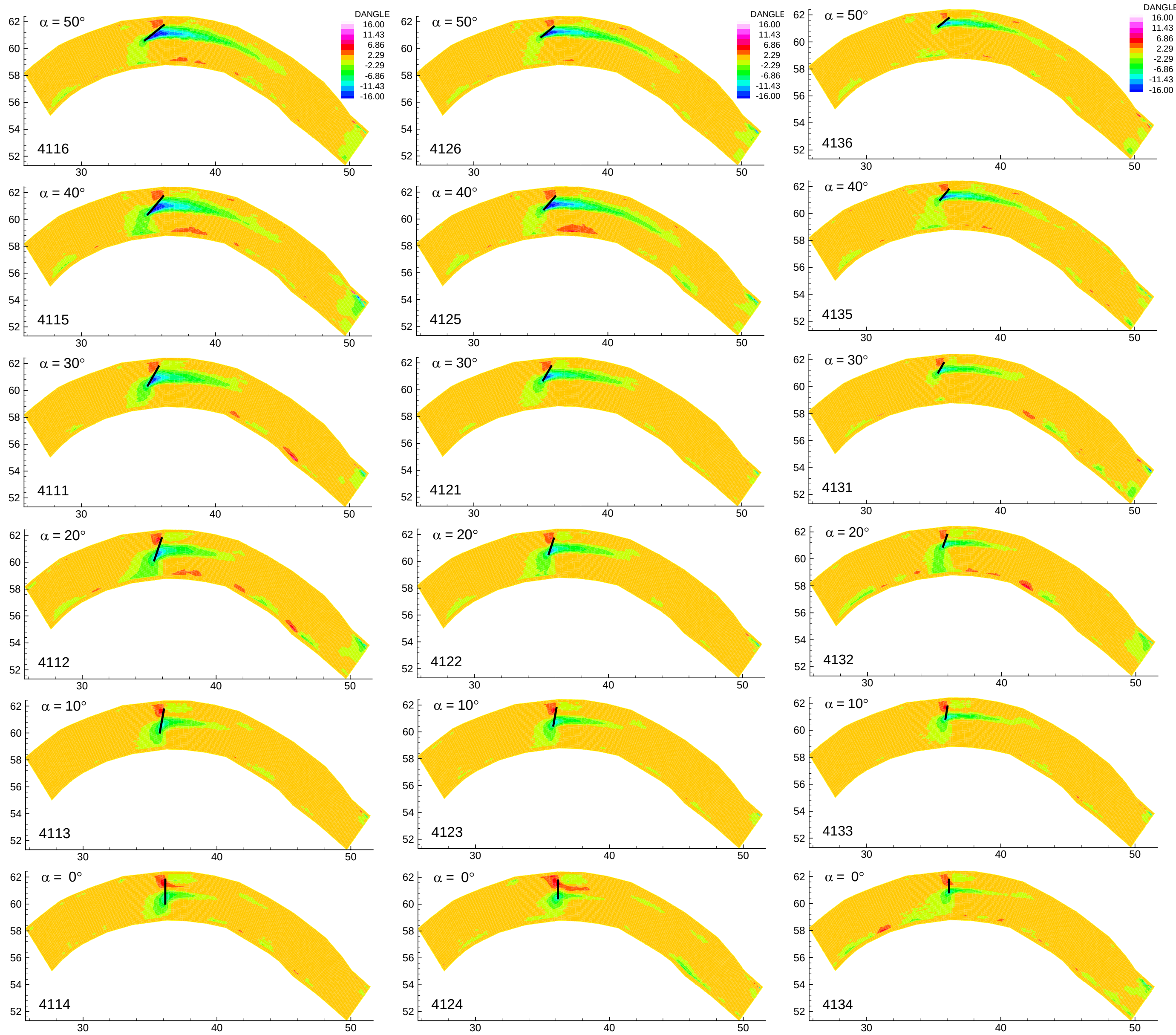

FIGURE 4.2: Flow Direction Change Based on Varying Weir Length and Weir Orientation (Jia et al., 2002)

Since several flow conditions with varying parameters of length, height and the weir angle, comparisons of the affect of submerged weirs on flow was determined. To establish the correlation of design parameters, the following objective function was proposed:

$$I = \sum_i |\Delta\theta| A_e \qquad (4.1)$$

Where: I = global measure of weir effectiveness representing not only the total area of favorable flow angle change but also the magnitude of the change in flow angle
$\Delta\theta$ = change in surface area at the center of the element
A_e = area of the element
i = element

From equation 4.1, a higher value of *I* would represent a higher improved navigation condition. Several comparisons were established and in all cases, *I* increased when α (weir orientation) was less than 40° and *I* decreased when α was greater than 40°. As a result, the effectiveness of submerged weirs to improve navigability reached the maximum near an upstream orientation angle of 40°.

