Numerical Investigation of the Impact of Distortion on the Hydrodynamics in the Lower Mississippi River Physical Model (LMRPM)

Ali Heidarizhaleh

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NUMERICAL INVESTIGATION OF THE IMPACT OF DISTORTION ON THE HYDRODYNAMICS IN THE LOWER MISSISSIPPI RIVER PHYSICAL MODEL (LMRPM)

A Dissertation

Submitted to the Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College in partial fulfillment of the requirements for the degree of Doctor of Philosophy in

The Department of Civil and Environmental Engineering

by

Ali Heidarizhaleh
B.S., Karaj Azad University, 2002
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December 2021
Acknowledgements

I truly appreciate Dr. Willson for taking me under his wing and guiding me to complete this research. Additional thanks to DHI (Danish Hydraulic Institute) for use of the sponsored MIKE Powered by DHI license file(s). Also, I would like to thank LSU Department of Civil & Environmental Engineering and Louisiana Coastal Protection and Restoration Authority as funding sources.
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Abstract

The Lower Mississippi River Physical Model (LMRPM) is a distorted-scale, 1:6000 horizontal and 1:400 vertical, movable-bed model that is being used to complement ongoing numerical and field studies directed at studying how non-cohesive sediment transport will be impacted by future changes in relative sea level rise and river discharges, as well various management strategies, such as river sediment diversions, in the lower ~190 miles of the Mississippi River. The LMRPM was designed using Froude number (Fr) similarity between the prototype and the model, while the flow Reynolds number is relaxed, but determined to be high enough to ensure rough turbulent conditions. There are, however, questions about whether the Reynolds number approach, used in the design, ensures fully turbulent flow.

It is well known that scale effects due to model distortion arise due to differences in force ratios between the model and its real-world prototype. Model distortion cause differences in the centrifugal forces, skewed helical flow patterns through bends, and steeper channel bank walls.

To investigate the impact of model distortion on the two-dimensional flow fields, two numerical models were developed using MIKE 21C software: one at the prototype scale and one at the LMRPM scale. The river curvature was calculated for all cross-sections in the model domain and used to classify each cross-section as straight, moderate or sharp. Both models were calibrated and validated, and comparisons, over a range of river discharges and reach types, were made between several two-dimensional velocity fields properties. In addition, the Dean Number, a dimensionless parameter that includes the river curvature, was calculated, and used to look at the levels of turbulence.
The two-dimensional flows in the straight and moderate bend reaches were mostly the same over the range of river discharges. However, the flow fields in the LMRPM sharp bends showed no or smaller separation zones, when compared to the prototype flow fields, due to the lower relative centrifugal forces. The walls steepness has a significant impact on the flow fields by pushing the water to the centerline of the channel and preventing deviation of the velocity vectors. The deviations from prototype flow fields also created different patterns in the eddy viscosity and bed shear stress values.

While both the vorticity and Dean Number values at each cross section are indirect measures of some processes that can promote turbulence, both indicate that there are hydrodynamic processes, even in areas where Reynolds numbers might only indicate transitional flow, that should contribute to the generation of more turbulence. These results indicate that the LMRPM design does generate sufficient turbulence at the medium and high river discharges when the non-cohesive sediment transport is occurring.
Chapter 1. Introduction

1.1. Problem Statement

Physical Models are often used for education, research and design purposes. Different categories of physical models (Maynord, 2006) range from simple demonstrations for education and communication, which don’t necessarily capture all the physics, to screening tools that are used to look at alternatives, whereas (failure to perform as predicted would not be damaging to the overall project or endanger human life) to screening tools for major projects where failure to perform as predicted could be damaging to the overall project or endanger human life. Therefore, it is critical that the design, validation, calibration and utilization of a physical model clearly lays out the limitations of what can and can’t be simulated/reproduced and results not be “oversold”.

Physical model distortion is sometimes necessary for several reasons. For example, when a large domain needs to be simulated and the resources (lab space, funding, etc.) are not sufficient, a distorted physical model is often used. In this work, model distortion is defined as the ratio of the horizontal scale ratio \( E(L) = \frac{L_p}{L_m} \) to vertical scale ratio \( E(H) = \frac{H_p}{H_m} \), where \( p \) is prototype and \( m \) is model. Advantages of distorted models are that you can simulate large domains and still have water depths that allow easier more accurate measurements, higher Reynolds numbers (i.e., turbulent flows), and movable beds.

Two of the most important distortion-related impacts on the model hydrodynamics are due to centrifugal force scaling and steeper side channel slopes. This is because model distortion creates conditions where the centrifugal forces are lower than in an undistorted model (due to deeper channel relative to the width–Froude similarity) and results in steeper side slopes.

The Lower Mississippi River Physical Model (LMRPM) is a large domain movable bed model of the lowermost (~190 miles) Mississippi River. The physical model domain was chosen
to focus on the lowermost river where bedload material is being used for marsh creation (using mechanically dredged sand from the river) and proposed to be diverted into adjacent wetlands through planned river sediment diversions. The LMRPM discharges were designed using Froude scaling and Reynolds independence and the model sediment was designed using particle Reynolds number and Shields parameter in order to reproduce and simulate the bulk downstream noncohesive bedload transport in order to understand how that material moves down river under various discharges, relative sea level rise scenarios and manmade changes (e.g., dredging, sediment diversions). To cover the domain and maintain Reynolds numbers that ensure rough turbulent conditions at medium and large river discharges, when the bedload transport occurs, the model was designed using a horizontal length ratio $E(L)$ of 6000 and a vertical length ratio $E(H)$ of 400, resulting in a distortion of 15.

A potential problem with simply using the Reynolds number to determine the level of turbulence is that it only uses the average cross-section velocity and average depth, thus potentially not capturing all of the turbulence-creating processes such as helical flow through bends. Due to the model distortion, the centrifugal forces in the LMRPM deviate from those in undistorted models. While the model was designed and is being used to simulate bulk (one-dimensional) downstream bedload transport and not detailed cross-section geomorphology, understanding how high distortion impacts the hydrodynamics is critical for identifying locations where bedload features (such as deposition at river crossings between bends) may not be accurately represented or how the flow into river sediment diversions or other river bifurcations is not accurately reproduced.

Here, MIKE 21C software is used to create two depth-averaged numerical models, one at the LMRPM scale and one at the prototype scale, to investigate the how the distortion impacts the
hydrodynamics (flow paths and magnitude, vorticity, bed shear stress, eddy viscosity) in different size bends and under different river discharges. In addition, application of the Dean Number, representing the influence of river curvature on secondary flow and the resulting increase in turbulence, is employed to demonstrate that the levels of turbulence in the LMRPM is often larger than those calculated simply through the use of the Reynolds number.

1.2. Objectives and Research Questions

The main objective of this dissertation is to examine the influence of the LMRPM physical model scaling and distortion on flow hydrodynamics. The following research questions will be addressed.

1. What flow regimes and river geometries have the most impact on the differences between the distorted (LMRPM) and prototype depth-averaged hydrodynamics?

2. Does the Dean Number and its incorporation of river curvature and helical flow indicate turbulent flows at medium- and high-flow rates, in locations where the Reynolds number does not?

Results from the LMRPM- and prototype-scale models are used to answer some of these questions through quantitative comparison of velocities, boundary shear stress, and vorticity in different river geometries (straight sections, mild bends and sharp bends) at different flow rates. Semi-quantitative insights from flow paths, separation zones, etc. are used to identify locations where the centrifugal forces and side channel steepness results in LMRPM flow deviations from the prototype. Finally, the Dean Number is directly compared to the Reynolds number at locations throughout the model domain to demonstrate that higher levels of turbulence is most likely being generated in reaches that is not being captured through the Reynolds number estimates.
Chapter 2. Literature Review

2.1. Background

Modeling There are three types of similitude that govern physical model design and performance. First, geometric similarity which is the change in physical dimensions of the model. Second, dynamic similarity which includes any forces related to fluid such as gravity, inertia, viscosity. Third, kinematic similarity which encompasses velocity and acceleration of the flow. (Ettema, Arndt, Roberts, & Wahl, 2000). Distortion is when the horizontal and vertical scales are not equal. This is usually necessary for moveable-bed models to ensure flow and sediment transport patterns can behave as closely as possible to the prototype. The scaling differences and distortion may limit the model’s ability to replicate some of the complex hydrodynamic and sediment transport processes. For instance, in LMRPM, the rough turbulent flow conditions and sediment movement are achieved in specific horizontal and vertical distortions, 1/6000 and 1/400. Distorted scale modeling can affect geometric scales (vertical, particle, slope), densimetric scales (density, fall velocity), flow (velocity), time, and sediment transport rate. Careful consideration must be given to distortion because 2- and 3-D flow patterns and pressure distributions are also distorted because of the change in geometric scales. Figure 2.1 (Ettema, Arndt, Roberts, & Wahl, 2000) shows a few of the most relevant impacts of vertical distortion in four scenarios. Most relevant to this research is where the vertical distortion can impact the helical flow patterns in the vicinity of river bends (scenario c) and where separation zones may deviate from prototype conditions (scenario d).

For open channel flow problems, the Froude number (ratio of inertial to gravitational forces) is used to determine the dynamic scaling:

\[ Fr = \frac{v}{\sqrt{gD}} \]  

(2-1)
Where $V$ is cross-section average velocity, $g$ is gravitational acceleration and $D$ is average depth of the channel.

Due to physical model scaling, the Reynolds number (ratio of inertial to viscous forces) cannot be satisfied. However, the Reynolds number independence principle (i.e., high enough $Re$ to ensure rough turbulent conditions) is often employed. The LMRPM was designed to maintain Froude similarity while still having Reynolds numbers in the rough turbulent range through an iterative approach by changing geometric scales as seen in Table 2.1 (BCG, 2011). Where $Re_P$, $Re_M$ are prototype and model Reynolds numbers respectively and $E(H)$, $E(L)$ are horizontal and vertical scales of the physical model.

