Composite 1-Dimensional Modeling of the Expanded Small Scale Mississippi River Model

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COMPOSITE 1-DIMENSIONAL MODELING OF THE EXPANDED SMALL SCALE MISSISSIPPI RIVER MODEL

A Thesis

Submitted to the Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College in partial fulfillment of the requirements of the degree of Master of Science in

The Department of Civil and Environmental Engineering

by

Benjamin J Hartman
B.S., Louisiana State University, 2012
December 2015
I’d like to dedicate this thesis to America, whose nurturing public education system has allowed me to receive a high school, undergraduate, and graduate education free of charge. Thank you tax payers.
Acknowledgements

We all have teachers in our lives that standout as excellent educators and role models, Dr. Willson tops my list. We first crossed paths during my undergraduate while I was enrolled in his fluids class. Fortunately, at the time I was probably more academically focused than ever, and made an okay impression. Dr. Willson is a readily likable guy; helpful, funny, intelligent, collected, family oriented, empathetic, and charismatic. I ended up taking his groundwater, environmental transport, hydraulic design, and river engineering classes. One day I was wearing a suit and tie for LSU’s career fair, although not intending to be negative, he made a comment that went something like “you’ll never get an internship from the career fair” to which I responded “not with that attitude”. In that moment, you could see his wheels turning; two weeks later he secured me an interview with Denbury Resources, leading to my first internship. As my grandfather’s health deteriorated, he employed me as a graduate student, allowing me to remain close to home during his final days. The following summer, he helped me secure an internship with Moffatt & Nichol, where I learned a great deal and made some close friends. This man has made a significant impact in my life, for which I am deeply grateful. One day, I hope to be able to help someone as much as he has helped me.

I’d like to thank my family, especially my grandparents who continued to spoil me well into my mid 20’s. They were constantly bragging about me (as grandparents often do) and having lost both of them within the last 15 months, I’m saddened that I couldn’t make them proud one last time. I’d also like to thank my father for being a steadfast model in work ethic, my mother for being a loving supporter, and my brother for setting a high standard.

A big shoutout to my fellow graduate students, Angela New, Getnet Agegnehu, and Gyan Basyal, for their comradery and technical assistance. Getnet, I appreciate your help in getting started with HEC-RAS. Gyan, thank you for helping me through Math 4038. There is a lot more to be said about our friendship, but I couldn’t do it justice in writing. In you, I know I’ve made a friend for life.

At this point, I want to mention some collegiate friends. Calvin and Big Ben, we passed many good times together, know that you are associated with some of my fondest memories. A big thank you to my fraternity brothers at Alpha Gamma Rho for entertainment, stories, and cheap rent. Undoubtedly they served as a terrible and ever-present influence. However, I was pretty depressed before I shared their company, so I have them to thank for my renewed enjoyment of life.

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<td>Xcr</td>
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Abstract

Stream wise 1-dimensional numerical modelling couples well with long term, large domain physical modelling because of its ability to perform simulations quickly. The downsides are limitations in replicating some complex hydrodynamics and sediment transport behavior. In this study, a 1-dimensional model of a section of the Expanded Small Scale Physical Model (ESSPM) is developed using the USACE HEC-RAS software with a goal of investigating the ability of a 1-dimensional model to accurately replicate hydraulics at ESSPM time scales. Additional simulations are conducted to examine the impact of varying distortion scales, non-frictional energy losses and synthetic sediment on hydraulic behavior. The ultimate goal of this work is assess the potential advantages and limitations of 1-D numerical modelling in capturing the hydraulics in small scale physical models of channelized riverine systems. big picture has seen significant changes (or may see) in terms of sediment diversions, flood management, etc.

The original bathymetry and topography utilized is at the ESSPM scale; i.e., 1:6000 horizontal and 1:400 vertical. First, the model was calibrated and validated to a series of steady and unsteady physical model experiments performed in the “guinea pig” model. Results indicate HEC-RAS is capable reproducing water surface profiles at ESSPM scale. The numerical model was then scaled to prototype size and a distortion of 7.5 (D7.5 = 1:3000H; 1:400V) and 1 (D1 = 1:400H; 1:400V) to assess the influence that distortion and scaling have on hydraulic behavior. Comparisons of water surfaces between measured values and distorted numerical models indicate roughness scaling is necessary, especially at D7.5 and D1. Models with scaled roughness show that HEC-RAS can accurately reproduce the water surface profiles for a range of distortion scales. Furthermore, velocity comparisons between 1) measured data 2) the 1-D numerical model and 3) a similar 3-D numerical model suggest accurate longitudinal ESSPM velocity predictions can be achieved with HEC-RAS, which is more favorable to cumbersome 3-D model. The lack of spatial difference in velocity suggests model types of a higher order should be used to capture more detail in velocity and sediment patterns. However, the model suggests that certain hydraulic behaviors may be accurately reproduced, providing a useful tool for edicting the big picture outcomes of changes in Mississippi River management.
1. Introduction

Coastal wetlands are very important to Louisiana’s culture and economy with federal and state agencies devoting valuable resources to halt and hopefully reverse land loss. In 2002, the Louisiana Coastal Protection and Restoration Authority (CPRA) initiated and funded a project to use a Small Scale Physical Model (SSPM) of the Mississippi River to explore the potential for using large-scale river sediment diversions in restoration efforts. While serving as an important screening and outreach tool, the distortion scales were considered too large to conduct quantitative studies. Building on the success of the SSPM and a desire to both increase model domain and improve the mobile bed physical modeling, the CPRA is currently funding construction of an Expanded Small Scale Physical Model (EESPM) of the Mississippi River to serve as a screening tool for proposed river and sediment diversions and river management strategies. The model expands on the Mississippi River physical modeling efforts by reducing horizontal and vertical scales (1:6000, 1:400) while increasing the number of river miles (~140) that can be modeled.

Distorted, small-scale, movable bed physical models are designed to capture the bulk hydraulic and sediment transport processes over much shorter time scales than most numerical models. Two- and three-dimensional numerical models provide great accuracy at the cost of computational run time: only one-dimensional (1-D) models can be used to simulate unsteady flow and sediment transport over the range of time scales that are simulated using large domain physical models. However, numerical models are highly valuable and useful tools that, once calibrated and validated, can provide quantitative details of processes that cannot be replicated in a physical model. Thus, numerical and physical modeling should be thought of as complementary tools.

Distorted physical models such as the ESSPM require extra care to ensure that the physics impacting the study-relevant prototype processes are being properly replicated in the model. The ESSPM needs to reproduce the correct conditions for total river sediment (sand) transport, meaning incipient bed material entrainment conditions for identical conditions between model and prototype scales must be similar. This requires careful scaling and testing of model sediment size and density; flume tests at model scale are necessary to ensure model sediment behaves as predicted. Reproducing adequate turbulence within the water column in order to keep model sediment in suspension is also a challenge due to the reduced model Reynolds numbers (Re).

Primary thesis objectives are to use a 1-D numerical model to simulate flows in the ESSPM and prototype in order to 1) test (numerically) the impact of some of the similitude assumptions on the hydraulics and sediment transport; and 2) compare the hydraulics in the ESSPM and the prototype; and 3) have a simple, computationally-inexpensive model for use with ESSPM tests.
Physical models (PMs) refer to the use of laboratory models at an appropriate scale for investigating relevant processes, numerical models (NMs) refer to the use of computer codes, and composite modeling refers to the integrated and balanced use of both (Gerritsen et al., 2011). Physical modeling has many strong points, providing
- observability, measurability, and repeatability of experiments and phenomena that are difficult to investigate in nature;
- short time scales allowing multiple scenarios of long or complex flow to be conducted quickly;
- input and process control to assess theoretical and numerical model behavior and overviews of spatial pattern formation (morphology); and
- cost effective ways to fill in field measurements.

Although physical modeling is reputable and a standard for many modeling problems, it does not come without limitations, such as
- inability to reproduce similitude for all scaling criteria at once;
- difficulty in obtaining precise measurements;
- collateral influence from model effects (erroneous boundary effects);
- expensive construction and retrofit costs;
- dedicated facilities for large domains; and
- dependence on modeler’s experience.

A large portion of these weaknesses can be overcome with the simultaneous use of numerical models, which can provide
- resistance to scale affects;
- accurate representation of most physical processes;
- multiple experimental scenarios and options;
- data from any point within the domain at any time;
- low costs; and
- easy operation and storage.

However, their own set of weaknesses that need to be acknowledged and circumvented are
- computational time constraints for large domains;
- minor processes that cannot be represented;
- incorrect production techniques that can produce numerical errors;
- output based on representations by parameterizations derived from old physical models; and
- alternative settings that yield different results.