In addition to examining the orientation angle, comparisons of *I* as a function of the weir length and height were conducted. The results indicated that the height of the weir has limited effect on the width of improved area. However, the weir height drastically affects the surface angle. As the weir height is reduced (the clearance depth above the weir increases), a significant decrease in the surface flow angle occurs and the area of improvement is drastically reduced. This is illustrated in Figure 4.3, which illustrates the effectiveness of the submerged weir as a function of the clearance height, H_c, over the total depth, H_{max} (a smaller ratio of H_c/H_{max} indicates a higher weir height).

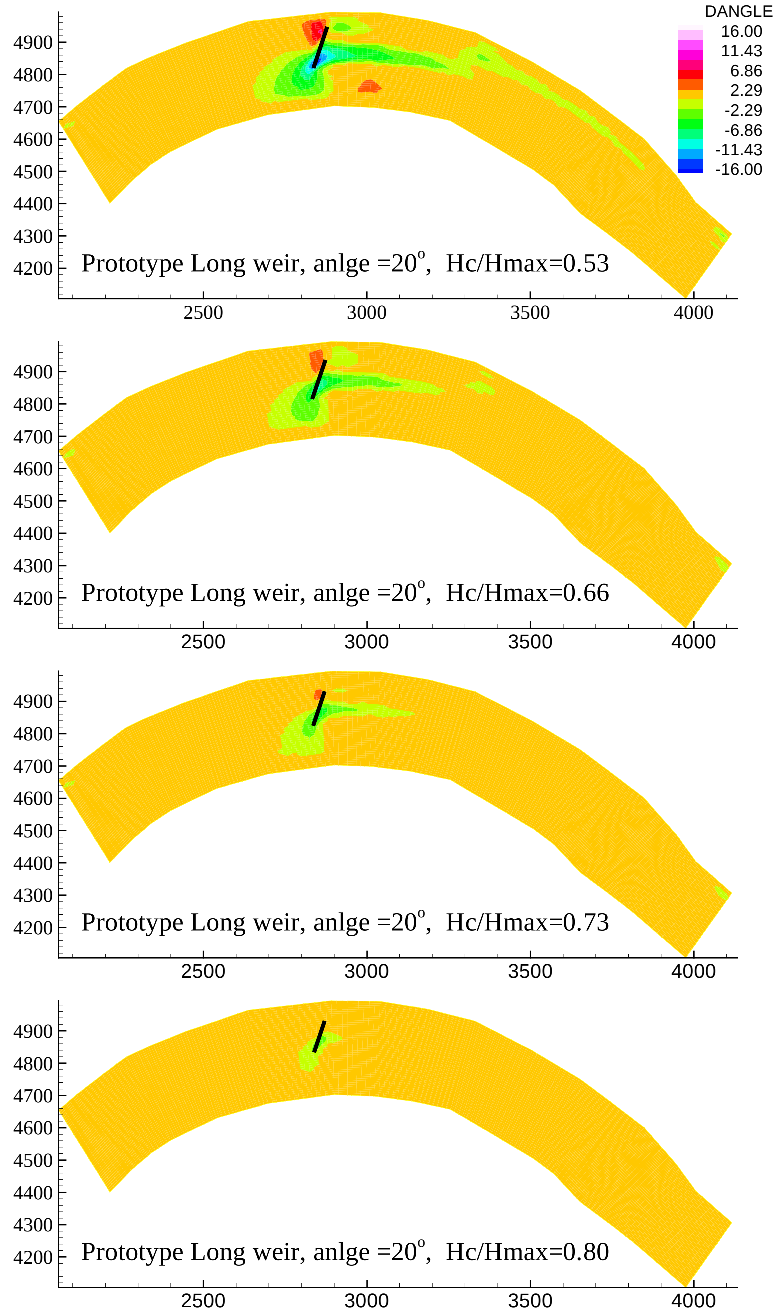

FIGURE 4.3: Variation of Effectiveness of the Submerged Weir as a Function of the Weir Height (Jia et al., 2002)

In addition to the weir height, the effectiveness of the weir length was examined. The results indicated that the longer the weir, the more effective it was at producing an area of improvement. As the length increased, the area of improved surface angle was longer and wider.