Figure 2.1. Impact of vertical distortion on flow patterns. (Ettema, Arndt, Roberts, & Wahl, 2000).
Table 2.1. Model Reynolds numbers used to iteratively selected LMRPM distortion scale

<table>
<thead>
<tr>
<th>Discharge (cfs)</th>
<th>E(H)</th>
<th>E(L)</th>
<th>Distortion (E(H)/E(L))</th>
<th>ReP (1*10^8)</th>
<th>Rem</th>
</tr>
</thead>
<tbody>
<tr>
<td>400,000</td>
<td>500</td>
<td>12000</td>
<td>24</td>
<td>4.57</td>
<td>2243</td>
</tr>
<tr>
<td>1,350,000</td>
<td>500</td>
<td>12000</td>
<td>24</td>
<td>15.4</td>
<td>7570</td>
</tr>
<tr>
<td>400,000</td>
<td>600</td>
<td>12000</td>
<td>20</td>
<td>4.57</td>
<td>1845</td>
</tr>
<tr>
<td>1,350,000</td>
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<td>12000</td>
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<td>6228</td>
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<tr>
<td>400,000</td>
<td>500</td>
<td>9000</td>
<td>18</td>
<td>4.57</td>
<td>2528</td>
</tr>
<tr>
<td>1,350,000</td>
<td>500</td>
<td>9000</td>
<td>18</td>
<td>15.4</td>
<td>8533</td>
</tr>
<tr>
<td>400,000</td>
<td>600</td>
<td>9000</td>
<td>15</td>
<td>4.57</td>
<td>2054</td>
</tr>
<tr>
<td>1,350,000</td>
<td>600</td>
<td>9000</td>
<td>15</td>
<td>15.4</td>
<td>6933</td>
</tr>
<tr>
<td>400,000</td>
<td>400</td>
<td>6000</td>
<td>15</td>
<td>4.57</td>
<td>3774</td>
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<td>1,350,000</td>
<td>400</td>
<td>6000</td>
<td>15</td>
<td>15.4</td>
<td>12736</td>
</tr>
<tr>
<td>400,000</td>
<td>500</td>
<td>6000</td>
<td>12</td>
<td>4.57</td>
<td>2897</td>
</tr>
<tr>
<td>1,350,000</td>
<td>500</td>
<td>6000</td>
<td>12</td>
<td>15.4</td>
<td>9777</td>
</tr>
<tr>
<td>400,000</td>
<td>600</td>
<td>6000</td>
<td>10</td>
<td>4.57</td>
<td>2316</td>
</tr>
<tr>
<td>1,350,000</td>
<td>600</td>
<td>6000</td>
<td>10</td>
<td>15.4</td>
<td>7818</td>
</tr>
</tbody>
</table>

The model is scaled in the horizontal (1:6000) and vertical (1:400) directions, resulting in a geometric distortion of fifteen. Figure 2.3 shows a cross section which is distorted vertically (1/400) and horizontally (1/6000) in LMRPM and undistorted in prototype model. Using the mean flow in the LMRPM, the Froude number (Fr) similarity between the prototype and the model is maintained. While the Reynolds number (Re) scaling is relaxed, rough turbulent flow conditions in the model are achieved, based upon the approach and assumptions used in the model design. As seen in Table 2.1, the LMRPM achieves fully turbulent flow (Reynolds number > 10,000) at the high river discharges and at least 3500 at low river discharges. (BCG, 2011). Using the horizontal and vertical scale ratios and applying Froude similarity results in the following relationships.

\[
Length\ Scale: \ E(L) = \frac{L_M}{L_P} = \frac{1}{6000} \tag{2-2}
\]

\[
Vertical\ Scale: \ E(H) = \frac{H_M}{H_P} = \frac{1}{400} \tag{2-3}
\]

\[
Distortion\ Scale: \ \Delta = \frac{E(H)}{E(L)} = 15 \tag{2-4}
\]
Bank Slope Scale: \( E(f) = \frac{1}{\Delta} = \frac{1}{15} \) (2-5)

Froude Scale: \( E(Fr) = \frac{Fr_M}{Fr_P} = 1 \) (2-6)

Velocity Scale: \( E(U) = \frac{U_M}{U_P} = \sqrt{E(H)} = \frac{1}{20} \) (2-7)

Discharge Scale: \( E(Q) = \frac{Q_M}{Q_P} = E(H)^{3/2} * E(L) = \frac{1}{48E6} \) (2-8)

Hydraulic Time Scale: \( E(T) = \frac{T_M}{T_P} = E(H)^{-1/2} * E(L) = \frac{1}{300} \) (2-9)

Values for the scales, shown in equations 2-2 through 2-9, evaluated using the LMRPM length scales as well as in an undistorted scale \( E(L) = 1/400 \) and \( E(H) = 1/400 \) are shown in Table 2.2. Values for a “D1” model \((1:400H; 1:400V)\) are also shown, in order to better assess the influence of distortion on the hydrodynamic of the flow when LMRPM and prototype are compared to each other.

Table 2.2. Summary of ratios at each scale relative to the prototype Mississippi River.

<table>
<thead>
<tr>
<th>Flow Parameter</th>
<th>Scaling Function</th>
<th>Prototype</th>
<th>D1</th>
<th>LMRPM(D15)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>( E(L) )</td>
<td>1</td>
<td>1/400</td>
<td>1/6000</td>
</tr>
<tr>
<td>Height</td>
<td>( E(H) )</td>
<td>1</td>
<td>1/400</td>
<td>1/400</td>
</tr>
<tr>
<td>Distortion</td>
<td>( \Delta = \frac{E(H)}{E(L)} )</td>
<td>1</td>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td>Bank Slope Factor</td>
<td>( E(f) = \frac{1}{\Delta} )</td>
<td>1</td>
<td>( 16E+04 )</td>
<td>1/24E+05</td>
</tr>
<tr>
<td>Area</td>
<td>( E(A) = E(L) * E(H) )</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Froude Number</td>
<td>( E(Fr) = 1 )</td>
<td>1</td>
<td>1/8000</td>
<td>1/8000</td>
</tr>
<tr>
<td>Reynolds Number</td>
<td>( E(Re) = E(H)^{3/2} )</td>
<td>1</td>
<td>1/20</td>
<td>1/20</td>
</tr>
<tr>
<td>Velocity</td>
<td>( E(U) = E(H)^{1/2} )</td>
<td>1</td>
<td>1/32E+05</td>
<td>1/48E+06</td>
</tr>
<tr>
<td>Discharge</td>
<td>( E(Q) = E(L) * E(H)^{3/2} )</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Hydraulic Radius</td>
<td>( E(HR) )</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Hydraulic Time</td>
<td>( E(T) = E(L) * E(H)^{-1/2} )</td>
<td>1</td>
<td>1/20</td>
<td>1/300</td>
</tr>
<tr>
<td>Roughness</td>
<td>( E(R) = E(HR)^{2/3} * E(f)^{1/2} )</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Eddy Viscosity</td>
<td>( E(EV) = E(L)^{2/E(T)} )</td>
<td>1</td>
<td>1/8000</td>
<td>1/120000</td>
</tr>
<tr>
<td>Bed Shear Stress</td>
<td>( E(BS) = E(U)^{2} = E(H) )</td>
<td>1</td>
<td>1/400</td>
<td>1/400</td>
</tr>
<tr>
<td>Dean Number</td>
<td>( E(De) )</td>
<td>1</td>
<td>1/8000</td>
<td>1/8000</td>
</tr>
<tr>
<td>Vorticity</td>
<td>( E(vo) = \frac{1}{E(T)} = \frac{1}{E(L) * E(H)^{1/2}} )</td>
<td>1</td>
<td>( 20 )</td>
<td>300</td>
</tr>
<tr>
<td>Centrifugal Force</td>
<td>( E(CF) = E(L) * E(H)^{2} )</td>
<td>1</td>
<td>1/64E+06</td>
<td>1/96E+07</td>
</tr>
</tbody>
</table>
Because the LMRPM was designed and is being used to replicate bulk noncohesive sand transport, fully turbulent conditions are necessary at medium and high river discharges when that mode of transport occurs. Reynolds number is calculated from:

\[
Re = \frac{\rho V R_h}{\mu}
\]  

(2-10)

Where \( V \) is cross-section average velocity, \( \rho \) is density, \( R_h \) is hydraulic radius of the channel and \( \mu \) is the dynamic viscosity. Reynolds number for each cross section is calculated in terms of cross-section average velocity and cross-section hydraulic radius. The ratio of the cross-section average velocity and the cross-section average depth between the prototype and LMRPM is 1/20 and 1/400, respectively.

The LMRPM design team (BCG, 2011) assumed that Reynolds numbers larger than 7500 were required to guarantee rough turbulent flow and evaluated the values for the range of discharges to be used on the model (400,000 cfs to 1,250,000 cfs). They determined that flows above 500,000 cfs would have enough turbulence to ensure the model sediment remains in suspension (Table 2.1).

**Wall Steepness**

Physical model distortion creates steeper channel banks than in the prototype or in undistorted models. The LMRPM Bank Slope Factor is 1/15 (Table 2.2). Yan et al (2020) investigated how channel wall steepness impacted secondary flows in rectangular and trapezoidal channels. One of the primary conclusions was that the walls reaction forces to centrifugal force in the bends are larger compared to prototype model. Because of the steeper walls in LMRPM, the horizontal component of walls reaction forces, which is in front of centrifugal force, is larger compared to prototype. In the straight sections of the model and prototype, due to very small centrifugal force, only the walls reaction forces work, while closer to the bends, the interaction
between walls reaction forces and centrifugal force starts growing particularly in LMRPM. Yan et al (2020) also show (Figure 2.2) that secondary flow in a rectangular channel bend is characterized by a double-cell pattern, where one cell is the clockwise-rotating primary circulation cell, M1, and the other is the counterclockwise-rotating outer-bank cell, C1 (scenario c). However, in a trapezoidal channel bend when the side slope run-to-rise ratio, m, increases to 1, an additional clockwise-rotating cell, M2, is formed (scenario d). For the cases with even higher values of m (wall slope), M2 becomes weaker and splits into multiple cells. Moreover, for a strongly curved channel bend with smaller m, a core of high unit discharge appears near the inner bend due to the potential-vortex effect, and it gradually moves toward the outer bend under the influence of secondary circulation. For the cases with greater m, the core of the high unit discharge is located closer to the middle of the channel, and the outward shift becomes less significant.

Figure 2.2. Schematic of the typical secondary flow cells in: a a straight rectangular channel (adapted from Tominaga et al. [17]); b a straight trapezoidal channel (adapted from Tominaga et al. [17]); c a rectangular channel bend and d a trapezoidal channel bend (Yan et al., 2020)
Figure 2.3. Undistorted cross section in prototype model (left) versus distorted cross section in LMRPM (Right). The cross section height and width in the prototype are 400 and 6000 times respectively larger than the cross section height and width of LMRPM.