It can be seen that using a suite of tools increases the overall robustness of modeler’s approaches (J. Sutherland, 2011).
2.1. SSPM

Jointly funded by the Louisiana Department of Natural Resources, LSU College of Engineering Foundation, and Private Sector Donations, LSU’s first physical model of the Mississippi River provided an introduction into distorted scale physical modeling. Capturing 77 river miles and an area of 3,526 square miles (Figure 1), the Small Scale Physical Model (SSPM) of the lower Mississippi river delta was a distorted scale mobile bed physical model with 1:12,000 horizontal to 1:500 vertical scales.

Figure 1 Overview of SSPM model domain showing sediment deposition along the lowermost 60 river miles

The model was capable of qualitatively reproducing effects of the Mississippi River’s transport of course grained sediment and gave engineers useful experience and valuable insight of lower river processes. The sediment transport characteristics of a water year were simulated correctly, with dredging quantities being reproduced accurately over multiyear or decadal time scales. Silt and clay deposition was modeled with time lapse photography of freshwater dispersion over salt water marsh.

The SSPM had some operational limitations that will be improved on in the ESSPM. Artificial sediment used for simulation begins to float at 74 degrees Fahrenheit; because the model is housed in warm Louisiana, water needs to be chilled before simulation. Water levels were measured with a caliper, dredge maintenance was done with a cooking baster, and sediment was
added to the water column manually; more automation of measurements is planned for better accuracy and reproducibility of results.

Engineers were able to qualitatively evaluate diversions scenarios and impacts of future without project (base case) over decadal time scales. Diversion operating times were optimized for sediment delivery and to minimize navigation problems. Solutions to river shoaling were explored; demonstrations of methods to store sediment in deep cross sections and predictions of future dredging based on management and sea level rise were investigated.

### 2.2. ESSPM

The goal of the ESSPM is to expand previous physical modeling efforts undertaken with the SSPM; a reduction in the distortion scale (24 to 15) facilitates more quantitative studies. The physical model is capable of precisely reproducing variables such as stage but must also capture spatial and temporal sedimentation trends. In this respect, the model is imperfect and must be considered “semi-quantitative”.

A domain extending all the way to Donaldsonville (two times that of the SSPM) increases the length and influence of potential management and diversion scenarios. Because of its large size, the model will essentially take up an entire warehouse. Instead of seeing the process of selecting a location as a burden, it was visualized as an opportunity, so the ESSPM will be housed in the Center for River Studies on the Baton Rouge Water Campus, a new collaborative, state of the art research hub located on the Mississippi River in downtown Baton Rouge.

### 2.3. Numerical Modeling of Physical Models

One of the most significant benefits of composite modeling is “modeling the model”, which means that the exact geometry of the initial or baseline physical model is numerically modeled at a 1:1 scale so that numerical modeling errors can be evaluated and corrected if possible. This quality control effort is effective in reducing or eliminating the uncertainties of the numerical modeling. (J. Sutherland, 2011) There are several relatively applicable papers in which composite modeling has been conducted.

(Grunnet, 2008) combined local physical modelling and large scale numerical to test a complimentary suite of modeling tools. A shallow water wave basin physical model was combined with high resolution modelling of waves, current, sediment transport, and morphological evolution of the bed. The numerical model was applied by scaling forcing data from prototype to model scale, providing valuable details and boundary conditions, good reproduction of morphological changes, and supplying information for the design of physical models (Grunnet, 2008).

In 2009, the National Laboratory for Civil Engineering in Portugal conducted a flume experiment measuring free surface as the scale varied; the main purpose was measurement of wave propagation, however an experimental framework for good composite modeling is outlined. Experimental data is used to calibrate a numerical model on which the methodology and scale errors are evaluated; it is shown that varying model scales can produce different wave heights (Lemost, 2009).
(Zanichelli et al., 2004) conducted a flood risk analysis which compared results obtained of a physical model with the ones produced by 2-D numerical model (FESWMS). Problems and limitations of the two different approaches are outlined to underline the applicability of each type in riverine environments. A detailed section on roughness scaling is included (Zanichelli et al., 2004).

A composite modeling approach was used as a design aid in the construction of a pump station and fish screen on the Sacramento River. A physical model and two-dimensional (2-D) numerical model were used to determine anticipated water surface elevations and velocities in the river with and without diversions. An additional 2-D numerical sediment and hydraulic model was developed at model scale for verification purposes, yielding predictions of sediment deposition and scour patterns along the proposed hydraulic structure. The collaborative results from the physical and 2-D numerical models allowed many design questions to be answered more accurately and thoroughly than using only one model (Kendra Russell, 2010).

### 2.4. Scaling the ESSPM

The theory behind physical model scaling is well documented with plenty of literature available to support design (Allen, 1952; American Society of Civil Engineers. Hydraulics Division. et al., 1978; Blench, 1969; Ivicsics, 1975; Novák et al., 1981; Research, 1941; Sharp, 1981). Designing physical models to maintain similarity of prototype systems at model size calls for the use of scale factors; the scale factor \( E = X_M / X_P \) is the linear scale ratio between the prototype P and the model M. For the ESSPM, there are three scales of interest: geometric, dynamic, and sedimentation. Geometric scaling alters the overall dimensions of a model in one or more planes, which predictably impacts the hydraulics. Dynamic scales are those that replicate flow parameters such as flow rate, velocity, and Reynolds Numbers. Sedimentation scales are those that govern sediment parameters such as grain size incipient motion and deposition rates. ESSPM scales are reduced as an improvement over the original SPPM, but because of differences in sensitivities, certain scales are similar. For example, limitations in grinding of synthetic sediment bar the grain size and sediment density from dropping below a certain threshold.

Open channel flow is governed by the balance of inertial and gravitational forces, typically evaluated using the Froude Number, which is defined as

\[
Fr = \frac{U}{\sqrt{gd}}
\]

Where

\( U \) = velocity
\( g \) = gravitational constant
\( D \) = depth

The SSPM and ESSPM were developed based on Froude Number scaling; equality of the Froude number on the model and prototype is essential, so Froude Number similarity must be 1.
\[ Fr_M = Fr_P \]  

The ratio between model and prototype Froude Numbers is called the Froude Scale and given as

\[ E(Fr) = \frac{Fr_M}{Fr_P} = \left( \frac{U_M}{\sqrt{gD}} \right) \left( \frac{U_P}{\sqrt{gD}} \right) = 1 \]  

The Reynolds number governs flow regimes; Rough/Turbulent flow must be maintained in the ESSPM to reproduce adequate sediment transport conditions. Sufficiently large Reynolds numbers (minimum for this type of model Re>7500) (BCG Engineering & Consulting, 2011) are required to guarantee rough turbulent flow for the range of discharges to be tested on the model (400,000 cfs to 1,250,000 cfs); it is expected that flows above 500,000 cfs (spring and early summer months; March to June) will have enough turbulence to ensure the synthetic sediment remains in suspension. The Reynolds number is defined here as

\[ Re = 4RhU/\nu \]  

Where  
\( U \) = mean velocity  
\( Rh \) = hydraulic radius  
\( \nu \) = kinematic viscosity

A Reynolds number ratio of 1 is impossible to achieve while maintaining similarity of other relevant parameters. Overlooking this is dependent upon maintaining rough turbulent conditions because the slopes of the moody diagram lines are nearly horizontal within this region and beyond.

2.5. Geometric Scales

The ESSPM 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 Figure 2 (ESSPM Feasibility Report).
Figure 2 Model Reynolds Numbers (yp=60 ft) used to iteratively selected ESSPM distortion scale

This led to a horizontal scale of 1:6000 and a vertical scale of 1:400, resulting in a distortion of 15. Reproducing hydraulics at the model scale necessitates the correct derivation of scaling formulas; variable descriptions based off the final horizontal (L) and vertical (H) scales chosen and used in scaling formals and derivations are as follows:

- **Length scale:**  
  \[ E(L) = \frac{L_M}{L_P} = \frac{1}{6000} \]

- **Vertical scale:**  
  \[ E(H) = \frac{H_M}{H_P} = \frac{1}{400} \]

- **Distortion Scale**  
  \[ \Delta = \frac{E(H)}{E(L)} \]

- **Area Scale**  
  \[ E(A) = E(L)E(H) \]

- **Bank slope:**  
  \[ f = \frac{L}{H} \]

- **Bank Slope Scale Factor**, \( E(f) = \frac{1}{\Delta} = \frac{1}{15} \)

2.6. Dynamic Scales

The ratio of all relative corresponding forces acting in the system, known as dynamic similarity, must be constant. The force ratios are scaled through the application of dynamic scales shown below.