It should be noted that an increase or decrease in the effectiveness of the weir is due both to the weir height and length.

The study also examined the effects of the radius of curvature on the objective function. By examining various radii of curvature with a fixed length and orientation, the total improved area created by the submerged weir was examined. As seen in Figure 4.4, the results illustrated that the total effectiveness does not change significantly except for very strong curvature. The maximum angle change increases with channel curvature indicating significant angle realignment near the weir. The length of the realignment zone decreased due to the secondary current is weaker for smaller bends.

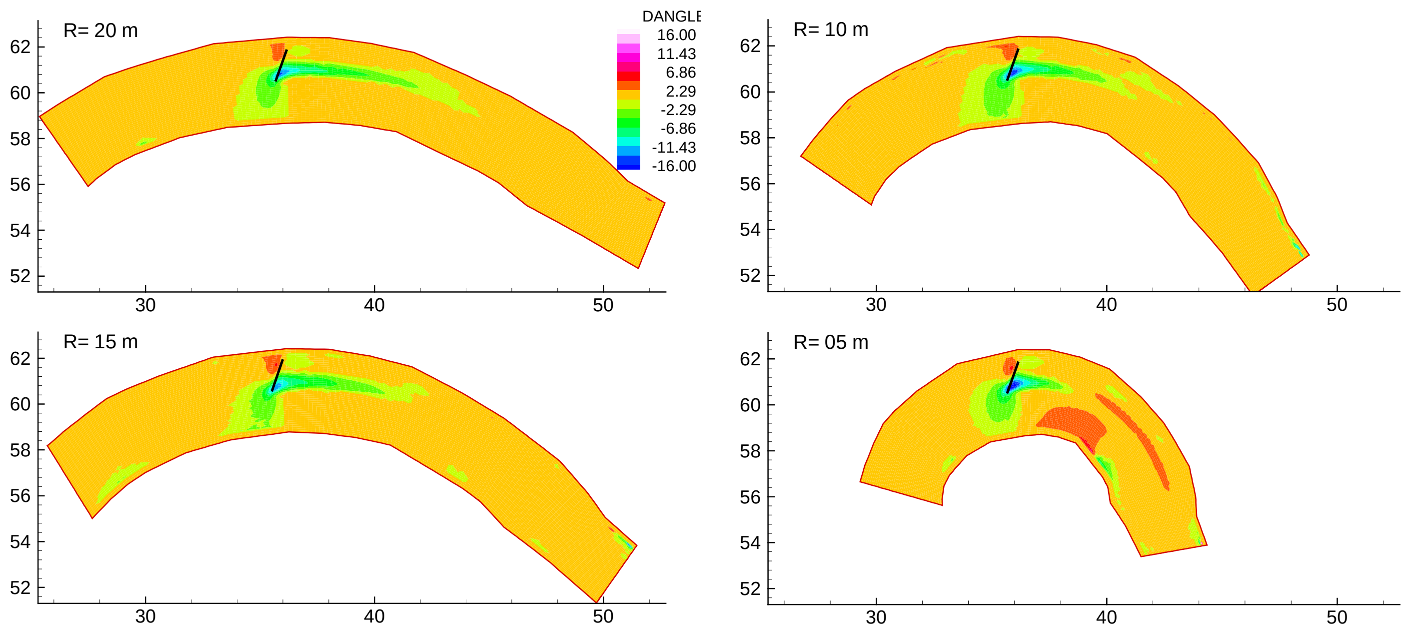

FIGURE 4.4: Flow Angle Change with Varying Curvature (Jia et al., 2002)

The front and back slopes also affect the performance of a submerged weir according to the study. Examining the objective function with two different slopes demonstrated that a larger weir slope established a more vertical flow and higher pressure to separate the approaching flow. As a result, a higher resistance was established forcing more flow around the weir tip. Therefore, an increase in the favorable realignment area is larger for higher side slopes.

Finally, the study analyzed the effects of weir roughness on the flow. The influence of the weirs roughness is not significant to realigning the flow because the structure itself produces the significant resistance to the flow. The structure produces significant form drag; however, the friction drag caused by the bendway weir roughness is minor.

4.5 Results of Multiple Submerged Weirs on Flow Characteristics

To simulate the effects of multiple weirs on flow characteristics, a median weir length was used with varying spacing of two, three, and four times the length. Similar to the single weir study, the objective function was utilized to compare the results.