**Centrifugal Forces**

Centrifugal forces must also be considered as a possible factor in the analysis of the effects of distortion on flow patterns (Pokrefke, 2005). The centrifugal force is calculated as:

\[ F = \frac{W V^2}{g R} \]  \hspace{1cm} (2-11)

Where \( F \) is centrifugal force, \( W \) is weight, \( V \) is velocity, \( g \) is gravitational acceleration, \( R \) is the radius of bend. The centrifugal force ratio, where the fluid densities and gravitational constants are the same can be calculated from:

\[ f = \frac{W V^2}{R} = \frac{L^2 H V^2}{L} = LH V^2 \]  \hspace{1cm} (2-12)

Where \( L \) is horizontal and \( H \) is vertical scale. Therefore, based on Froude number and velocity scaling, the centrifugal force ratio (model/prototype) for distorted and undistorted models are

Distorted models:

\[ f = LH^2 \]  \hspace{1cm} (2-13)

undistorted models:
\[ f = H^3 \]  \hspace{1cm} (2-14)

According to Table 2.2, the centrifugal force ratio for prototype, undistorted (1/400, 1/400) model and distorted LMRPM (1/400, 1/6000) are 1, 1/64E+06, 1/96E+07 respectively. Of particular note is that the centrifugal force ratio between LMRPM and undistorted physical model is 15 and as a result, we expect lower centrifugal forces in the LMRPM and therefore, the flow velocity vectors in the bends will deviate less in the LMRPM than in the prototype or undistorted model. Of course, the centrifugal forces in any scaled model are going to be smaller than the prototype.

**River Curvature**

River curvature can be classified based upon the ratio of the bankfull river width, B, and channel radius, R, (Figure 2.4 from Blanckaert, 2010). In general, channel bends are classified to three types; if the ratio \( B/R > 0.5 \), the bend is sharp; if the ratio is \( 0.15 < B/R < 0.5 \), the bend is moderate; and if the ratio is \( B/R < 0.15 \), the bend is mild or straight.

![Figure 2.4. Classification of sharp, moderate and mild curvatures. (Blanckaert, 2010)](image-url)
**Dean Number**

Calculation of the Dean Number (Ligrani, 1994) provides a way to account for how the development of secondary flows in curved pipes or channels can increase the levels of turbulence. The Dean Number, which combines the Reynolds number and channel curvature, is defined as:

\[
\text{Dean Number} = Re \times \left(\frac{B}{R}\right)^{0.5}
\]  

(2-15)

where \(Re\) is Reynolds number, \(B/R\) is curvature of the channel, where \(B\) is the channel width and \(R\) the radius. Therefore, any curvature, which will almost always induce secondary flows, will cause the Dean number to get larger.

Transition from laminar to turbulent flow has been also examined in a number of studies, even though no universal solution exists since Dean number is highly dependent on the curvature ratio (Kalpakli, 2012). However, Ligrani (1994) studied flow in a curved channel with mild curvature, an aspect ratio of 40 to 1 (width/height), and flow conditions for Dean numbers ranging from 35 to 430. He found that fully turbulent flow forms for Dean number > 400 where the vortices appear, and eventually connect to each other.

The curvature values \((B/R)\) are the same in both LMRPM and Prototype. If one uses the average depth for the hydraulic radius, then the Reynolds number ratio (model/prototype) is 1/8000, the Dean number ratio (model/prototype) will be 1/8000.

**Vorticity**

Vorticity in a three-dimensional flow field is calculated using:

\[
\zeta = \left(\frac{\partial w}{\partial y} - \frac{\partial v}{\partial z}\right) i + \left(\frac{\partial u}{\partial z} - \frac{\partial w}{\partial x}\right) j + \left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right) k
\]  

(2-16)

For 2D modeling because there is not vertical velocity component, the equation is simplified to
\[
\vec{\zeta} = \left( \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right) \vec{k}
\]  

(2-17)

Which means that the vorticity vector is perpendicular to the plane of the flow, i.e., the \( k \) direction. Due to the larger cross-stream velocities (\( v \)) in river bends, the vorticity values there should be higher than straight parts of the channel. In addition, any deviations between the LMRPM and prototype velocities should result in different vorticity fields.

Using the Froude velocity scale ratio of 20, the vorticity scale ratio (LMRPM/prototype) is \( 1/E(T)=300 \), which is the reverse of hydraulic time ratio (Table 2.2). Therefore, the vorticity values in the LMRPM could be approximately 300 time larger than prototype.

Referring back to the (Yan et al., 2020) (Figure 2.2) investigation of channel wall steepness (\( m \)) on flows, the streamwise vorticity generally decreases with \( m \) (walls slope) increasing until \( m=1 \). When \( m=1 \), an additional core of high positive vorticity becomes quite obvious near the outer bank. With the increase of \( m \), the core of high positive vorticity in the inner side increases and that in the outer side becomes weaker and splits. Although the overall strength of M1 in the trapezoidal channel bend is weaker than that in the rectangular one, the vorticity near the inner bend actually increases. In the cases with a very high value of \( m \), the positive vorticity in the inner half of the cross section is much higher than that in the outer half.

2.2. Distortion and Scaling

In order to achieve a complete similarity between model and prototype behavior, hydraulic physical models should display geometric, kinematic, and dynamic similitude (Gallisdorfer et al., 2014). For geometric similitude, homologous spatial dimensions between the prototype and the model must have equal scale factors and shape. The kinematic similitude governs motions of physical phenomena, for example, velocity fields of a fluid between the prototype and its scaled
model, with a similar scale factor. Dynamic similitude implies that all force distributions are parallel and are related with equal proportions at all corresponding points (Wallerstein et al., 2001).

Distortion in mobile bed physical models is achieved by varying any one or several of five different aspects of the models (Ettema et al., 2000): 1) geometric (vertical dimension, particle, slope), 2) densimetric (density, fall velocity), 3) flow (velocity), 4) time, and 5) sediment transport rate. Geometric distortion is one of the first aspects typically evaluated when distortion in models is needed. The distortion of the vertical dimension in models increases turbulence, improves accuracy in measurements and provides larger Reynolds numbers (Chanson, 2004). In addition, vertically distorted models can improve the accuracy of flow-velocity and depth model measurements and, due to smaller physical model surface areas, reduce the costs. In the case of physical river models, modelers usually build with a distortion varying from two to seven to reduce the impact of the distortion (Henderson, 1966). However, these levels of distortion may result in exaggeration of secondary currents, distortion of eddies, different lateral distributions and model geometry appearing to be out of proportion (Ettema et al., 2000).

Reynolds number (Re) is the ratio of inertial forces to viscous forces within a fluid. It is defined as: 

\[ Re = \frac{\rho V R_h}{\mu} \]

Where \( V \) is cross-section average velocity, \( \rho \) is density, \( R_h \) is hydraulic radius of the channel and \( \mu \) is the dynamic viscosity. At the model scale, it is important that Re be in the rough turbulent range (i.e., \( > 7500 \)) in order to have the turbulence/mixing conditions that are necessary to keep model sediment in suspension. Because the hydraulic radius is a function of depth, distorted models can only achieve similarity at a single depth (Novak et al., 1981). Geometrically distorted models have a large horizontal to vertical scale ratio (greater than unity) in order to model larger prototype domains, while maintaining adequate model flow depth for fully turbulent conditions (Peakall et al., 1996). Scale effects arise due to differences in force ratios.
between the model and its real world prototype. The hydraulic similarity in the vertical direction is usually affected in distorted physical models (Lu et al., 2013).

Flow, time and sediment transport scaling are inherently related to geometric and densimetric distortions (Ettema et al., 2000) and they should be changed accordingly. However, since the replication of the river bed is of the great importance, these parameters may be adjusted independently until models satisfy prototypes similar bed conditions (Franco, 1978). The natural geometric slope of models is achieved from the dimensional scale factors of models; however, when this slope is not sufficient for transporting sediments, a supplementary slope is required (Franco, 1978). It is recommended that, for rivers, the Froude similitude is required while relaxing the Reynolds number similitude (Green, 2014). Careful consideration must be given to distortion because 2- and 3-D flow patterns and pressure distributions are also distorted because of the change in geometric scales (Ettema et al., 2000). Tsujimoto (1990) stated that distorting a model is reasonable as long as it is in the turbulent flow regime and the similitude in sediment motion exists. Graf (1971) developed an empirical method for the design of mobile bed models based on Manning formula and model verification with known past events. The author stated that dynamic similarity is not achievable once the model is distorted since the longitudinal slope is increased and therefore, the velocity profile is distorted, which at the same time influences the sediment transport. This distortion benefits bed material transport since the shear stress is also increased as a result of the slope distortion.

Using distorted scales of 1, 2, 5, and 10 , Fang et al. (2008) showed that changing distortion does not significantly impact the velocity profile but does influence the spatial distributions of sediment erosion and deposition rates. The suspended sediment concentration and deposition rates have a direct and indirect correlation, respectively, with the distortion scale. Deviations in the
vertical velocity profile brings differences not only in the turbulence structures but also in the scaled sediment transport rates between the physical model results and prototype measurements (Agegnehu, 2015). According to Lu et al. (2013), the effect of distortions 2, 4, 6, 8 and 10 on bed load is observed in sediment movement and transport rates due to increases of vertical and horizontal slopes at the riverbed. Furthermore, it was noted that the secondary flow pattern in the meandering reach could be affected by distortion, and part of the fully developed secondary flow moved downstream as the distortion ratio increases. Zhao et al. (2013) developed a mathematical function for Chezy coefficient using distortion ratio, water depth in the prototype, and the roughness height and showed that the Chezy coefficient is greater than unity for distorted models and it should be adjusted based on the distortion ratio and bed roughness.

A scaling and self-similarity study was performed by Ercan et al. (2014) on unsteady open channel flows through one-parameter Lie group scaling. Lie groups were introduced by Sophus Lie in the 19th century to solve differential equations. Nonlinear partial differential equations governing the flow problems could be reduced to lower-order equations utilizing the Lie group of point transformations. Ercan et al. (2014) recommended transformations for the use of equal scaling ratios of channel depth and width to get better flow characteristics in the cross-stream direction than the traditional approach for distorted hydraulic models. If the width-to-depth ratio and the inclination angles of the banks are not conserved, the velocity distribution in the model cross-section cannot be similar, the relative location of the maximum velocity may not be the same, and the structure of the secondary currents can be significantly affected (Yalin, 1989). Moreover, Carr et al. (2015) extended the findings of Ercan et al. (2014) for one dimensional non-equilibrium suspended sediment transport by applying Lie group scaling on the governing equations and boundary conditions. With elimination of the need for scaling sediment density and diameter, the
prescribed distortion of length and depth scaling maintains the benefit of decreased cost and space requirements while ensuring increased flow velocities in the model; reduced time required for model simulations; an increased model Reynolds number, resulting in improved dynamic similarity; and greater accuracy in flow depth measurements.