Rewriting the Froude Number ratio with velocity as the dependent term yields the velocity scale factor, \( E(U) \).
\[
E(U) = \frac{U_M}{U_P} = \sqrt{\frac{H_P}{H_M}} = E(H)^{1/2} = \frac{1}{20}
\] (5)

This can be interpreted as 1 unit velocity on the model being equivalent to 20 units in the prototype. A discharge scale factor, \(E(Q)\), is developed through inserting the velocity and area scale factors into the discharge equation: \(Q = \text{Velocity} \times \text{Area}\), and is calculated as

\[
E(Q) = \frac{Q_M}{Q_P} = E(H)^{3/2} E(L) = \left(\frac{1}{400}\right)^{\frac{3}{2}} \left(\frac{1}{6000}\right) = \frac{1}{48,000,000}
\] (6)

This can be interpreted as 1 unit discharge on the model being equivalent to 48,000,000 units in the prototype. The average annual long-term hydrograph used for the present testing series has a peak flow of 1,250,000 cfs (0.026041667 cfs at model), so the corresponding model discharge is equivalent to:

\[
\left(\frac{1250000}{35.3}\right) \times 1000 = .74 \text{ l/s}
\] (7)

The hydraulic time scale, \(E(T)\), is developed through solving for time in the uniform motion equation \(time = distance/velocity\), and given as

\[
E(T) = \frac{T_M}{T_P} = \frac{E(L)^{1/2}}{E(H)^{1/2}} = \left(\frac{1}{400}\right)^{1/2} = \frac{1}{300}
\] (8)

A single flow year could then be modeled in 1.2 days.

2.7. Sediment Material Scale

Shields law is used in order to properly scale incipient sediment particle motion. According to Shields theory and experiments, the beginning of cohesionless bed material movement is given by \(Y_{cr} = f(X_{cr})\).

\[
X_{cr} = U_{cr}^* \frac{D}{\nu} \text{ (sediment particle Reynolds number)}
\] (9)

\[
Y_{cr} = \rho \frac{U_{cr}^*}{(\rho_S - \rho)gD} \text{ (mobility number)}
\] (10)
where:

- $X_{cr}$ and $Y_{cr}$ are dimensionless numbers
- $U_{cr}^*$ = critical shear velocity
- $D =$ diameter of the sediment particle
- $\rho =$ fluid density
- $\rho_s =$ sediment density
- $g =$ gravitational acceleration
- $\nu =$ kinematic viscosity

A similarity will be obtained if:

\[
E(X_{cr}) = 1 \\
E(Y_{cr}) = 1
\]  

(11)  

(12)

Sediment material scale factors can be developed by rearranging the mobility and sediment particle Reynolds number equations and solving for unknowns. The model sediment (a synthetic plastic) specific gravity was chosen to be 1.05; therefore, the density scale factor, $E(\rho_s)$, is calculated as:

\[
E(\rho_s) = \left( \frac{\rho_{SM}}{\rho_{SP}} \right) = \left( \frac{1050}{2650} \right) = \frac{1}{2.5}
\]  

(13)

The dry density scale factor, $E(\rho_s - \rho)$, can be written as

\[
E(\rho_s - \rho) = \frac{\rho_{SM} - \rho}{\rho_{SP} - \rho} = \frac{1}{33}
\]  

(14)

From $E(X_{cr}) = 1$, it is implied that $E(\rho_s) \cdot E(D)^3 = 1$. A sediment diameter scale factor, $E(D)$, can be calculated by rewriting the equation with diameter as the dependent variable, yielding

\[
E(D) = \left( \frac{1}{E(\Delta \rho)} \right)^\frac{1}{3} = 3.2
\]  

(15)

This implies that the model sediment diameters are 3.2 times larger than the corresponding prototype sediment (sand) diameters. Solving for mass in the traditional equation of density =
mass/volume and inserting the corresponding scale factors yields the mass scale factor, which is the ratio of prototype mass to synthetic sediment mass to prototype sand mass. The mass scale factor, $E(P)$, is given by:

$$E(P) = E(\rho_S) * E(\Omega) = \left(\frac{1}{2.5}\right) \times \left(\frac{1}{1.44 \times 10^{10}}\right) = \frac{1}{3.6 \times 10^{10}}$$

(16)

Where:

$\Omega$ = Volume

Notice this is the same equation as used in the sediment diameter scale factor, with diameter cubed being replaced with volume.

### 2.8. Sedimentation Time Scale

The purpose of the ESSPM is to simulate the bulk suspended sediment load transport and deposition in the river during flood flows. The sedimentation time is defined as the time necessary for filling in a volume $V_s$ (m$^3$) with a sediment transport $Q_s$ (kg/s) (BCG Engineering & Consulting, 2011). In general, the time is defined during model calibration by comparison of well known morphological features of the river or sea bed in nature and reproduced on the model: for example, evolution of coastal features like the creation of a large sand bank, or accretion of a delta area, etc.

For large scale water diversions, sand transport and deposition patterns are captured by model sediment reproducing sands of particle size between 62 and 300 m which comprise about 20% to 25% of the total sediment load transported by the Mississippi River. The 75-80% remaining sediment load, consisting of silts and clays, can be estimated through cyclical dye injection and time lapse photography. The sediment time scale factor, $E(t_S)$, is approximated with

$$E(t_S) = E(T)E(\rho_S - \rho) = .0001,52.56 \text{ minutes}$$

(17)

The sediment time scale works out to 1:10,000 or roughly that one year of prototype time equals 53 minutes of ESSPM time. This time scale is used for the general use of the model, because the purpose of these typical model runs is to measure the 1-D bulk sediment transport process.

ESSPM sediment load is intended to represent the total sand load transported by the Mississippi River, which is around 20,000,000 tons per water year. Scaling the sand load shows the amount of synthetic (model) sediment that will need to be added each year (53 minutes). The amount of mass, $P_M$, required to operate the model for an average water year is seen to be

$$P_M = Pp * E(P) = 20,000,000 \times \frac{1000}{3.6 \times 10^{10}} = .555 kg$$

(18)

The corresponding SSPM load and sediment time scale was about .110 kg and 30 minutes of run time per year. The new model will require 555 grams and 53 minutes. The following equation approximates the amount of sediment needed for future tests above and beyond sediment in initial condition.
Mass Required, Kg = .555 * \left( \frac{t}{53} \right) \tag{19}

This equation is only an approximation for an average yearly flow. Considering a typical yearly hydrograph for the Mississippi River, it is obvious that transport isn’t uniform; there will be peaks and lulls in sediment loading. Therefore this result is completely dependent on assumed sediment loading in the prototype and isn’t accurate for times shorter than 1 year.

### 2.9. Roughness Scaling

The slope of the energy grade line, known as the friction slope \((S_f)\), indicates where energy is lost in the model. The ratio between model and prototype friction slopes can be used as an indication where numerical models are losing more energy relative to one another, accurately reproducing this relationship helps ensure deposition and erosion patterns are matched. Losses in HEC-RAS model come from friction or expansions and contractions; the energy grade line for adjacent cross sections with similar geometry under uniform flow is approximately the topographic channel slope. Hence, friction slope ratio should be nearly the bank/bed slope scale factor. For non-uniform flow conditions, the friction slope is calculated from the manning’s equation as

\[ S_f = \left( \frac{Q}{K} \right)^2 \tag{20} \]

Where
- \(Q\) = flow
- \(K\) is channel conveyance. The channel conveyance is defined as

\[ K = \frac{AR_h^2}{n} \tag{21} \]

Where
- \(A\) = area
- \(R_h\) = hydraulic radius
- \(n\) = manning’s roughness

As previously stated, HEC-RAS evaluates losses through friction and expansion/contraction. Frictional losses vary by Manning’s roughness values. For a given flow, higher roughness coefficients will raise water levels and slow velocities. Small scale physical models tend to have problems reproducing model roughness. An important question should be addressed: what is the required roughness to reproduce prototype conditions? Roughness values can be scaled through rearranging the manning’s equation (Webb et al 2013), such that the roughness ratio, \(n_r\), equals:

\[ n_r = \frac{R_h^{2/3} S_f^{1/2}}{U_r} \tag{22} \]

Where
It should be noted that the hydraulic radius and friction slope are both numerical model outputs; the equation could be rearranged to be a function of hydraulic radius and area as friction slope. Webb also indicates that there are no current publications that validate the roughness scaling equation. It should also be noted flows that are hydraulically smooth or in the transition flow regime do not scale accurately according to equation 22.