First, an investigation of multiple weirs with a spacing of two times the length was conducted. The results illustrated how the angle change developed by each individual weir in the system was similar to that of a single weir simulation. However, by utilizing the multiple weirs, the favorable zone produced by each individual weir was continuous throughout the entire bend due to each weirs influence. Therefore, by placing multiple weirs in a river bend, the zone for favorable navigation continues throughout the bend due to the reinforcement of downstream weirs. This is illustrated in Figure 4.5 below.

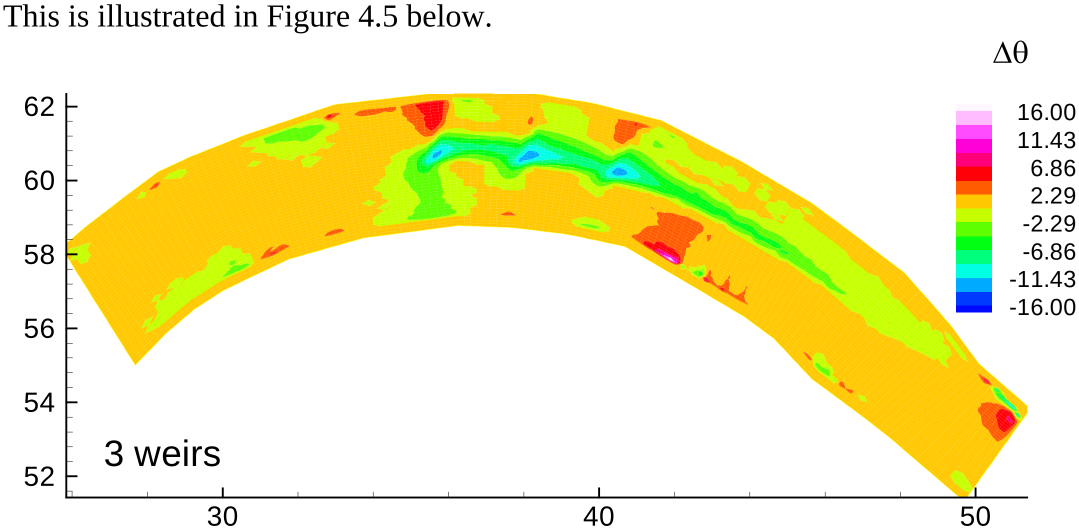

FIGURE 4.5: Distribution of Flow Direction Created by Three Weirs (Jia et al., 2002)

Analyzing the effects of the varied weir spacing along the reach properly determined an effective spacing of weirs. By varying the spacing two, three, and four times the length and examining the objective function, the results illustrated that when weirs were close, the favorable zones were connected. This was due to the reinforcement of the downstream weir before the favorable zone decayed. With a greater spacing, the width of the favorable zone diminishes prior to the downstream weir. Therefore, the total improved zone for navigation would be longer and wider if more weirs are installed. This is illustrated in Figure 4.6, which illustrates the total effectiveness increases with the number and length of weirs.