Pokrefke (2005) conducted tests to investigate the effects of distortion on physical model results. The tests were conducted using distortions of 1, 2, 4, 6, 8, and 10 and the Froude criteria was applied to determine the appropriate velocity and discharge scales for these tests. He showed that the effects of distortion on the results of models of a straight reach are negligible. Also, the flow around bends is affected by model distortion, and the effect extends for a considerable distance downstream depending upon the amount of distortion. Moreover, the current directions in models with distortions of 4 and higher and with curvilinear flow is affected to the degree that the influence extends to the downstream model limits. Pokrefke (2005) conducted some other tests using distortion rations of 1, 2, 3, 4, and found that the currents in a bend would be deflected toward the concave side of the channel as the linear-scale distortion is increased. Also, results indicated that changes in the width-depth ratio of the channel was the principal cause of the deviation in the alignment of currents in a bend. Finally, he showed that increasing the roughness of the model channel as the distortion was increased would tend to reduce the effect of distortion.
Chapter 3. Methodology

3.1. Input Data

The numerical model domain covers 90 miles of the Mississippi River: the upstream location is at the Reserve station (RM:138.7) and the downstream location at West Pt A La Hache station (RM:48.7) (Figure 3.1). The bathymetry and topography of the model, all NAVD88, was obtained from USACE (US Army Corps of Engineers). Two models were created: one, prototype scale model, using the elevation data directly; and the second, the LMRPM scale model, using the same scaling as in the LMRPM (i.e., 1/6000 horizontal and 1/400 vertical). Prototype observed river stage data were obtained from the US Army Corps of Engineers (www.Rivergages.com) and rating curves, showing the relationship between discharge and water surface elevation at each station, were created. The observed water surface elevations for all stations, used for model calibration, were extracted from the rating curve. LMRPM river water surface elevations were obtained by simply dividing the prototype elevations by 400.
Figure 3.1. The study area of the Lower Mississippi River from Reserve to WPH

Figure 3.2. Left: A rectilinear (standard) MIKE 21 model. Right: A curvilinear MIKE 21C model (MIKE21C user manual, 2020)
The curvilinear grid created at the end of this process is a single grid, which has a set number of cells in the flow direction (j-coordinate) and a set number in the transverse direction (k-coordinate). For an ideal curvilinear grid, the orthogonality measure would be equal to zero everywhere. However, for practical applications one should try to create a curvilinear grid with values inside the range from -0.05 to 0.05, depending of the complexity of the grid.

The model accuracy is reduced when grid cells are not orthogonal and when the difference in adjacent cell sizes is too great. The model accuracy is also reduced when grid cells are too coarse or are not aligned to bed contours sufficiently to accurately describe the bed.

The aspect ratio is important in the sense that it can be used to choose the optimal number of points needed to resolve the flow in the stream wise direction (given the number of points across the model area). For convection dominated flow problems like river flow aligned with the curvilinear grid, the optimal aspect ratio is in the range from 3 to 8. For floodplain flow with a less significant flow direction the aspect ratio criteria should be reduced to the range 1 to 3. (MIKE21C User Manual).

For the prototype model, the maximum grid area is 7230m² (2e-4 m² in LMRPM) located in (k=1, j=333) and the minimum grid area is 85m² (2.36e-6 m² in LMRPM) located in (k=76, j=378). The orthogonality and aspect ratio of the model are shown in Figure 3.3.
The hydrodynamics model solves the vertically integrated equations of continuity and conservation of momentum in two directions. There are three main approximations. First, the shallow water approximation which is the lateral exchange of momentum due to friction in the fluid is neglected. Second, hydrostatic pressure is assumed, meaning that the gradients of vertical velocity component are neglected. Third, is the rigid lid approximation, meaning that the water surface is considered as being a rigid impermeable and shear stress free plate only with normal stresses (MIKE21C user manual 2021).

The vertically integrated equations in the curvilinear hydrodynamics model are:

$$\frac{\partial H}{\partial t} + \frac{\partial p}{\partial s} + \frac{\partial q}{\partial n} - \frac{q}{R_s} + \frac{p}{R_n} = 0$$  \hspace{1cm} (3-1)

$$\frac{\partial p}{\partial t} + \frac{\partial}{\partial s} \left( \frac{p^2}{h} \right) + \frac{\partial}{\partial n} \left( \frac{pq}{h} \right) - 2 \frac{pq}{hR_n} + \frac{p^2-q^2}{hR_s} + gh \frac{\partial H}{\partial s} + \frac{g}{C^2} \frac{\sqrt{p^2+q^2}}{h^2} = RHS$$  \hspace{1cm} (3-2)

$$\frac{\partial q}{\partial t} + \frac{\partial}{\partial n} \left( \frac{q^2}{h} \right) + \frac{\partial}{\partial s} \left( \frac{pq}{h} \right) + 2 \frac{pq}{hR_s} - \frac{q^2-p^2}{hR_n} + gh \frac{\partial H}{\partial n} + \frac{g}{C^2} \frac{\sqrt{p^2+q^2}}{h^2} = RHS$$  \hspace{1cm} (3-3)
Where

s, n : Coordinates in the curvilinear coordinate system

p, q: Mass fluxes in the s,n directions, respectively

H: Water level

h: Water depth

g: Acceleration of gravity

C: Chezy roughness coefficient

$R_n, R_s$: Radius of curvature of s,n lines respectively

RHS: The right-hand side in the force balance which contains Reynolds stress, Coriolis force and atmosphere pressure

Reynolds Stress in p direction: \[
\frac{\partial}{\partial x} \left( E \frac{\partial p}{\partial x} \right) + \frac{\partial}{\partial y} \left( E \frac{\partial p}{\partial y} \right) = \frac{\partial}{\partial s} \left( E \frac{\partial p}{\partial s} \right) + \frac{\partial}{\partial n} \left( E \frac{\partial p}{\partial n} \right) - \frac{2E}{R_s} \frac{\partial q}{\partial s} - \frac{2E}{R_n} \frac{\partial q}{\partial n} \]

(3-4)

Reynolds Stress in q direction: \[
\frac{\partial}{\partial x} \left( E \frac{\partial q}{\partial x} \right) + \frac{\partial}{\partial y} \left( E \frac{\partial q}{\partial y} \right) = \frac{\partial}{\partial s} \left( E \frac{\partial q}{\partial s} \right) + \frac{\partial}{\partial n} \left( E \frac{\partial q}{\partial n} \right) + \frac{2E}{R_s} \frac{\partial p}{\partial s} + \frac{2E}{R_n} \frac{\partial p}{\partial n} \]

(3-5)

Where E is turbulent (eddy) viscosity coefficient

The sub-grid scale Smagorinsky eddy viscosity is given by

\[
\nu^h_i = c_s^2 l^2 \sqrt{2(S_{xx}S_{xx} + 2S_{xy}S_{xy} + S_{yy}S_{yy})} \]

(3-6)

Where $c_s$ is a constant, $l$ is a characteristic length and the deformation rate is given by

\[
S_{xx} = \frac{\partial u}{\partial x}, \quad S_{xy} = \frac{1}{2} \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right), \quad S_{yy} = \frac{\partial v}{\partial y} \]

(3-7)
Depth-averaged flow equations are used in hydrodynamic model. The shear stress is calculated from the following equation. (It assumes that the viscous friction is much smaller than turbulent friction, uses Reynolds stress concept and Prandtl mixing length hypothesis).

\[ \tau_s = \rho E \frac{\partial u}{\partial z} \]  

(3-8)

Where

\( \rho \) density of water

\( u \) velocity in main flow direction

\( z \) vertical coordinate

\( E \) turbulent (eddy) viscosity coefficient

\( \tau_s \) shear stress in main flow direction

Using Navier-Stokes equations and assuming steady state conditions the following equations for the flow are used:

\[ u \frac{\partial u}{\partial s} + v \frac{\partial u}{\partial n} + w \frac{\partial u}{\partial z} + \frac{uw}{R} + \frac{1}{\rho} \frac{\partial P}{\partial s} = \frac{\partial}{\partial z} \left( E \frac{\partial u}{\partial z} \right) \]  

(3-9)

\[ u \frac{\partial v}{\partial s} + v \frac{\partial v}{\partial n} + w \frac{\partial v}{\partial z} - \frac{u^2}{R} + \frac{1}{\rho} \frac{\partial P}{\partial n} = \frac{\partial}{\partial z} \left( E \frac{\partial v}{\partial z} \right) \]  

(3-10)

Where

\( \rho \) density of water

\( u \) velocity in longitudinal flow direction

\( v \) velocity in transverse flow direction

\( u \) velocity in vertical direction

\( P \) pressure

\( s \) coordinate in stream wise direction

\( n \) coordinate in transverse direction
vertical coordinate

radius of curvature of the main streamline

turbulent (eddy) viscosity coefficient

By assuming hydrostatic pressure distribution \( P \) over the vertical, water pressure is a function of water depth.

Both LMRPM and prototype model were run with steady-state discharges as upstream flow rate type boundary conditions of the channel (Reserve). The water levels at WPH was set as the downstream zero gradient (convective) boundary conditions. This boundary condition assumes all the hydrodynamic variables reaching the boundary leave the computational domain freely. The banks and the channel bed were treated as a no slip condition.

3.2. Mesh Resolution

There are two steps before running the model to get the results. First, performing a mesh resolution test and second, calibrating the model. To calibrate the models, the most appropriate mesh resolution, showing all details of the hydrodynamics of the channel, should be selected. Only an accurate mesh resolution could show the variation of all parameters along the channel such as velocity components, vorticity, bed shear stress etc. A coarse mesh could not show all details in the flow and on the other side, a very fine mesh only increases the run time of the model. Therefore, the optimum mesh resolution is that shows all details of the flow and it does not take much time to run. If we make the optimum mesh finer, there should not be any changes in the flow details.

To do this, four types of resolutions, 1000*27, 2000*52, 3000*77 and 4000*102 are tested for 700k cfs discharge and finally the mesh 3000*77 is selected. Increasing the grid resolution from 3000*77 to 4000*102 did not create any changes in hydrodynamics of the river and stages. Using observed data, both LMRPM and prototype model were calibrated for four steady state flows.
To calibrate LMRPM and prototype, both models were run using spatially varying bed resistances (1/Manning coefficient) and then compared with observed data. The best agreement between the observed and simulated WSE in the stations along the channel is obtained with some specific Manning coefficients along the channel shown in Figure 3.6 to Figure 3.9. shows the characteristics of both physical and prototype models.