2.10. Scaling Summary

The hydraulic similarity in the vertical direction is usually affected in distorted physical models, however since 1-D models overlook such distinctions due to their cross sectional averaged results. HEC-RAS is limited to bulk deductions about sediment transport represented in the Reynolds Number, but vertical results provide better accuracy and extra detail when investigating scaled sediment transport rates. 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. Effect of distortion on bed load is observed in sediment movement and transport rates due to increases of vertical and horizontal slopes at the riverbed Lu et al. (2013). Figure 3, below, contains the dynamic scaling ratios for D1 and D7.5 alongside the previously outlined results at prototype and model scale.

<table>
<thead>
<tr>
<th>Scale/Ratio</th>
<th>P</th>
<th>D1</th>
<th>D7.5</th>
<th>D15</th>
</tr>
</thead>
<tbody>
<tr>
<td>E(L)</td>
<td>1</td>
<td>1/400</td>
<td>1/3000</td>
<td>1/6000</td>
</tr>
<tr>
<td>E(H)</td>
<td>1</td>
<td>1/400</td>
<td>1/400</td>
<td>1/400</td>
</tr>
<tr>
<td>E(A)</td>
<td>1</td>
<td>1/160,000</td>
<td>1/1,200,000</td>
<td>1/2,400,000</td>
</tr>
<tr>
<td>E(f)</td>
<td>1</td>
<td>1</td>
<td>7.5</td>
<td>15</td>
</tr>
<tr>
<td>Δ</td>
<td>#N/A</td>
<td>1/1</td>
<td>1/7.5</td>
<td>1/15</td>
</tr>
<tr>
<td>E(Fr)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>E(Q)</td>
<td>1</td>
<td>1/3,200,000</td>
<td>1/24,000,000</td>
<td>1/48,000,000</td>
</tr>
<tr>
<td>E(U)</td>
<td>1</td>
<td>1/20</td>
<td>1/20</td>
<td>1/20</td>
</tr>
<tr>
<td>E(T)</td>
<td>1</td>
<td>1/20</td>
<td>1/150</td>
<td>1/300</td>
</tr>
<tr>
<td>E(Rh)</td>
<td>1</td>
<td>1/400</td>
<td>1/514</td>
<td>1/646</td>
</tr>
<tr>
<td>n_r</td>
<td>1</td>
<td>0.37</td>
<td>0.85</td>
<td>1.04</td>
</tr>
</tbody>
</table>

Figure 3 Summary of Scale Ratios at each distortion relative to Prototype

The biggest takeaways of Figure 3 should be the roughness ratios at D1 and D7.5; the mannings roughness coefficient at D1 is 0.37 of that at prototype scale while D7.5 is 1.21 higher.
As previously mentioned, an iterative process was used to select a geometric scale that could maintain rough-turbulent conditions, yielding a final distortion of 15. Relevant scales at each distortion are summarized in the Figure 4. It is assumed the sediment material scale does not change between distortion scales.

<table>
<thead>
<tr>
<th></th>
<th>D15</th>
<th>D7.5</th>
<th>D1</th>
<th>D1</th>
<th>D1</th>
<th>D1</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>E(L)</td>
<td>1/6000</td>
<td>1/3000</td>
<td>1/400</td>
<td>1/100</td>
<td>1/10</td>
<td>1/5</td>
<td>1</td>
</tr>
<tr>
<td>E(H)</td>
<td>1/400</td>
<td>1/400</td>
<td>1/400</td>
<td>1/100</td>
<td>1/10</td>
<td>1/5</td>
<td>1</td>
</tr>
<tr>
<td>Wp</td>
<td>0.98</td>
<td>1.56</td>
<td>9.15</td>
<td>36.60</td>
<td>366.00</td>
<td>732.00</td>
<td>3660</td>
</tr>
<tr>
<td>A</td>
<td>0.116</td>
<td>0.232</td>
<td>1.75</td>
<td>28.00</td>
<td>2800.00</td>
<td>11200.00</td>
<td>280000</td>
</tr>
<tr>
<td>Rh</td>
<td>0.118</td>
<td>0.15</td>
<td>0.19</td>
<td>0.77</td>
<td>7.65</td>
<td>15.30</td>
<td>76.50</td>
</tr>
<tr>
<td>Sf</td>
<td>15</td>
<td>7.5</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Vr</td>
<td>0.05</td>
<td>20.00</td>
<td>0.05</td>
<td>0.10</td>
<td>0.32</td>
<td>0.45</td>
<td>1</td>
</tr>
<tr>
<td>Rhr</td>
<td>0.0015</td>
<td>0.0019</td>
<td>0.0025</td>
<td>0.0100</td>
<td>0.1000</td>
<td>0.2000</td>
<td>1</td>
</tr>
<tr>
<td>nr</td>
<td>1.036</td>
<td>0.853</td>
<td>0.368</td>
<td>0.464</td>
<td>0.681</td>
<td>0.765</td>
<td>1</td>
</tr>
<tr>
<td>nr (from 15)</td>
<td>1</td>
<td>0.823</td>
<td>0.356</td>
<td>0.448</td>
<td>0.657</td>
<td>0.738</td>
<td>0.965</td>
</tr>
</tbody>
</table>

Figure 4 Roughness Ratio Behavior vs Distortion as Horizontal and Vertical Scales Change
3. Methods

The software used in this thesis is the Hydraulic Engineering Center River Analysis System (HEC-RAS) version 4.2 (http://www.hec.usacarmy.mil/software/hec-ras/downloads.aspx), which can be used to predict hydraulics, sediment transport, and water quality. HEC-RAS provides a user interface in which inputs are entered using tables and outputs are offered in graphical or tabular format. The model is capable of simulating steady and unsteady, as well as quasi-unsteady flow for long term predictions over large spatial domains.

3.1. Description of HEC-RAS

The Hydraulic Engineering Center has produced in-depth technical explanations of the program’s computational methods called the Hydraulic Reference Manual; the following descriptions are based on the material contained therein.

3.1.1. Geometric Data Editor

A reach is a channel, river, stream, or a section of these drawn within the geometry data interface. Multiple cross sections are added to each reach, which can be independently edited for potential adjustments, added detail, and numerical stability. Each cross section has a maximum of 500 points that should be entered from left to right looking downstream and should include data such as Manning’s roughness, bank stations, reach lengths, and expansion/contraction coefficients. Primary methods to vary roughness for calibration depend on space, flow, and time. Spatial tools allow control of the coefficient both within and along the model domain, flow roughness factors adjust the manning’s coefficient during between user input flow sizes, and seasonal roughness factors allow for adjustments based on monthly model input time.

3.1.2. Steady Flow Data Editor

The user can simulate up to 25,000 profiles, each requiring an upstream and downstream boundary condition. In addition to an upstream input flow, available boundary conditions include: critical depth, normal depth, known water surface, and a rating curve. There are options for flow change locations, adding observed water surface elevations, and flow ratios.

3.1.3. Unsteady Flow Data Editor

To simulate unsteady flows, boundary and initial conditions are required. Downstream boundary conditions for each reach may consist of stage hydrographs, flow hydrographs, stage/flow hydrographs, normal depth, or rating curves. Initial conditions consist of the initial flow distribution for the upstream cross-section of each reach and the initial elevation of water in any storage areas.

3.1.4. Unsteady Flow Analysis Editor

A plan is described as a simulation file linked to specific geometry and flow files and with a set start and ending time. A computational time interval, hydrograph output interval, and detailed output interval must be selected, which are available in a drop down menu to a frequency of one
second. HEC-RAS offers multiple programs to run, included geometry preprocessor, unsteady flow simulation, or the post processor. This window also allows the user to edit the computational options and tolerances, runtime computational options, initial backwater flow, mixed flow, and more. After initializing a run, the program will ensure that all boundary conditions are satisfactory, or will otherwise output a detailed error message. After a simulation is complete, hydrodynamic parameters are available in graphical or tabular output.

3.1.5. Governing Equations

3.1.5.1. Steady Hydraulics

HEC-RAS performs one-dimensional subcritical, supercritical, and mix flow regime water surface profile calculations for steady flow. Water surface profiles are calculated from cross section to cross section through the energy equation and standard step method;

\[ Y_2 + Z_2 + \frac{\alpha_2 V_2^2}{2g} = Y_1 + Z_1 + \frac{\alpha_1 V_1^2}{2g} + h_e \]  \hspace{1cm} (23)

The headloss term is calculated as:

\[ h_e = L S_f + Z_2 + \left| \frac{\alpha_2 V_2^2}{2g} - \frac{\alpha_1 V_1^2}{2g} \right| \]  \hspace{1cm} (24)

where:

\( Y_1, Y_2 = \) depth at cross sections

\( Z_1, Z_2 = \) elevation of main channel inverts

\( \alpha_1, \alpha_2 = \) velocity weighting coefficients

\( V_1, V_2 = \) an expansion or contraction loss coefficient

\( g = \) gravitational accelerations

\( L = \) discharge weighted reach length

\( S_f = \) representative friction slope between XS1 and XS2

The friction slope and discharge weighted reach length are given by equations 25 and 26, respectively:

\[ S_f = Z_2 + \left( \frac{Q_1 + Q_2}{K_1 + K_2} \right)^2 \]  \hspace{1cm} (25)

\[ L = Z_2 + \left( \frac{L_{lob} Q_{lob} + L_{ch} Q_{lob} + L_{rob} Q_{rob}}{Q_{lob} + Q_{ch} + Q_{rob}} \right) \]  \hspace{1cm} (26)

where:
$K =$ conveyance,

$L =$ cross-section reach length for flow,

$Q =$ the arithmetic average of flows between sections, and

$lob, ch, rob =$ the subscripts indicating left over-bank, channel, and right over-bank, respectively.