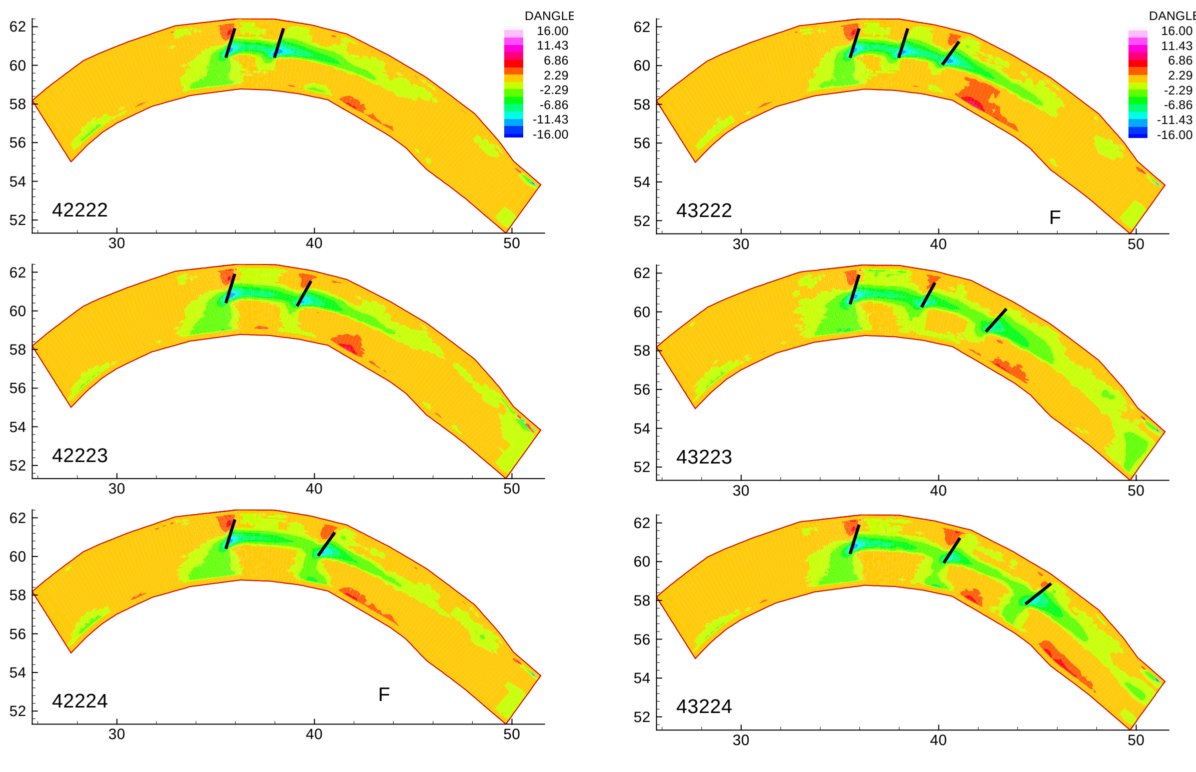

FIGURE 4.6: Flow Angle Change for Varying Weir Spacing (Jia et al., 2002)

4.6 Conclusion

An in-depth investigation of the optimum parameters of submerged weirs was conducted by the NCCHE. Analysis of single weir and multiple weirs on a channel reach were modeled with CCHE3D. To establish the optimum parameters of weirs, the study utilized varying weir length and orientation for four flow conditions. From the study, a significant correlation of varying weir parameters and the effectiveness of those parameters on the flow were established with an objective function.

The surface flow realignment from the outer bank to the inner bank is favorable for navigation improvements. In general, longer weirs and larger weir angles establish a better flow realignment. The optimum angle was established around a weir angled 40° upstream. As the flow depth over the weir increased, the weir effectiveness decreased. Flow realignment increased with the side slope of bendway weirs. In addition, the study indicated that the weir surface roughness does not appear to significantly influence flow realignment. Finally, a closer spacing of 2 to 3 times the weir length for high curvature bends produces an increase in the area of favorable flow realignment.

OPTIMUM DESIGN CRITERIA

5.1 INTRODUCTION

The development of optimum design criteria of bendway weirs is vital to improve navigation and maintain bank stabilization in river bendways. Based on the numerical and physical models and prototype validation, a first generation of bendway weir design criteria for navigation is proposed. The parameters that influence functional bendway weirs include: the bendway weir angle, length, height, spacing, radius of curvature, weir side slope and roughness.

5.2 WEIR ANGLE

The weir angle drastically influences the effectiveness of bendway weirs. Bendway weirs generally realign the flow normal to the orientation weir. Therefore, for the realigned flow to be favorable for navigation and bank stabilization, a bendway weir must be oriented *upstream* to redirect flow from the concave (outer) bank to the convex (inner) bank. If bendway weirs are oriented downstream, they can redirect flow toward the outer bank damaging bank stability and creating adverse navigational flows. In addition, a bendway weir angle at 0°, or perpendicular to the flow, would create an adverse flow pattern on the surface.

A bendway weir most importantly affects the surface flow. The angle of the weir drastically influences the total area of the favorable zone behind the weir. As illustrated from the previous work conducted, a weir angle of 40° has the largest favorable zone. Angles greater than or less than 40° indicates that weir effectiveness for flow realignment is reduced.

The effectiveness of the weir angle is optimal around 40° as shown in Figure 4.2. At 40°, a bendway weir efficiently alters the surface flow for a maximum favorable zone for navigation while encouraging bank stabilization.

5.3 Weir Length

The weir length is a vital parameter that determines the effectiveness of a submerged weir on flow. In general, the longer the weir length, the more effective the weir is at producing a longer and wider zone of improved flow around a bend. The length of the weir should be dependent on the channel geometry and determined on a case-by-case basis.