Table 3.1. Characteristics of physical and prototype 2D models (MIKE21C)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Physical Models #1/#2/#3/#4</th>
<th>Prototype Models #1/#2/#3/#4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cores/ Processors</td>
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<td>8/16</td>
</tr>
<tr>
<td>PC/RAM</td>
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<td>2.4GHz/32 GB</td>
</tr>
<tr>
<td>System Type</td>
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<td>Windows10: x64 bit</td>
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<tr>
<td>Drying /Flood Depth</td>
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<td>(0.01/0.02) m</td>
</tr>
<tr>
<td>Simulation Time</td>
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<td>1 hour</td>
</tr>
<tr>
<td>Grid</td>
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<td>Curvilinear</td>
</tr>
<tr>
<td>Number of Timesteps</td>
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</tr>
<tr>
<td>Time Step Interval</td>
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</tr>
<tr>
<td>Interpolation Method</td>
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<td>Natural neighbor</td>
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<td>Upstream Discharge</td>
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<td>11327/19822/28317/33980 cms</td>
</tr>
<tr>
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<td>Eddy viscosity</td>
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<td>K Direction Elements</td>
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Figure 3.4. Results of mesh resolution test with 11327 cms (700k cfs) discharge

<table>
<thead>
<tr>
<th>Mesh</th>
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<th>Min Cell Area (m²)</th>
<th>Run Time (min)</th>
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<td>80</td>
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</tbody>
</table>

Figure 3.5. Results of mesh resolution in terms of velocity 11327 cms (700k cfs)
The RMSE (Root Mean Square Error) values of water depth are calculated for both models. According to (Meselhe and Rodrigue, 2013), the RMSE should be less 0.15 for the Models. RMSE is calculated from the following equation.

$$RMSE\% = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (P_i - O_i)^2} \times \frac{n}{\sum_{i=1}^{n} O_i} \times 100\%$$  \hspace{1cm} (3-11)

Where

P: predicted value

O: observed value

n: number of observations

\(\bar{P}\) mean of predicted values

\(\bar{O}\) mean of Observed values

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
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<td>Reserve</td>
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<td>Bonnet Carre</td>
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<td>Algiers Lock</td>
<td>0.064</td>
<td>0.056</td>
</tr>
<tr>
<td>Alliance</td>
<td>0.047</td>
<td>0.039</td>
</tr>
<tr>
<td>WP a la Hache</td>
<td>0.0018</td>
<td>0.0</td>
</tr>
</tbody>
</table>
3.3. Calibration

Figure 3.6. Water surface elevations for calibrated physical models

Figure 3.6, Figure 3.7 show the comparison of calibrated water surface elevations for both physical and prototype models with the observed data. Moreover, for each graph, the difference between calibrated water surface elevation and observed data is shown in the attached table. As shown, for all of the stations along the channel the difference between water surface elevations and observed data is less than 13cm which is negligible. Also, according to Table 3.3 the maximum difference between the water surface elevations of both physical and prototype models is pretty low showing reasonable comparison between both models in the next steps.
Figure 3.7. Water surface elevations for calibrated prototype models

<table>
<thead>
<tr>
<th>Station</th>
<th>Obs-Calibration (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reserve</td>
<td>-6.33</td>
</tr>
<tr>
<td>BC North</td>
<td>0.25</td>
</tr>
<tr>
<td>BC</td>
<td>5.33</td>
</tr>
<tr>
<td>Carrollton</td>
<td>-6.47</td>
</tr>
<tr>
<td>Harvey Lock</td>
<td>0.00</td>
</tr>
<tr>
<td>IHNC</td>
<td>2.49</td>
</tr>
<tr>
<td>Algiers Lock</td>
<td>-3.93</td>
</tr>
<tr>
<td>Alliance</td>
<td>2.27</td>
</tr>
<tr>
<td>WPH</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Figure 3.8. Bed Resistance Values (1/n) for the Calibrated Prototype Models
The values of calibrated bed resistances are shown in Figure 3.8, Figure 3.9. The bed resistance \((1/n)\) is equal to the inverse of Manning coefficient \((n)\). The bed roughness values decrease from upstream of the model to downstream. Generally, the physical model shows lower bed resistance values than prototype model. The bed resistance ratio (Prototype/LMRPM) ranges from 1.4 to 1.5. Also, the higher discharges show the larger bed resistances and as a result, the lower roughness coefficient \((n)\). The depth of the water is one of the most important parameters that can impact the value of bed resistance along the channel. It seems that, the vertical distortion in the physical model causes the bed roughness difference between LMRPM and prototype.

Several simulations were run to investigate the impact of eddy viscosity on the simulations. It was found that the eddy viscosity value did not have any impact on the calibration results, therefore only bed resistance \((1/n)\) is used to calibrate the model.
Table 3.3 shows the water surface elevations difference between LMRPM and prototype model. The maximum difference is about 4cm in Bonnet Carre' N of Spillway station which is negligible. Obviously, the least difference between the water surface elevations of both models will give the most accurate results in the subsequent simulations and allow for more direct comparisons.

Table 3.3. Water surface elevation difference (cm) between LMRPM and prototype model

<table>
<thead>
<tr>
<th>Station/Discharge</th>
<th>400k</th>
<th>700k</th>
<th>1000k</th>
<th>1200k</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reserve</td>
<td>2.21</td>
<td>2.41</td>
<td>-2.86</td>
<td>-3.47</td>
</tr>
<tr>
<td>Bonnet Carre' N of Spillway</td>
<td>1.92</td>
<td>2.65</td>
<td>-1.75</td>
<td>-3.57</td>
</tr>
<tr>
<td>Bonnet Carre</td>
<td>1.72</td>
<td>2.32</td>
<td>-2.49</td>
<td>-3.21</td>
</tr>
<tr>
<td>Carrollton</td>
<td>-0.08</td>
<td>0.56</td>
<td>-0.4</td>
<td>-2.09</td>
</tr>
<tr>
<td>Harvey Lock</td>
<td>-0.03</td>
<td>0.17</td>
<td>0.09</td>
<td>-0.67</td>
</tr>
<tr>
<td>IHNC</td>
<td>-0.17</td>
<td>0</td>
<td>0.35</td>
<td>-0.1</td>
</tr>
<tr>
<td>Algiers Lock</td>
<td>-0.1</td>
<td>0.24</td>
<td>0.7</td>
<td>2.01</td>
</tr>
<tr>
<td>Alliance</td>
<td>-0.12</td>
<td>-0.24</td>
<td>1.55</td>
<td>3.07</td>
</tr>
<tr>
<td>WP a la Hache</td>
<td>0</td>
<td>0.01</td>
<td>0.25</td>
<td>0.36</td>
</tr>
</tbody>
</table>

DHI MATLAB toolbox is used as a primary source to read the output files of MIKE21C model. The outputs include the water depth, water surface elevation, discharge and velocity components. To have a more accurate comparison between prototype and physical model some other parameters such as local velocity components, Reynolds number, Dean number, vorticity, eddy viscosity and bed shear stress etc. are needed. Since they are not calculated by the software and DHI MATLAB toolbox, a series of MatalB codes were developed to calculate the rest of the parameters. All of these calculations were made at 3000 cross section along the model domain. The average cross section width for each of the 3000 cross sections are calculated for bank full discharge 700k cfs, from the following equation. The model width does show any significant changes for all four discharges. So, the bank full discharge, 700k cfs, is selected for width calculation.
\[ B = \sum b_i \]  

Where \( B \) is the width of the channel and \( b_i \) is the width of the grid cells along each cross section.

The minimum and maximum channel widths along the physical model are 9cm and 20cm which are corresponding to 540m, 1200 m in the prototype model (scale ratio: 1/6000). The islands are ignored in calculation of channel width.

To calculate the curvature both width of channel (\( B \)) and radius of the bends (\( R \)) along the channel for all 3000 cross sections are needed. Another MATLAB code (Lauer, 2006) is used to calculate the variation of the radius along the model. Once \( B \) and \( R \) are known, the values of curvature (\( B/R \)) for each of the 3000 cross sections is calculated.

Average cross section depth, hydraulic radius and average cross section velocity are needed to calculate Reynolds number along the channel. For all four discharges the average depth velocity is calculated from the equation below:

\[ A = \sum b_i \times d_i \]  

Where \( A \) is the cross section area and \( b_i \) is the width of the grid cells and \( d_i \) is the depth of grid cells along each cross section.

The minimum and maximum average cross section depths along the physical model are 3.5cm and 10.5 cm which are corresponding to 14m, 42m in the prototype model (scale ratio: 1/400).

In the next step the average cross section velocity is created from equation:

\[ V \times A = \sum V_i \times A_i \]  

Where \( V \) is the cross section average velocity and \( V_i \) is the cross section average velocity in the grid cells and \( A_i \) is the grid cells are along each cross section.
The minimum and maximum average cross section velocities along the physical model are 0.045 m/s and 0.0825 m/s which are corresponding to 0.9 m/s to 1.65 m/s in the prototype model (scale ratio: 1/20). Finally, the Reynolds number, Dean number, and curvature are calculated as explained in chapter 3.

3.4. Validation

Validation of the LMRPM and prototype model was done before comparison of both models. The average cross section velocity values for a straight section (RM:128), a moderate bend (RM:59) and a sharp bend (RM:104) along the model were compared with the surface velocity values measured by Scott (2019) (Figure 3.10, Figure 3.11, Figure 3.12). Using particle image velocimetry, Scott measured the surface velocity values for low flows of 4.6-5 gpm (490,000 -530,000 cfs in the prototype), medium flows of 6.7-6.9 gpm (710,000-740,000 cfs in the prototype), and high flows of 9.4-9.8 gpm (1,000,000-1,050,000 cfs in the prototype). The depth-averaged velocities from the LMRPM scale simulations are for 400k, 700k, and 1000k cfs discharges. As seen in Figure 3.10, Figure 3.11, Figure 3.12, the surface velocities are higher than the simulated LMRPM depth-averaged velocities. However, the velocity vector patterns are generally the same. In the straight section of the model the velocity core is at the middle of the channel while in the moderate and sharp bends, a separation zone is created after the bend and visible in both the simulations and observations.
Figure 3.10. Straight Section of the Model (RM:128): Surface Velocity Values from the Lower Flow (Top-Left) to the Higher Flow (Bottom-Left) Versus Average Depth Velocity Values of the Simulated Model from the Lower Flow (Top-Right) to the Higher Flow (Bottom-Right)
Figure 3.11. Moderate Bend (RM:59): Surface Velocity Values from the Lower Flow (Top-Left) to the Higher Flow (Bottom-Left) Versus Average Depth Velocity Values of the Simulated Model from the Lower Flow (Top-Right) to the Higher Flow (Bottom-Right)
Figure 3.12. Sharp Bend (RM:104): Surface Velocity Values from the Lower Flow (Top-Left) to the Higher Flow (Bottom-Left) Versus Average Depth Velocity Values of the Simulated Model from the Lower Flow (Top-Right) to the Higher Flow (Bottom-Right)
To validate the prototype model, the observed velocity data from Meselhe et al (2016), for two cross sections (RKs: 126, 128 or RM: 78.3, 79.5) are selected and compared with simulated prototype model results. Figure 3.13 shows the comparison between the Meselhe’s model and simulated prototype model. In both cross sections, the Meselhe et al (2016) model underpredicts the observed velocity while the simulated model overpredicts the observed velocity particularly between 50 and 500 from the right bank. However, the shape of the simulated model velocity is closer to observed data than Meselhe’s model velocity.