The total conveyance and the velocity coefficient are determined by subdividing the flow in the main channel from the over-banks. Flow and conveyance are calculated for each section by equations

$$Q = KV_f^{1/2}$$

$$K = \frac{1.489}{n} A R_h^{2/3}$$

Where:

$K =$ channel conveyance

$n =$ manning’s roughness coefficient

$A =$ flow area

$R_h =$ Hydraulic Radius

Rapidly varying flow conditions for which the energy equation is not applicable, employ the momentum equation. The most recent version of steady state HEC-RAS (4.2) assumes the river channels have small slopes (i.e. less than 1:10), which is perfect for the lower Mississippi river having a slope of $10^{-5}$.

### 3.1.5.2. Unsteady Hydraulics

Unsteady flow regimes are solved through derivations of the momentum and continuity equations. A flow hydrograph of discharge versus time is applied as the upstream boundary condition while the downstream boundary condition can be a stage hydrograph, flow hydrograph, single-valued rating curve, or normal depth. Internal boundary conditions can also be added at user-defined areas. Initial conditions for the system are established through either a steady flow backwater run or a restart file from a previous run. HEC-RAS allows adjustable computation intervals, which is advantageous for rapidly varying inflow hydrographs, such as the ESSPM (Center, 2010)

The continuity equation is presented as
where

\[ x = \text{distance along the channel}, \]
\[ t = \text{time}, \]
\[ Q = \text{flow}, \]
\[ A = \text{cross-sectional area}, \]
\[ S = \text{storage from non conveying portions of cross section} \]
\[ q_1 = \text{lateral inflow per unit distance} \]

The momentum equation states that the rate of change in momentum is equal to the external forces acting on the system.

\[ \frac{dA}{dt} + \frac{dS}{dt} + \frac{dQ}{dx} - q_1 = \frac{1.489}{n} AR_h^{2/3} \]

\[ \frac{dQ}{dt} + \frac{d(VQ)}{dx} + gA \left( \frac{dz}{dx} + S_f \right) = 0 \]

Where

\[ g = \text{acceleration of gravity} \]
\[ S_f = \text{friction slope} \]
\[ V = \text{velocity} \]

### 3.2. Model Development

#### 3.2.1. Geometry Data Description

ESSPM geometry data sets are comprised of billions of xyz points coming from LiDAR, topographic/bathymetric surveys from USACE, USGS, and NOAA, and modeled data points (cite C&C Technologies). River points come from USACE 2004 Mississippi River Decadal Hydrographic Survey but some cross sections were lowered to accommodate placing a bed of synthetic model sediment (personal communication, C. Soileau, 2014). An overview of the entire ESSPM model domain can be seen in Figure 5; the area delimited in green represents an already completed, shortened section of the domain on which preliminary experiments and numerical modeling are performed- commonly referred to as the “Guinea Pig” model.
Per C&C Technologies (personal communication, 2014), all data was processed and projected into LA-S, NAD83 coordinate system as the horizontal datum with a 10 degree rotation from grid north. The vertical datum is NAVD88. All of the xyz points were then scaled by the horizontal (1:6000) and vertical (1:400) scales creating an ESSPM model domain of approximately 120 by 90 feet. The ESSPM model domain was then divided into 216 5 ft x 10 ft sections/panels (Figure 5). Each panel is about 200 mega bites in size and contains roughly 6 million points in ASCII format; each panel dataset was simplified with ArcMap by trimming points lying outside the main channel. The data was pulled into AutoCAD Civil 2013 to create a Triangular Irregular Network (TIN) surface on which a 43 mile alignment and 180 cross section lines (checked with Samuels equation) were generated. The new geometry was exported in ASCII format, where it was copied and scaled to the distortions of 7.5, 1, and prototype, creating identical scale models; aerials views of the numerical model and distortion for the Guinea Pig section can be seen in Figure 6 and Figure 7.
From Figure 7, a distortion of 15 transforms a typical cross section from 3500 feet wide and 80 deep feet into a space 7 inches wide and 2.4 inches deep; a 7.5 distortion shares the same depth, but is twice as wide. Increasing distortion to 7.5 and 15 leads to a relative increase in depth, as seen in Figure 8; distortions of 1 through 15 share the same depth but become incrementally narrower.
On October 7th 2014, LSU graduate students and BCG engineers Cecil Soileau and Bhuban Ghimire conducted a series of experiments on the Guineapig ESSPM. Both steady and unsteady flow rates were run through the model with water surface measurements being recorded every half second at 5 locations within the model (Figure 6), including the downstream boundary condition. Data was collected using U-Gage ultrasonic water level sensors that can accurately measure up to half a millimeter (.0016 ft). Four steady flow profiles (SF1 – SF4) were taken with water surface readings recorded at river miles 138.8, 126.9, 113, 102.5, and 98.1 (Figure 9).

<table>
<thead>
<tr>
<th>Profile</th>
<th>P Flow (cfs)</th>
<th>D15 Flow (cfs)</th>
<th>Reserve (ft)</th>
<th>Bonnet Carre (ft)</th>
<th>River Ridge (ft)</th>
<th>Carrollton (ft)</th>
<th>Harvey (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SF1</td>
<td>600,000</td>
<td>0.013</td>
<td>0.0227</td>
<td>0.0226</td>
<td>0.0204</td>
<td>0.0196</td>
<td>0.0186</td>
</tr>
<tr>
<td>SF2</td>
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<td>0.017</td>
<td>0.0333</td>
<td>0.0333</td>
<td>0.0295</td>
<td>0.0279</td>
<td>0.0265</td>
</tr>
<tr>
<td>SF3</td>
<td>1,000,000</td>
<td>0.021</td>
<td>0.0388</td>
<td>0.0388</td>
<td>0.0335</td>
<td>0.0310</td>
<td>0.0298</td>
</tr>
<tr>
<td>SF4</td>
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<td>0.025</td>
<td>0.0436</td>
<td>0.0429</td>
<td>0.0369</td>
<td>0.0338</td>
<td>0.0320</td>
</tr>
</tbody>
</table>

Data from Figure 9 can also be represented graphically (Figure 10 & Figure 11), which better reflects water surface slopes at both model and prototype scale.
Figure 10 Four Observed Steady Flow Water Surface Profiles

Figure 11 Four Observed Steady Flow Water Surface Profiles at Prototype Scale
BCG has developed a five day average hydrograph simulating a flood wave of gradually rising and falling flow which can be seen in Figure 12 and Figure 13.

Figure 12 Observed Unsteady Flow Hydrograph for each Gage Station

Figure 13 Observed Unsteady Flow Hydrograph for each Gage Station at Prototype Scale
In Figure 12 and Figure 13 peak flow (~1,100,000 cfs) transitions from and into steady flows which are bounded by low flows (~500,000 - 450,000 cfs). Data loggers measure changes in water surface elevation every half second, which correspond to a prototype hydraulic scale of 12 hours. There are approximately 210 prototype days of simulation time.

Lastly, three series of surface velocity measurements were collected for each steady flow. Lightweight foam was placed 3ft in front of the gage corresponding to Bonnet Carre (RM 138.8) and travel time between gages was measured using a stopwatch. Averaged results can be seen below in Figure 14, with data points being placed evenly between gages.

3.2.3. Channel Roughness

The ESSPM model surface consists of a smooth, sprayed on layer of paint with an unknown roughness. Random locations have spots where the paint has been scraped off, but the vast majority of the domain is still covered. The manning’s roughness coefficient will be determined through the calibration procedure, and represents most of the energy loss that occurs in the model, so it cannot solely represent the channel roughness. Simulations varying the manning’s roughness will be conducted until a calibrated, spatially dependent roughness will be selected.