5.4 Weir Height

Weir height can drastically influence the effectiveness of a submerged weir. A properly designed weir height can drastically reduce the magnitude and persistent secondary helical current, which hinders navigation in bends. However, the weir influence to the secondary helical current is reduced as the depth over the weir increases. In addition, the height of the weir has limited effect on the width of improved surface flow realignment behind the weir. As depth increases, the influence of the weir decreases; as a result, the area of improved flow angle realignment is also significantly reduced. Bendway weirs are more effective at low flows than during floods. Therefore, the weir height must be evaluated according to a depth in the channel where the water depth above the weir is adequate for navigation and the weir heights influence is a maximum.

A sufficient clearance of water depth above the weir is necessary for navigation. Selecting the appropriate low flow reference plane of the channel is vital when determining the height of the weir. If the design stage of the river is determined incorrectly, the height of the weir may be ineffective or inadequate to allow navigation if the depth is to low. Designing the height of the weir should be dependent on the ratio of the depth clearance above the weir and the total depth of the channel. As the ratio decreases, the influence of the weir on the flow increases. Careful consideration into determining the appropriate channel depth is critical for optimizing the weir heights influence on the flow while inhibiting a clearance depth suitable for navigation.

5.5 Weir Spacing

Multiple weirs are more effective for improving flow through a bend than one weir. As previously stated, a favorable zone is established downstream of a weir. However, the strength of the favorable zone diminishes downstream behind a weir. By placing multiple weirs in a series, the decrease in the favorable flow direction can be maintained and the total positive zone will be longer and wider. Furthermore, with multiple weirs the favorable flow direction established by an individual weir is coupled and extends throughout the entire bend. In addition, an increase can also be attributed to the resistance of the weirs on the central flow.

Proper spacing of multiple weirs is essential to optimize the favorable zone developed behind a weir. A spacing of 2L (two times the length of the weir) and 3L (three times the length of the weir) permits the favorable zone to be consistent from one weir to the next downstream weir. If spacing is greater than 4L (four times the length of the weir), an indication of decay of the favorable zone between weirs develops and the width of becomes narrower.

5.6 Radius of Curvature

The radius of curvature of a bend influences the area of favorable flow realignment. As channel curvature increases, the flow angle change increases and becomes more confined closest to the weir. Consequently, the area of favorable flow realignment decreases. Therefore, with high curvature channel bends, closer spacing of multiple weirs is needed.

5.7 WEIR SIDE-SLOPE

In construction of bendway weirs, the front and back side slopes should be placed at the submerged repose angle for the riprap rocks used to build the weir. Higher local pressure and more vertical flow to divide the approach flow develop with a larger weir side slope. This establishes a higher resistance and forces more flow to move around the weir tip. As a result, the flow angle change is stronger and a larger realignment zone is present for higher side slopes. Therefore, by maximizing the side slope angle to the submerged repose angle promotes a more effective bendway weir.

5.8 WEIR ROUGHNESS

The weir roughness does not influence the flow at the surface significantly. Submerged weirs are typically built by large riprap that possesses a large roughness coefficient. The sizes of roughness elements in the structure of a weir are negligible compared to the size of the weir, which is the largest obstacle in the flow. Therefore, the roughness element of the submerged weir is secondary compared to the weir size, scales, and position.

5.9 CONCLUSION OF OPTIMUM DESIGN PARAMETERS

The purposed design for bendway weirs are summarized in Table 5.1. In Figure 5.1 is a visual representation of the plan view and cross-sectional profile of the design criteria is illustrated.

PARAMETER	CRITERIA
Angle, α	Oriented 40^o upstream of perpendicular to flow
Length, L	Longer weirs are better
Height, H_c	Maximum influence on flow that permits navigation based on a low flow reference plane
Spacing, S	2 - 3 L
Radius of Curvature, R	Closer spacings for higher degree of curvature
Side - Slope, θ	Angle of Repose of material, $\theta = \phi$
Roughness, k_s	Material roughness has minimal effects