![Comparison of Average Cross Section Velocity Between Meselhe’s Model and Simulated Prototype Model (RKs: 126, 128 and Discharge: 1000k cfs)](image)

Figure 3.13. Comparison of Average Cross Section Velocity Between Meselhe’s Model and Simulated Prototype Model (RKs: 126, 128 and Discharge: 1000k cfs)
Chapter 4. Results and Discussions

4.1. Curvature

Usually, the most significant changes in the flow hydrodynamics happens in the bends where the water velocity vectors directions start deviating toward the outside bank of the bend. Therefore, the first step in comparing differences in LMRPM and prototype flow hydrodynamics, is classifying the planform geometry along the model domain: sharp; moderate or mild/straight. Following Blanckaert (2010), the classification is based on the value of B/R, where B is the bankful channel width and R is the radius. The values of 1/R, B and B/R for each cross-section along the model domain are found in Figure 4.1, Figure 4.2, Figure 4.3 respectively. The maximum 1/R, 12.5, happens in ~RM 64 (Figure 4.1), which gives the minimum radius of 0.08m and 480m in LMRPM and prototype model respectively. As seen in Figure 4.2, the ranges of the river width for bank full discharge for the LMRPM is between 0.09m to 0.2 which is about 540m to 1200m in the prototype model. Figure 4.3 shows the curvature (B/R) values along the channel, calculated using the B and 1/R values. According to the classification scheme in Blanckaert (2010), there are eleven sharp bends (B/R>0.5) and eight moderate bends (0.15<B/R<0.5) in the channel. The remaining sections of the channel are considered straight or mild. Figure 4.4 shows the location of the eleven sharp and eight moderate bends that were used in this research. A majority of the results (e.g., velocity vectors, eddy viscosity, vorticity, bed shear stresses) that will be shown here are from a straight section of the channel (~RM 20) located between bends M3 and S3, one moderate bend, M4, and two sharp bends, S4 and S7, including several cross-sections before, in and after those two bends.
Figure 4.1. $1/R$ values in LMRPM, bank full discharge: 700k cfs

Figure 4.2. The width of the LMRPM channel (For prototype the values are multiplied by 6000)
Figure 4.3. B/R ratio (curvature) along the channel for bank full discharge 700k cfs. (sharp bend: B/R>0.5 moderate bend: 0.15<B/R<0.5 and straight section: B/R<0.15)

Figure 4.4. Location of the sharp bends and moderate bends along the channel
4.2. Velocity: Straight and Moderate Bends

In all of the current speed and velocity figures, the color bar ranges are scaled using the LMRPM velocity ratio of 1/20 in an attempt to normalize the ranges of values and allow for more direct comparisons. Since the velocity ratio is based on Froude scaling and gives the ratio of cross-section average velocities, it is acknowledged that this isn’t the most rigorous way to do it. However, in most cases, it appears to allow for good comparisons. This means that the left color bar values showing the velocity magnitudes for LMRPM are 20 times smaller than the right color bar values for the prototype models.

The LMRPM and prototype simulated current speeds and downstream and lateral velocity components for all four flow rates in a straight section (~RM 20) are shown in Figure 4.5, Figure 4.6, Figure 4.7. As expected, due to the primarily downstream direction of the flow there are no differences between both LMRPM and prototype results in terms of current speeds or velocity components in the straight section of the channel.

Next, the velocity magnitudes and components were compared for a moderate bend, M4, (~RM 30) to see whether or not a slight increase in centrifugal force differences would have an impact. As can be seen in Figure 4.8, Figure 4.9, Figure 4.10 there are no significant differences between the simulated velocity magnitude or the components, even at medium and high discharges where the velocities could have an impact on centrifugal forces.
Figure 4.5. Prototype and LMRPM Current Speeds in the Straight Section (~RM 20 in model domain) for Four Discharges (color bar scale: 1/20)
Figure 4.6. Prototype and LMRPM Downstream Velocity Component in the Straight Section (~RM 20 in model domain) for Four Discharges (color bar scale: 1/20)
Figure 4.7. Prototype and LMRPM Lateral Velocity Component in the Straight Section (~RM 20 in model domain) for Four Discharges (color bar scale:1/20)
Figure 4.8. Prototype and LMRPM Current Speed in the Moderate Bend #4 (~RM 30 in model domain) for Four Discharges (color bar scale: 1/20)

Figure 4.9. Prototype and LMRPM Downstream Velocity Component in the Moderate Bend #4 (~RM 30 in model domain) for Four Discharges (color bar scale: 1/20)
Figure 4.10. Prototype and LMRPM Lateral Velocity Component in the Moderate Bend #4 (~RM 30 in model domain) for Four Discharges (color bar scale: 1/20)
4.3. Velocity: Sharp Bend #4

As river curvature increases, the deviation in centrifugal forces is expected to have more of an impact, particularly at the higher velocities, associated with the medium and high river discharges. Any differences in the velocity magnitudes and components should also be found in other important variables such as bed shear stress, eddy viscosity and vorticity. Figure 4.11, Figure 4.12, Figure 4.13 show the simulated Prototype and LMRPM current speeds and downstream and lateral velocities in two sharp bends, S4. As can be seen, before the bend there is not much difference between both hydrodynamics. However, when flow gets close to the middle of the bends the differences start to increase. Two reasons that might be causing the differences are the differences in centrifugal forces and in wall slope. The main differences occur immediately after the bend apex, where separation zones are located. According to centrifugal force scaling, 15 times smaller in the physical model than undistorted model, the tendency of the LMRPM flow patterns to move towards the outside of the bend should be less and, as a result, there should smaller separation zones. At the lower discharge, 400k cfs, and due to the lower velocities, there is no separation zone in either model. However, when the discharges increase to 700k cfs and higher, the higher velocities and resulting increase in centrifugal forces create separation zones. As the simulated flow in both models continues further downstream, as seen in Figure 4.11, Figure 4.12, the velocity magnitudes and directions are roughly the same, but the prototype patterns show a wider low velocity magnitude near the inner side of the bend compared to LMRPM, due to higher deviation of velocity vectors. The steepness of the wall slope can also impact the separation zone. Because of distortion, the walls slope in the physical model is 15 time steeper than prototype slope. This means that the walls reaction force in the physical model is larger than prototype and pushes
the water out from the inside bend and prevents the creation of separation zone in the physical model. (Xiaohui et al. 2020)

The impacts due to differences in the channel walls steepness forces and centrifugal forces between the LMRPM and prototype is complex. In the LMRPM the walls steepness reaction force is larger than undistorted model and pushes water away from the inside of the bend, while the centrifugal forces in the physical model result in the flow paths being more towards the inside of the bend than what occurs in the prototype or undistorted models. The interaction of the reduced centrifugal force and inner wall steepness subtracts from outer wall steepness force and creates a force in the bends that is smaller in the physical model and as a result it does not push as much flow toward the outside of the bends. Therefore, the separations zones in the LMRPM are either non-existent or much smaller than prototype. This phenomenon is seen in sharp bend 4 (Figure 4.11).
Figure 4.11. Prototype and LMRPM Current Speed in the Sharp Bend #4 (~RM 32 in model domain) for Four Discharges (color bar scale: 1/20)
Figure 4.12. Prototype and LMRPM Downstream Velocity Component in the Sharp Bend #4 (~RM 32 in model domain) for Four Discharges (color bar scale:1/20)
Figure 4.13. Prototype and LMRPM Lateral Velocity Component in the Sharp Bend #4 (~RM 32 in model domain) for Four Discharges (color bar scale: 1/20)
In an attempt to look more closely at the patterns, seven cross sections 1025, 1036, 1048, 1060, 1072, 1084, 1095, from the beginning to the end of the sharp bend 4 (Figure 4.4) were selected to more closely investigate the variation of downstream and lateral velocity components. Figure 4.14 to Figure 4.21 show the comparison of the cross sections’ downstream and lateral velocity components for discharges: 400k, 700k, 1000k and 1200k. The difference at higher discharges is more considerable than lower discharges. There is not a significant difference between both models before the bend in cross sections 1025, 1036, 1048. As you see, because of lower centrifugal forces in the physical model, the downstream velocity values in the inner bank of the physical model are higher than prototype, while for the outer bank it is vice versa. This phenomenon starts happening in the middle of the bends (cross section 1060) where the highest difference occurs between downstream velocity components and become smaller as the flow goes further downstream of the bend (cross sections 1072, 1084, 1095). Also, because of less deviation of velocity, the physical model shows lower lateral velocity in the inner bank compared to prototype. Actually, the difference between lateral velocity profile is the main reason in creation of separation zone in the prototype but not physical model.
Figure 4.14. Prototype and LMRPM Downstream Velocity Component in the Sharp Bend #4 (~RM 32 in model domain) Cross sections: 1025, 1036, 1048, 1060, 1072, 1084, 1095 for 400k cfs Discharge (color bar scale: 1/20)
Figure 4.15. Prototype and LMRPM Lateral Velocity Component in the Sharp Bend #4 (~RM 32 in model domain) Cross sections: 1025, 1036, 1048, 1060, 1072, 1084, 1095 for 400k cfs Discharge (color bar scale: 1/20)
Figure 4.16. Prototype and LMRPM Downstream Velocity Component in the Sharp Bend #4 (~RM 32 in model domain) Cross sections: 1025, 1036, 1048, 1060, 1072, 1084, 1095 for 700k cfs Discharge (color bar scale: 1/20)
Figure 4.17. Prototype and LMRPM Lateral Velocity Component in the Sharp Bend #4 (~RM 32 in model domain) Cross sections: 1025, 1036, 1048, 1060, 1072, 1084, 1095 for 700k cfs Discharge (color bar scale: 1/20)
Figure 4.18. Prototype and LMRPM Downstream Velocity Component in the Sharp Bend #4 (~RM 32 in model domain) Cross sections: 1025,1036,1048,1060,1072,1084,1095 for 1000k cfs Discharge (color bar scale:1/20)
Figure 4.19. Prototype and LMRPM Lateral Velocity Component in the Sharp Bend #4 (~RM 32 in model domain) Cross sections: 1025, 1036, 1048, 1060, 1072, 1084, 1095 for 1000k cfs Discharge (color bar scale: 1/20)
Figure 4.20. Prototype and LMRPM Downstream Velocity Component in the Sharp Bend #4 (~RM 32 in model domain) Cross sections: 1025, 1036, 1048, 1060, 1072, 1084, 1095 for 1200k cfs Discharge (color bar scale: 1/20)
Figure 4.21. Prototype and LMRPM Lateral Velocity Component in the Sharp Bend #4 (~RM 32 in model domain) Cross sections: 1025,1036,1048,1060,1072,1084,1095 for 1200k cfs Discharge (color bar scale:1/20)
4.4. Velocity: Sharp Bend #7