3.2.4. Boundary Conditions

3.2.4.1. Steady

Model boundary conditions include measured upstream flow and downstream water surface elevations, as described in 3.2.2. A summary of the boundary conditions between model and prototype scale can be found in Figure 15, below. The boundary conditions for a distortion of 7.5 and 1 have been omitted, as those simulations are only performed for unsteady state.
It is important to remember that the downstream boundary conditions are the measured water surface elevation at the Harvey Lock gage (RM 98.1) and technically a few inches upstream from the overflow weir, which controls the water surface. However, this can be overlooked because the known water surface input from the Harvey gage is sufficiently close to the bottom of the ESSPM model domain.

### 3.2.4.2. Unsteady

Model boundary conditions include a known upstream flow and downstream water surface, which were recorded from experimental data and are detailed in 3.2.2. A summary of the boundary conditions between model and prototype scale can be found in Figure 16 to Figure 19, below.
Figure 17 Unsteady State Boundary Conditions at a Distortion of 7.5

Figure 18 Unsteady State Boundary Conditions at a Distortion of 1
3.3. Calibration and Validation

3.3.1. Steady

During calibration, the manning’s roughness coefficient is adjusted to cause the water surface slope to resembled observed values; the goal of ESSPM calibration was to bring simulated water surfaces to match the observed data collected and detailed in section 3.2.2. Three typically used goodness-of-fit statistics were used with performance metrics outlined by Meshele and Rodrigue 2013: (1) the root mean square error (RMSE) percentage, (2) the Pearson product-moment correlation coefficient, and (3) bias. The RMSE provides a variation of predicted or modeled data to observed data and the bias helps test if the model is consistently over or underestimating critical quantities. The correlation coefficient is omitted from statistical analysis in steady flows as it is a measure of the phasing between the predicted and observed data. Note that the numerical model, with a distortion of 15, is the only one capable of being calibration due to available data.

Initially, steady state simulations were performed with roughness coefficients varying from $n = 0.01$ to $n = 0.03$ in order to see which coefficients are most representative within each part of the domain and for each flow. Water surface comparisons between simulated data with varying roughness and experimental data and simulated can be seen in Figure 20 to Figure 23. The lower most gage stations (98.1 and 102.8) are disregarded in calibration analysis due to their proximity to the downstream boundary condition, but are shown nonetheless.
Figure 20 Water Surface Slope along domain for SF1

Figure 21 Water Surface Slope along domain for SF2

Figure 22 Water Surface Slope along domain for SF3
Figure 23 Water Surface Slope along domain for SF4

Figure 20 through Figure 23 reflect the computed water surface elevation at each roughness for every steady flow profile. The left graphs display all data, the right shows observed versus computed results for roughness most similar. Clusters of data represent individual gage locations and the solid black line has a 1:1 slope, representing perfect a model that would perfectly reproduce the observed water surface. Lower flows matched more closely with \( n = 0.02 \) while higher flows shifted towards \( n = 0.01 \), especially at RM 113 and RM 138.8. The roughness value that appeared to be most representative of measured data was \( n = 0.15 \). Upstream roughness values may shift down with flow rate, but further calibration with flow varying roughness factors can be disregarded as calibration criteria are satisfied. Moreover, early attempts with flow roughness factors would lead to physically unjustifiable roughness values. Figure 24 and Figure 25 present steady state calibration metrics alongside statistics for steady state simulation results.

<table>
<thead>
<tr>
<th>Roughness/Location</th>
<th>0.0125</th>
<th>0.0168</th>
<th>0.0208</th>
<th>0.025</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bias</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.010</td>
<td>-0.038</td>
<td>0.040</td>
<td>-0.029</td>
<td>-0.026</td>
<td>&lt;10</td>
</tr>
<tr>
<td>Calibration</td>
<td>0.008</td>
<td>0.002</td>
<td>0.003</td>
<td>0.001</td>
<td>&lt;10</td>
</tr>
<tr>
<td>0.015</td>
<td>-0.004</td>
<td>-0.002</td>
<td>-0.021</td>
<td>-0.037</td>
<td>&lt;10</td>
</tr>
<tr>
<td>0.020</td>
<td>0.043</td>
<td>0.050</td>
<td>0.088</td>
<td>0.118</td>
<td>&lt;10</td>
</tr>
<tr>
<td>0.025</td>
<td>0.102</td>
<td>0.195</td>
<td>0.263</td>
<td>0.315</td>
<td>&lt;10</td>
</tr>
<tr>
<td>0.030</td>
<td>0.008</td>
<td>0.002</td>
<td>0.003</td>
<td>0.001</td>
<td>&lt;10</td>
</tr>
</tbody>
</table>

Figure 24 Bias Comparisons for Steady Flow

<table>
<thead>
<tr>
<th>Roughness/Location</th>
<th>0.0125</th>
<th>0.0168</th>
<th>0.0208</th>
<th>0.025</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>%RMSR</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.010</td>
<td>4.939</td>
<td>4.918</td>
<td>3.879</td>
<td>3.251</td>
<td>&lt;15%</td>
</tr>
<tr>
<td>Calibration</td>
<td>1.692</td>
<td>0.432</td>
<td>0.384</td>
<td>0.300</td>
<td>&lt;15%</td>
</tr>
<tr>
<td>0.015</td>
<td>2.632</td>
<td>1.947</td>
<td>3.245</td>
<td>4.795</td>
<td>&lt;15%</td>
</tr>
<tr>
<td>0.020</td>
<td>6.872</td>
<td>7.485</td>
<td>11.630</td>
<td>13.930</td>
<td>&lt;15%</td>
</tr>
<tr>
<td>0.025</td>
<td>14.290</td>
<td>16.019</td>
<td>22.361</td>
<td>24.478</td>
<td>&lt;15%</td>
</tr>
<tr>
<td>0.030</td>
<td>23.290</td>
<td>26.094</td>
<td>33.894</td>
<td>40.109</td>
<td>&lt;15%</td>
</tr>
</tbody>
</table>

Figure 25 % RMSE for Steady Flow Data
Results for bias and %RMSE indicate that a manning’s roughness coefficient of .015 is most representative from river mile 98.1 to 126.8, at which a lower coefficient may be more applicable. Specifically, the bias shows the roughness may under predict upstream and over predicts downstream, but only by very little. The calibration statistics can also be compared based on individual location, as in Figure 26 and Figure 27, which helps describe spatially varying trends.

<table>
<thead>
<tr>
<th>Roughness/Location</th>
<th>RM 138.8</th>
<th>RM 126.8</th>
<th>RM 113</th>
<th>RM 102.8</th>
<th>RM 98.1</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>-0.039</td>
<td>-0.072</td>
<td>-0.016</td>
<td>-0.025</td>
<td>0.000</td>
<td>&lt;10</td>
</tr>
<tr>
<td>Calibration</td>
<td>0.056</td>
<td>0.001</td>
<td>0.003</td>
<td>0.000</td>
<td>0.000</td>
<td>&lt;10</td>
</tr>
<tr>
<td>0.015</td>
<td>0.011</td>
<td>-0.001</td>
<td>0.027</td>
<td>0.011</td>
<td>0.000</td>
<td>&lt;10</td>
</tr>
<tr>
<td>0.02</td>
<td>0.181</td>
<td>0.095</td>
<td>0.086</td>
<td>0.009</td>
<td>0.000</td>
<td>&lt;10</td>
</tr>
<tr>
<td>0.025</td>
<td>0.33</td>
<td>0.213</td>
<td>0.161</td>
<td>0.034</td>
<td>0.000</td>
<td>&lt;10</td>
</tr>
<tr>
<td>0.03</td>
<td>0.491</td>
<td>0.345</td>
<td>0.249</td>
<td>0.064</td>
<td>0.000</td>
<td>&lt;10</td>
</tr>
</tbody>
</table>

Figure 26 Bias Comparisons based on RM for Steady Flow Data

<table>
<thead>
<tr>
<th>Roughness/Location</th>
<th>RM 138.8</th>
<th>RM 126.8</th>
<th>RM 113</th>
<th>RM 102.8</th>
<th>RM 98.1</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>3.961</td>
<td>7.263</td>
<td>1.760</td>
<td>2.540</td>
<td>0.000</td>
<td>&lt;15%</td>
</tr>
<tr>
<td>Calibration</td>
<td>1.277</td>
<td>0.249</td>
<td>0.283</td>
<td>0.177</td>
<td>0.000</td>
<td>&lt;15%</td>
</tr>
<tr>
<td>0.015</td>
<td>6.736</td>
<td>2.442</td>
<td>3.543</td>
<td>1.405</td>
<td>0.000</td>
<td>&lt;15%</td>
</tr>
<tr>
<td>0.02</td>
<td>19.951</td>
<td>11.400</td>
<td>9.839</td>
<td>1.863</td>
<td>0.000</td>
<td>&lt;15%</td>
</tr>
<tr>
<td>0.025</td>
<td>35.509</td>
<td>23.759</td>
<td>17.887</td>
<td>4.295</td>
<td>0.000</td>
<td>&lt;15%</td>
</tr>
<tr>
<td>0.03</td>
<td>52.213</td>
<td>37.599</td>
<td>27.274</td>
<td>7.495</td>
<td>0.000</td>
<td>&lt;15%</td>
</tr>
</tbody>
</table>

Figure 27 %RMSE based on RM for Steady Flow Data

### 3.3.2. Unsteady

The calibrated, spatially varying manning’s roughness coefficients from steady state were first used for the unsteady simulation runs (Figure 28 through Figure 30). Unsteady simulations results, using the n values from the steady state calibration process, showed relatively significant differences with the unsteady experimental observations.