TABLE 5.1: Summary of Optimum Design Criteria

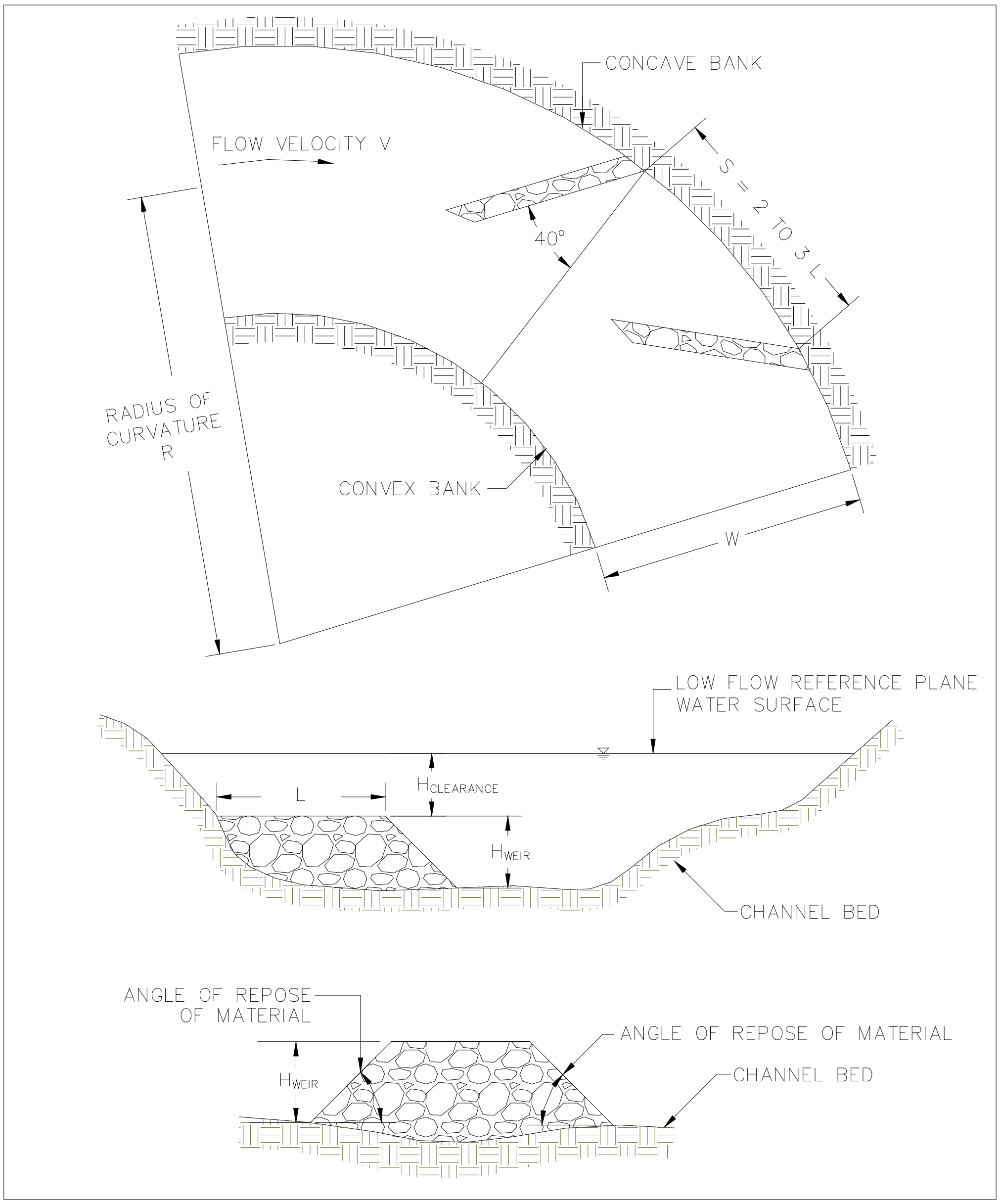

FIGURE 5.1 Plan and Cross-Sectional Views for Bendway Weir Design

LIMITATIONS / FUTURE INVESTIGATIONS

This investigation was a first phase in developing optimum design criteria for submerged bendway weirs to improve navigation and bank stabilization in river systems. Developed from previous lab models, prototype models, and numerical models conducted by the National Center for Computational Hydroscience and Engineering, the effects of submerged bendway weirs on two- and three- dimensional flow throughout a river bend were evaluated. These studies have only begun to explain the effects of bendway weirs justifying this investigation as a first generation design criteria for bendway weirs. Therefore, limitations of the design criteria and recommendations of further research are provided.

Further investigations into the weir height, influences of the radius of curvature, spacing, and length could be conducted to determine the optimum design criteria. Determination of the effective weir height with the minimum clearance of flow necessary for navigation could be further researched to develop the maximum relationship. Further investigations on the degree of radius curvature could also be further analyzed with a variety of spacing in order to determine the appropriate spacing for the severity in curvature of bends. Furthermore, additional research could be conducted into the optimal length. A longer weir is better to a specific point, where the influences of realigning the flow are optimal for navigation. However, establishing too long of a bendway weir can create point bar erosion and can degrade the reach.