In sharp bend 7, which is sharper than sharp bend 4, the story is a bit little different. Figure 4.22, Figure 4.23, Figure 4.24 show the current speed, downstream and lateral velocity in both models. As you see, there is not a remarkable difference between both models, before the bend. But, when flow gets close to the middle of the bends the difference starts. The main difference between both models happen immediately after the bend apex where the separation zone is located. In this bend, because of larger curvature compared to bend 4, the separation zone is created in both physical and prototype model. The centrifugal force is 15 times smaller in the physical model than undistorted model which creates less deviations in the velocity vectors of the physical models and smaller separation zone in the physical model. Unlike bend 4, the separation zone is seen in all of the discharges. When the flow goes further downstream in both models, as you see in Figure 4.22, Figure 4.23, the prototype model shows wider low velocity magnitude near the inner side of the bend compared to LMRPM, due to higher deviation of velocity vectors. Moreover, the walls reaction force in the physical model is larger than prototype and pushes the water out form the inside bend and prevent the creation of separation zone in the physical model. The main difference between the bends 4 and 7 is curvature values that can impact the location and magnitude of the velocity components after the bend apex.

Bend 7 because of larger curvature creates larger centrifugal force than bend 4 and as a result this leads to more deviation of flow in the physical model. Therefore. The separation zone is created in the physical model. It seems that the curvature values somewhere between B/R=1 to B/R=1.25 the separation zone starts creating in the physical model and this can be considered as a threshold for creation of the separation zone in physical model.
Figure 4.22. Prototype and LMRPM Current Speed in the Sharp Bend #7 (~RM 47 in model domain) for Four Discharges (color bar scale: 1/20)
Figure 4.23. Prototype and LMRPM Downstream Velocity Component in the Sharp Bend #7 (~RM 47 in model domain) for Four Discharges (color bar scale: 1/20)
Figure 4.24. Prototype and LMRPM Lateral Velocity Component in the Sharp Bend #7 (~RM 47 in model domain) for Four Discharges (color bar scale: 1/20)
In bend 7, seven cross sections 1505, 1515, 1526, 1537, 1548, 1559, 1570, from the beginning to the end of the sharp bend 7 (Figure 4.4) are selected to investigate the variation of downstream and lateral velocity components.

Figure 4.25 to Figure 4.32 show the comparison of the cross sections downstream and lateral velocity components for discharges: 400k, 700k, 1000k and 1200k. in this bend, unlike bend 4, the difference between downstream and lateral velocity components of both models are less. The reason is that because of higher curvature there is larger centrifugal force and deviation in bend 7 physical model and therefore this makes the difference between prototype and physical model smaller.

The change in velocity components, starts from the middle of the bends, cross section 1537, with the highest difference between downstream velocity components of both models and become smaller and smaller when flow goes further downstream of the bend in cross sections 1548, 1559, 1570. There is not a significant difference between both models before the bend in cross sections 1505, 1515, 1526. It seems that mechanism of the interaction between walls slope and centrifugal force in bend 7 for both models are close to each other and the magnitude of the curvature has a direct impact on the velocity magnitude and directions.
Figure 4.25. Prototype and LMRPM Downstream Velocity Component in the Sharp Bend #7 (~RM 47 in model domain) Cross sections: 1505,1515,1526,1537,1548,1559,1570 for 400k cfs
Discharge (color bar scale:1/20)
Figure 4.26. Prototype and LMRPM Lateral Velocity Component in the Sharp Bend #7 (~RM 47 in model domain) Cross sections: 1505, 1515, 1526, 1537, 1548, 1559, 1570 for 400k cfs Discharge (color bar scale: 1/20)
Figure 4.27. Prototype and LMRPM Downstream Velocity Component in the Sharp Bend #7 (~RM 47 in model domain) Cross sections: 1505, 1515, 1526, 1537, 1548, 1559, 1570 for 700k cfs Discharge (color bar scale: 1/20)
Figure 4.28. Prototype and LMRPM Lateral Velocity Component in the Sharp Bend #7 (~RM 47 in model domain) Cross sections: 1505, 1515, 1526, 1537, 1548, 1559, 1570 for 700k cfs Discharge (color bar scale: 1/20)
Figure 4.29. Prototype and LMRPM Downstream Velocity Component in the Sharp Bend #7 (~RM 47 in model domain) Cross sections: 1505, 1515, 1526, 1537, 1548, 1559, 1570 for 1000k cfs Discharge (color bar scale: 1/20)
Figure 4.30. Prototype and LMRPM Lateral Velocity Component in the Sharp Bend #7 (~RM 47 in model domain) Cross sections: 1505, 1515, 1526, 1537, 1548, 1559, 1570 for 1000k cfs Discharge (color bar scale: 1/20)
Figure 4.31. Prototype and LMRPM Downstream Velocity Component in the Sharp Bend #7 (~RM 47 in model domain) Cross sections: 1505,1515,1526,1537,1548,1559,1570 for 1200k cfs Discharge (color bar scale:1/20)
Figure 4.32. Prototype and LMRPM Lateral Velocity Component in the Sharp Bend #7 (~RM 47 in model domain) Cross sections: 1505, 1515, 1526, 1537, 1548, 1559, 1570 for 1200k cfs Discharge (color bar scale: 1/20)
4.5. Vorticity: Sharp Bends #4, #7

Vorticity is one of the parameters that is related to magnitude and direction of the velocity components. Usually, the vorticity is generated at a no-slip wall condition. There are two types of vorticity: curvature and shear vorticities. (Katopodes, 2019) The first is dominated near the bends while the second indicates the change in velocity across the streamlines that causes shearing of fluid layers. Therefore, large values of vorticity are generated in the sharp bends where both curvature and velocity components change. Figure 4.33 shows the average cross section vorticity calculated at each cross section along the model domain. The results show that, although there is no significant difference between the average cross section vorticity of the both models, the local vorticity in both models is different. Figure 4.34, Figure 4.35 show the local vorticity for bends 4 and 7 in both models.

![Figure 4.33. Average cross section vorticity values of the LMRPM channel. The values for 700k cfs and 1000k cfs are between 400k cfs and 1200k cfs. (For prototype the average cross section vorticity values are divided by 300)](image-url)
Average cross section vorticity ranges from 0.5 to 3.5 $1/s$. The scale factor is $1/300$ which 300 is the hydraulic time scale. Figure 4.34, Figure 4.35 show the local vorticity for bends 4 and 7 in both models. The velocity components change mainly after the bend apex. This can result in change in the vorticity in this section of the bends. Before the bend apex, the difference between local vorticity values is negligible while after the bend there are some differences is the location and magnitude vortices. In the separation zone, other than magnitude, there is a difference in the direction of vorticity because of difference in direction of current speed vectors in the zone.
Figure 4.34. Vorticity (1/sec) in the Sharp Bend #4, LMRPM vs Prototype
Figure 4.35. Vorticity (1/sec) in the Sharp Bend #7, LMRPM vs Prototype
4.6. Eddy Viscosity: Sharp Bends #4, #7

MIKE21C uses the sub-grid Smagorinsky equation to calculate the eddy viscosity in the model. The grid size is considered in Smagorinsky equation (Equation 3-6) to calculate the eddy viscosity and therefore, the impact of scaling and distortion is taken into account. The magnitude of eddy viscosity is directly related to rate of strain of downstream and vertical velocity components. As mentioned in above, the main variation in velocity components happens after the bend apex, so any differences in the eddy viscosity, between two models, should occur where separation zone is located. Based on Froude number scaling, the horizontal eddy viscosity scale ratio 1/120000. The comparison of eddy viscosity in both models is shown in Figure 4.36, Figure 4.37. Although the pattern of eddy viscosity is the same in both model, the maximum core eddy viscosity locations after the bend are not the same. The difference in the higher discharges is considerable. This is shown in Figure 4.36, Figure 4.37, discharges 1000k cfs and 1200k cfs, after the bend, near the inner walls where the magnitude and location of the maximum eddy viscosity cores are different in both models. The comparison of eddy viscosity in both models is shown in Figure 4.36, Figure 4.37. Maximum eddy viscosity is near the walls while the minimum eddy viscosity happens at the middle, while the variation of velocity is vice versa. Based on k-e turbulent model, the eddy viscosity is directly related to TKE. The higher eddy viscosity means higher turbulent kinetic energy and the lower dissipation of turbulent kinetic energy. Prototype shows lower values of eddy viscosity near the walls than physical model. According to dimensional analysis the scale factor 1/120000. As mentioned before, the main variation in velocity components happens after the bend apex, therefore the maximum difference in the eddy viscosity, between two models, is related to after the bend apex where separation zone starts creating. Compared to bend
4, there is less difference in the pattern of eddy viscosity in both models which is the result of the same velocity pattern in both models.