<table>
<thead>
<tr>
<th>Roughness</th>
<th>RM 138.8</th>
<th>RM 126</th>
<th>RM 113</th>
<th>RM 102.5</th>
<th>RM 98</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>-0.121</td>
<td>-0.123</td>
<td>-0.038</td>
<td>-0.038</td>
<td>0.000</td>
<td>&lt;10</td>
</tr>
<tr>
<td>Calibration</td>
<td>-0.050</td>
<td>-0.066</td>
<td>-0.020</td>
<td>-0.020</td>
<td>0.000</td>
<td>&lt;10</td>
</tr>
<tr>
<td>0.015</td>
<td>-0.039</td>
<td>-0.063</td>
<td>-0.013</td>
<td>-0.013</td>
<td>0.000</td>
<td>&lt;10</td>
</tr>
<tr>
<td>0.02</td>
<td>0.072</td>
<td>0.016</td>
<td>-0.011</td>
<td>-0.011</td>
<td>0.000</td>
<td>&lt;10</td>
</tr>
<tr>
<td>0.025</td>
<td>0.209</td>
<td>0.119</td>
<td>0.009</td>
<td>0.009</td>
<td>0.000</td>
<td>&lt;10</td>
</tr>
<tr>
<td>0.03</td>
<td>0.367</td>
<td>0.240</td>
<td>0.033</td>
<td>0.033</td>
<td>0.000</td>
<td>&lt;10</td>
</tr>
</tbody>
</table>

Figure 28 Bias for Steady State Calibrated n
The bias indicates the steady state calibration consistently under predicts the water surface elevation and suggest that \( n=0.02 \) is a better fit. The correlation coefficient suggests that both \( n=0.02 \) and \( n=0.015 \) align well with observed data. Percent Root Mean Square Error implies that \( n=0.02 \) is more representative of observed conditions than \( n=0.01 \), excluding RM 126 and above. Simulations and statistical analysis were repeated with a new spatially varying roughness (Figure 31 to Figure 33). The most representative roughness from RM 126.8 to RM 98.1 and from RM 126.8 up becomes \( n=0.02 \) and \( n=0.015 \), respectively.

### Correlation Coefficient

<table>
<thead>
<tr>
<th>Roughness</th>
<th>RM 138.8</th>
<th>RM 126</th>
<th>RM 113</th>
<th>RM 102.5</th>
<th>RM 98</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>0.924</td>
<td>0.933</td>
<td>0.949</td>
<td>0.949</td>
<td>1.000</td>
<td>&gt;.9</td>
</tr>
<tr>
<td>Calibration</td>
<td>0.955</td>
<td>0.957</td>
<td>0.951</td>
<td>0.951</td>
<td>1.000</td>
<td>&gt;.9</td>
</tr>
<tr>
<td>0.015</td>
<td>0.957</td>
<td>0.958</td>
<td>0.953</td>
<td>0.953</td>
<td>1.000</td>
<td>&gt;.9</td>
</tr>
<tr>
<td>0.02</td>
<td>0.972</td>
<td>0.970</td>
<td>0.949</td>
<td>0.949</td>
<td>1.000</td>
<td>&gt;.9</td>
</tr>
<tr>
<td>0.025</td>
<td>0.978</td>
<td>0.974</td>
<td>0.950</td>
<td>0.950</td>
<td>1.000</td>
<td>&gt;.9</td>
</tr>
<tr>
<td>0.03</td>
<td>0.979</td>
<td>0.974</td>
<td>0.951</td>
<td>0.951</td>
<td>1.000</td>
<td>&gt;.9</td>
</tr>
</tbody>
</table>

### %RMSE

<table>
<thead>
<tr>
<th>Roughness</th>
<th>RM 138.8</th>
<th>RM 126</th>
<th>RM 113</th>
<th>RM 102.5</th>
<th>RM 98</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>15.32</td>
<td>15.16</td>
<td>8.54</td>
<td>8.54</td>
<td>0.26</td>
<td>&lt;15%</td>
</tr>
<tr>
<td>Calibration</td>
<td>8.97</td>
<td>9.74</td>
<td>7.91</td>
<td>7.91</td>
<td>0.26</td>
<td>&lt;15%</td>
</tr>
<tr>
<td>0.015</td>
<td>8.39</td>
<td>9.49</td>
<td>7.66</td>
<td>7.66</td>
<td>0.26</td>
<td>&lt;15%</td>
</tr>
<tr>
<td>0.02</td>
<td>10.53</td>
<td>6.84</td>
<td>7.93</td>
<td>7.93</td>
<td>0.26</td>
<td>&lt;15%</td>
</tr>
<tr>
<td>0.025</td>
<td>23.33</td>
<td>14.44</td>
<td>8.03</td>
<td>8.03</td>
<td>0.26</td>
<td>&lt;15%</td>
</tr>
<tr>
<td>0.03</td>
<td>39.29</td>
<td>26.39</td>
<td>8.82</td>
<td>8.82</td>
<td>0.26</td>
<td>&lt;15%</td>
</tr>
</tbody>
</table>

### Bias

<table>
<thead>
<tr>
<th>Roughness</th>
<th>RM 138.8</th>
<th>RM 126</th>
<th>RM 113</th>
<th>RM 102.5</th>
<th>RM 98</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0100</td>
<td>-0.121</td>
<td>-0.123</td>
<td>-0.038</td>
<td>-0.038</td>
<td>0.000</td>
<td>&lt;10</td>
</tr>
<tr>
<td>0.0150</td>
<td>-0.039</td>
<td>-0.063</td>
<td>-0.013</td>
<td>-0.013</td>
<td>0.000</td>
<td>&lt;10</td>
</tr>
<tr>
<td>Calibration</td>
<td>0.039</td>
<td>0.017</td>
<td>-0.011</td>
<td>-0.011</td>
<td>0.000</td>
<td>&lt;10</td>
</tr>
<tr>
<td>0.0200</td>
<td>0.072</td>
<td>0.016</td>
<td>-0.011</td>
<td>-0.011</td>
<td>0.000</td>
<td>&lt;10</td>
</tr>
<tr>
<td>0.0250</td>
<td>0.209</td>
<td>0.119</td>
<td>0.009</td>
<td>0.009</td>
<td>0.000</td>
<td>&lt;10</td>
</tr>
<tr>
<td>0.0300</td>
<td>0.367</td>
<td>0.240</td>
<td>0.033</td>
<td>0.033</td>
<td>0.000</td>
<td>&lt;10</td>
</tr>
</tbody>
</table>

Figure 29 Correlation Coefficient for Steady State Calibrated \( n \)

Figure 30 %RMSE for Steady State Calibrated \( n \)

Figure 31 Bias for Unsteady State Calibrated \( n \)
All three statistical parameters suggest an improved fit with the new spatially varying roughness. Figure 34 through Figure 38 provide a direct comparison of measured unsteady water surface elevations and simulated values at their corresponding gage locations. The downstream boundary condition is shown to overlap perfectly with measured data.
Figure 35 Unsteady State Calibration vs Observed Data at RM 126.8

Figure 36 Unsteady State Calibration vs Observed Data at RM 113
Calibration results

Figure 34 through Figure 38 are agreeable with statistics; a direct overlay between simulated and observed water surface profiles indicates a satisfactory calibration. The calibrated model can now utilized for hydraulic comparisons.
3.4. Application

3.4.1. Unsteady Simulations

Unsteady simulation comparisons between distortion scales are as follows:

1. Water surface comparisons between observed and expected values for varying manning’s roughness;
2. Velocity Ratio, used to determine how reproducing velocity, which consequently influences sediment transport; from equation 5, for D15 it should be 20;
3. Froude Number Ratio, determines the quality of the scaling process; deviation from a 1:1 ratio would indicate error;
4. Friction Slope Ratio, indicates where energy is lost between each model;
5. Roughness Ratio, indicates areas where more or less roughness may be required
6. Hydraulic Radius Ratio shows how scaling impacts the hydraulic radius for a range of flow rates; and
7. Reynolds Numbers along reach. Determines how much energy is available for sediment transport and gives an idea of when rough turbulent conditions may be met.
4. Results

4.1. Hydraulic Comparisons

This section reflects data compilation and analysis for unsteady simulations. Results have been adjusted to prototype scale based on the ratios in Figure 3.