A future study of the influence of sediment transport on the performance of submerged weirs may also be conducted to examine the effects of scouring, aggradation and degradation of the channel bed.

CONCLUSION

Bendway weirs effectively enhance navigation in river bends. They reduce the strength of secondary flows and thus improve bank stabilization by minimizing erosion on the concave bank. Bendway weirs are more effective at low flow than during floods. A first generation of optimum design criteria for bendway weirs is purposed. The guidelines are based on numerical and physical models with field validation on the Mississippi River at Victoria Bend. These studies were conducted at the NCCHE and ERDC-WES testing facilities.

The key characteristics that influence the effectiveness of a bendway weir include orientation, length, height, spacing, and the radius of curvature, to maximize the favorable zone created by the weir. The optimum orientation of a bendway weir is at an angle of $\alpha = 40°$ upstream perpendicular to the flow. The length is dependent on the channel geometry, but in general, longer weirs perform better. The height depends on the low flow reference plane, barge depth and navigation. To maximize the influence the height possesses on the flow, the weir height should be a positioned to a maximum depth that will still provide enough clearance for navigation barges to transport at the low reference depth. Spacing is dependent on the radius of curvature. In general, a spacing of 2 to 3 times the length is adequate to maintain a maximum improved zone throughout the reach. However, since an increase in the radius of curvature decreases the zone of improvement, closer spacing of the weirs may be needed to maintain the improved zone throughout the bend. An increase in the side slopes of the weir increases the effectiveness of the weir to improve navigation conditions. Therefore, to maximize the vertical component, which improves separation and alters the flow, created by the side-slope, the materials angle of repose should be utilized as the front and back side-slope of the weir. The roughness of the weir has minimal effects on the characteristics of flow.

The first generation optimum design criteria established in this study were based on previous physical, prototype, and numerical models with a reasonable range of flow conditions and variability in weir parameters. Applications of this design criterion to practical engineering problems are suitable but care should be utilized since all rivers are unique and are prone to different system responses. To further enhance the accuracy of this design criterion, additional research could be conducted with a broader range of flows and weir parameters. Direct physical or numerical modeling of specific field sites should be considered as a viable solution to practical river engineering problems.

REFERENCES

Chien, N. and Wan, Z., 1999, Mechanics of Sediment Transport, ASCE press, ASCE, 1801 Alexander Bell Drive, Reston, Virginia.

Derrick, D. L., Pokrefke, T., Boyd, M., Crutchfield, J. and Henderson, R., 1994, "Design and Development of Bendway Weirs for the Dogtooth Bend Reach, Mississippi River." Technical Report: HL-94-10, U.S. Army Engineer Waterways Experiment Station.

Derrick, D. L., 1998, "Four Years Later, Harland Creek Bendway Weir / Willow Post Bank Stabilization Demonstration Project." Proceedings of the 1998 International Water Resources Engineering Conference, Part 1 (of 2), August 3-7, Memphis, Tennessee.

The Federal Highway Administration, 1990, "Highways in the River Environment." Engineering Research Center, Colorado State University, Prepared for U.S. Department of Transportation Federal Highway Administration.

Heintz, M., 2002, "Investigation of Bendway Weir Spacing." MS Thesis, Department of Civil Engineering, Colorado State University, Fort Collins, Colorado.

Knighton, D., 1998, <u>Fluvial Forms and Processes: A New Perspective</u>. Oxford University Press, Inc., New York, New York.

Jia, Y. and Wang, S.S.Y., 2000, "Numerical simulations of the channel flow with submerged weirs in Victoria Bendway, Mississippi River," NCCHE Technical Report: NCCHE-TR-2000-3, National Center for Computational Hydroscience and Engineering, The University of Mississippi.

Jia, Y., Wang, S.S.Y., Xu, Y., and Huang, S., 2002, "Research on Optimal Parameters of Submerged Weirs Using Numerical Simulation and Physical Model Data." NCCHE Technical Report: NCCHE-TR-2002-2, National Center for Computational Hydroscience and Engineering, The University of Mississippi.

Scott, S., Jia, Y., Wang, S.S.Y., and Xu, Y., 2001, "Analysis of Near-Field Hydrodynamics of Submerged Weir." Coastal and Hydraulics Engineering.

Waterway Simulation Technology, Inc. 1999, "A physical model test plan for bend way weir design criteria."