Figure 4.36. Prototype and LMRPM Eddy Viscosity in the Sharp Bend #4 (~RM 32 in model domain) for Four Discharges (color bar scale:1/120000)
Figure 4.37. Prototype and LMRPM Eddy Viscosity in the Sharp Bend #7 (~RM 47 in model domain) for Four Discharges (color bar scale: 1/120000)
4.7. Bed Shear Stress: Sharp Bends #4, #7

Figure 4.38, Figure 4.39 show the comparison of the bed shear stress in both models. Based on Froude number scaling and use of the velocity scale ratio, the bed shear stress in the prototype is 400 times larger than physical model, assuming that the velocities pattern is the same. The bed shear stress is proportional to the square of current speed. Because the velocity vectors in the LMRPM scale simulations do not move as far towards the outer bank, the maximum bed shear stress is located near the inner bank of the bend while in the prototype the maximum bed shear stress is located father from the inner bank of the bend. This is shown in Figure 4.38, Figure 4.39, discharges 1000k cfs and 1200k cfs, after the bend, near the inner walls where the current speed magnitude and pattern are not the same in both models and as a result, this creates different bed shear stresses in the both models. This can give us some insight about the distribution and movement of sediment in this part of the channel. For instance, as you see in Figure 4.38, Figure 4.39, in the inner bank of the bend the current speed is lower and this creates smaller bed shear stress and therefore there is more sediment deposition in that area. On the other side, in the outer bank of the bend, because of higher current speed which makes larger bed shear stress, less sediment is deposited.

Bed shear stress is an important parameter in river flows to investigate the bed erosion and deposition processes. From the results, it is clear that the magnitude of boundary shear stress on the inner bank is higher than outer banks values. In river flows, the inner and outer banks are usually represented by slow and fast moving flows, respectively and the magnitude of boundary shear stress is related to the development of the shear layers and production of turbulent kinetic energy. Downstream of the bends, the distribution of the bed shear stress is highly heterogeneous due to the acceleration of the flow field introduced by the spatially variable roughness elements.
Very low shear stress areas around channel bends are introduced due to the flow separation that creates a free shear layer along the recirculation region. These areas play a key role on the formation of sandbars in fluvial environments. Figure 4.39 shows the comparison of the bed shear stress in both models. In this bend 7, it seems that the location of maximum and minimum bed shear stress, particularly after the bend apex, for both models are very close together and therefore the distribution and movement of sediment in this part of the channel for both physical and prototype model is more similar compared to bend.
Figure 4.38. Prototype and LMRPM Bed Shear Stress in the Sharp Bend #4 (~RM 32 in model domain) for Four Discharges
Figure 4.39. Prototype and LMRPM Bed Shear Stress in the Sharp Bend #7 (~RM 47 in model domain) for Four Discharges
4.8. Application of Dean Number to Evaluate LMRPM Turbulence levels

As discussed in Chapter 2, the Dean number is a dimensionless parameter that uses curvature (B/R) in an attempt to incorporate the helical flows in channel bends and the resulting increases in turbulence generation. Calculation of the Dean number requires both the Reynolds number and Curvature (Equation 2-15). The curvature was calculated in Section 4.1. Calculation of the Reynolds number requires the cross section average velocity and hydraulic radius. Figure 4.40 shows the LMRPM hydraulic radius values along the model domain for bank full flow. It ranges from 0.02m to 0.035m in the physical model. Figure 4.41 shows the LMRPM average cross section velocities along the model domain for bank full flow. The scale ratio for velocity is 1/20. It ranges from 0.045m/s to 0.082m/s in the physical model and 0.9 m/s to 1.64 m/s in the prototype.

![Figure 4.40. The hydraulic radius of the LMRPM channel](image)

Figure 4.40. The hydraulic radius of the LMRPM channel
Figure 4.41. The average cross section velocity of the LMRPM channel

Using the hydraulic radius, velocities and the density and dynamic viscosity of water, the LMRPM Reynolds number is calculated for 3000 cross section along the channel for the four discharges (Figure 4.42). Reynolds number in the physical model ranges from minimum (~500) to maximum (~4000). Laboratory flows have Reynolds numbers (Re < 1000) lower than the critical Reynolds number Re\textsubscript{cr} necessary to sustain fully inertial, three-dimensional turbulent fluctuations (Re\textsubscript{cr} ~ 10^3–10^4) (Princevac et al, 2005). Figure 4.42 shows that the flow for 400k is almost located in transition zone while for 700k, 1000k and 1200k the flow is located in transition and turbulent zones.
According to calculations in the LMRPM Design Report (BCG, 2011), the physical model achieves a fully turbulent flow at medium to high river discharges and is transitional at the low river stages. However, the calculations and assumptions were simplistic and led to the detailed calculations shown here. It can be inferred from Figure 4.42 that other than 400k cfs and 700k cfs discharges the higher discharges have a potential to create a turbulent flow in the physical model.

The calculated LMRPM Dean number values for 400 kcf and 1200 kcf along the model domain are shown in Figure 4.43. As expected, due to the incorporation of channel curvature, the Dean number is not necessarily in a direct relation with Reynolds number. (Figure 4.44). In some parts of the channel although Dean number is high, Reynold number is not high. As demonstrated by Ligrani’s experiments (1994), when the Dean numbers is higher than 400 the flow starts showing turbulent behavior with creating some vortices particularly in the sharp bends and fully turbulent flow. Where the Dean numbers is lower than 400, which is mostly in the straight and
moderate bends along the channel, the flow is not turbulent because there are no vortex pairs in the flow in the lower Dean numbers.

However, to see the impact of Dean number on the hydrodynamics of the flow, both curvature and Reynolds number should be considered. It is clear that the higher curvature creates larger centrifugal force and as a result larger change in velocity components due to helical flow. This mainly happen in the sharp bends. To have a Dean number higher than 400, both curvature and Reynolds number should be high enough to exceed the criterion for a turbulent flow. According to above definitions, it appears that for curvature values $B/R > 0.5$ (sharp bends) and Reynolds numbers ranges from 1000 to 10000, the flow can be a turbulent flow. The degree of the turbulence can be based on the magnitude of curvature and Reynolds number. The higher curvature and Reynolds number in the calculated ranges determines the level of turbulence in the physical model. According to Figure 4.44, Dean number for the most straight sections of the channel falls below 400. In a few moderate bends, although the Reynolds number is below the turbulent criterion, the incorporation of the curvature results in Dean numbers higher than 400. In the sharp bends, both Reynolds number and curvature are high enough to produce a Dean number higher than 400. The complexity of the flow is directly related to the magnitude of Reynolds number, the curvature and the bathymetry of the channel in the bends.
Figure 4.43. Dean number values of the LMRPM channel. The values for 700k cfs and 1000k cfs are between 400k cfs and 1200k cfs. (For prototype Dean number values are multiplied by 8000)

Figure 4.44. Variation of cross section average vorticity, Curvature, Reynolds and Dean numbers along the physical model (700k cfs)
Chapter 5. Summary, Conclusions and Recommendations

Conclusions

In this study, numerical models were used to investigate the impact of physical model distortion on the two-dimensional hydrodynamics in the Lower Mississippi River Physical Model (LMRPM). The LMRPM is distorted due to its differences in the horizontal (1/6000) and vertical scales (1/400). While the scale and distortion were chosen in order to achieve the design objective of reproducing the prototype river hydraulics (river flows and hydraulics) and bulk one-dimensional non-cohesive sediment transport, it is still important to understand how well the LMRPM reproduces the prototype hydrodynamics, particularly at a distortion of 15. It is well known that model distortion creates differences in centrifugal forces in the bends and can result in flow paths that deviate from prototype conditions. In the case of the LMRPM, the expectation was that the flow paths would move towards the middle or inside of the bends and result in smaller or no separation zones, particularly in the sharp bends and at high flow rates.

Two numerical models were created using MIKE 21C software: one at LMRPM scale and one at prototype scale. After calibration, both models were run at four discharges that covered the full range of prototype river flows (e.g., 400k, 700k, 1000k and 1200k cfs). Direct (e.g., current speeds, downstream and lateral velocity components) and calculated (e.g., eddy viscosity, bed shear stress, vorticity) hydrodynamic data were compared for the four river flows at four locations, representing different planform geometry: one straight, one mild bend, and two sharp bends. Little or no significant differences between any of the hydrodynamic properties were found in the straight or moderate bend sections, regardless of flow rate. This is not unexpected since any differences in centrifugal force impacts would be negligible.
The current speed and downstream and lateral velocity components showed a significant difference between the simulated results in both sharp bends. A more detailed look highlighted that the main differences in the hydrodynamics through the sharp bends are related to the separation zone, located immediately after the bend apex, and downstream of the bend. Further insights were found by comparing the patterns in the two bends, noting that sharp bend 7 has a larger curvature than sharp bend 4. A detailed look at the hydrodynamics in sharp bend 4 showed that there was no separation zone in the LMRPM scale model, while a separation zone was created in the prototype scale model. In sharp bend 7 there was a separation zone created after the bend apex that was smaller than the separation zone in the prototype scale model. Finally, a larger separation zone is expected in sharp bend 7 due to its larger curvature and resulting larger centrifugal force.

Simple application of the Reynolds number to determine the levels of turbulence in the LMRPM may be of limited value due to the use of cross section average velocities and depths, as well as no exact definition of the transition from transitional to fully turbulent flow. The LMRPM was designed assuming that the flow was fully turbulent at medium and high river flow rates. However, the Reynolds number calculations do not always support that. Therefore, the Dean number was calculated for every cross section along the model domain. In addition to including the Reynolds number, the Dean number includes the river curvature, B/R, in an attempt to incorporate the helical flow patterns in river bends. Since helical flow induces larger lateral and vertical velocity components, there is a higher likelihood of turbulence generation. Ligrani (1994) did a series of open channel flow experiments and determined that flows with a Dean number > 400 were fully turbulent. While not an exhaustive set of experiments, it appears that there are no other similar studies and, therefore, that criteria is applied here.
A vast majority (90%) of the Dean number values along the model domain were larger than 400, and the cross sections that were lower than 400 were few and spread out along the channel. Therefore, it is likely that few, if any, reaches within the model domain would not be fully turbulent. In addition, the cross section average vorticity values along the model domain indicate no difference between LMRPM and prototype model, while the local vorticity values show significant differences between both models particularly in sharp bends.

**Future Recommendation**

A more comprehensive and detailed investigation of the flow hydrodynamics should be completed using three-dimensional hydrodynamic software. As with this study, LMRPM and prototype scale models should be set up and run at multiple discharges: 400k, 700k, 1000k, 1200k cfs with comparisons done in different reach geometries. This type of study will more clearly identify the complex flow patterns (e.g., helical flows) and impacts of the wall steepness and centrifugal forces. Ideally, the 3D models could also be set up to perform comparisons of RANS and LES turbulence schemes that could give more accurate insights about the levels of turbulence particularly near the bends.

Since a major question is how well the LMRPM is able to simulate the flows upstream, into and downstream of the proposed river sediment diversion, 2D and 3D model domains should be created that include these structures. Results from these simulations can be compared to dye and particle image velocimetry experiments that are or will be conducted on the LMRPM and used to determine what, if any, modifications need to be made to the physical model in order to more accurately reproduce the flow fields.
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