4.1.1. Stage

Figure 39 to Figure 43 show the unsteady stage comparisons along the river for all simulation runs (D15, D7.5, D1, P, plus D7.5 and D1 after scaling n) and demonstrate the necessity of roughness scaling. All simulated stage levels are scaled to the prototype as described in Figure 3 and all plots share identical vertical bounds and scale for easy comparison. The dotted lines correspond to model results run under unscaled roughness, solid lines represent results under scaled roughness values.

Figure 39 Unsteady State Stage Comparison at RM 138.8 for All Distortion Scales
Figure 40 Unsteady State Stage Comparison at RM 126.8 for All Distortion Scales

Figure 41 Unsteady State Stage Comparison at RM 113 for All Distortion Scales
Figure 42 Unsteady State Stage Comparison at RM 102.8 for All Distortion Scales

Figure 43 Unsteady State Stage Comparison at RM 98.1 for All Distortion Scales
HEC-RAS simulated water surfaces behave as expected; profiles are high upstream (~+18.0 ft) and decrease with downstream progression. It can be seen on Figure 43 that all simulations converge to the downstream boundary condition. These results indicate that HEC-RAS can accurately reproduce unsteady water surfaces at multiple distortion scales and at ESSPM hydraulic time scales.

4.1.2. Froude Number

Froude Number comparisons at each gage location are shown in Figure 44 through Figure 48. Froude Numbers for all distortion scales are between .04 and .16, reaffirming the obvious subcritical flow condition, and indicating the models show good similarity for all flow rates the data series overlap. The Froude Number plays a very important part in the appropriate flow equations (Chanson, 1999) used to describe the system processes; maintaining similarity indicates the system can be represented with the same governing equations. It can be noticed that the boundary condition causes a gradual spread in the data points of D15, D7.5, D1, which will be further discussed after the velocity comparisons are presented. The data overlay amongst distortion scales is again apparent, suggesting similitude. Downstream progression observes widening separation in data points.

Figure 44 Unsteady State Froude Number Comparison at RM 138.8 for All Distortion Scales
Figure 45 Unsteady State Froude Number Comparison at RM 126.8 for All Distortion Scales

Figure 46 Unsteady State Froude Number Comparison at RM 113 for All Distortion Scales
Figure 47 Unsteady State Froude Number Comparison at RM 102.8 for All Distortion Scales

Figure 48 Unsteady State Froude Number Comparison at RM 98.1 for All Distortion Scales
4.1.3. Velocity

Simulated velocity for cross sections at each gage location are shown in Figure 49 to Figure 53. The data overlay amongst distortion scales is again apparent, suggesting similitude. Velocity comparisons suggest all numerical models accurately reproduce the same average velocity for a range of flow rates over the entire model reach.

Figure 49 Unsteady State Velocity Comparison at RM 138.8 for All Distortion Scales

Figure 50 Unsteady State Velocity Comparison at RM 126.8 for All Distortion Scales
Figure 51 Unsteady State Velocity Comparison at RM 113 for All Distortion Scales

Figure 52 Unsteady State Velocity Comparison at RM 102.8 for All Distortion Scales
4.1.4. Friction Slope

Friction Slope plots in Figure 54 to Figure 57 show the representative friction slope between two cross sections (the gage location and the nearest downstream cross section), i.e. there is no plot for the gage at RM 98.1 because it is the last cross section. For sub critical free surface flow, the friction slope is often identical to the water surface slope, which is approximately the bed slope. At prototype scale, the Mississippi river has a slope of $10^{-5}$ (Jeffery A. Nittrouer, 2011).
Figure 55 Unsteady State Friction Slope Comparison at RM 126.8 for All Distortion Scales

Figure 56 Unsteady State Friction Slope Comparison at RM 113 for All Distortion Scales
4.1.5. Hydraulic Radius

Hydraulic Radius values or an unsteady flow simulation are shown in Figure 58 to Figure 62.

Figure 57 Unsteady State Friction Slope Comparison at RM 102.8 for All Distortion Scales

Figure 58 Unsteady State Hydraulic Radius Comparison at RM 138.8 for All Distortion Scales
Figure 59 Unsteady State Hydraulic Radius Comparison at RM 126.8 for All Distortion Scales

Figure 60 Unsteady State Hydraulic Radius Comparison at RM 113 for All Distortion Scales
Figure 61 Unsteady State Hydraulic Radius Comparison at RM 102.8 for All Distortion Scales.

Figure 62 Unsteady State Hydraulic Radius Comparison at RM 98.1 for All Distortion Scales.
Each distortion scale has a different ratio and each cross section deviates slightly from one another. The hydraulic radius is perhaps the best tool to investigate the impacts of varying distortion; prototype and D1 have identical values while D7.5 and D15 have lower values due to a relative decrease in flow area, which is expected due to a varying horizontal scale with an identical vertical scale. Figure 60 is an exception, as the cross values of D15 and D7.5 appear above prototype and D1. This may be attributed to the cross sections that those locations being narrower, reducing the change noticed in horizontal scaling. Troughs in hydraulic radius between P and D1 can be seen for the cross section at Carrollton in Figure 61. This could perhaps be attributed to point removal as the user can have no more than 500 points within a cross section and some overlapping ones were removed. At higher flow rates, the hydraulic radius drops slightly as the overbank tends to increase the wetted perimeter more than flow area. The hydraulic radius ratio will vary with flow and may be better-calculated using steady state simulations.

4.1.6. Reynolds Number

Reynolds numbers at each cross-section for unsteady simulations at each scale can be seen in Figure 63 to Figure 67. The black line represents the threshold where adequate turbulence is present, ensuring enough mixing to keep sediment suspended, as described in section 2.4.

![Figure 63 Unsteady State Reynolds Number Comparison at RM 138.8 for All Distortion Scales](image-url)
Figure 64 Unsteady State Reynolds Number Comparison at RM 126.8 for All Distortion Scales

Figure 65 Unsteady State Reynolds Number Comparison at RM 113 for All Distortion Scales
Figure 66 Unsteady State Reynolds Number Comparison at RM 102.8 for All Distortion Scales

Figure 67 Unsteady State Reynolds Number Comparison at RM 98.1 for All Distortion Scales
From inspection of Figure 63 through Figure 67, it can be seen that the Reynolds Numbers behave predictably; at flows below 500,000 cfs the Reynolds Number is less than 7500 and conditions do not favor sand transport. Figure 19 indicates 500,000 cfs begins around 840 hours of simulation which is agreeable with Reynolds Number plots. Spatial trends suggest the areas around RM 113 and RM 102.5 will require higher flows for insipient motion to being.

4.1.7. Velocity Comparisons

Figure 68 shows a velocity comparison between measured surface velocity, as described in 3.2.2, and simulated average velocity at the entire cross section. Measured data points representing the average velocity between gage stations were placed midway between gages and simulated values were taken from the nearest cross section (less than a tenth of a mile for all locations).

![Figure 68 Steady State Measured and Simulated Average Velocity for D15](image)

The standard deviation for the measured profiles of SF4, SF3, SF2, and SF1 is 1.7, 1.4, 1.0, and 0.8 respectively. The measured velocity data is higher than simulated data, which makes sense when considering HEC-RAS computed velocity represents the average cross section velocity while the measured values reflected the surface velocity, which is one of the fastest areas in a velocity profile. Measured values show a gradual decrease, while the corresponding simulated values do not change significantly, excluding a spike in the center. The large upstream difference in measured and simulated values indicates possible errors; simulated velocity shown in Figure
behaves differently than other velocities in section 4.1.3. This is evidence that the majority of
the model domain is controlled by the downstream boundary condition. As previously
mentioned, HEC-RAS presents velocity as single value average through the cross section; non
zero horizontal and vertical velocities are over overlooked. Flow structures and spatial velocity
differences existing near the bed layer become important considerations for sediment transport
modelling; the applicability of 1-D results should be acknowledged.
5. Summary of Findings and Discussion

The roughness ratios seen in Figure 3 suggest that D7.5 and D1 both need significantly less roughness than prototype scale, while the ESSPM should have a roughness very similar to as the prototype. This could be checked by calculating the roughness ratio after calculating the hydraulic radius, velocity, and friction slope ratios between model and prototype. In the stage plots of Figure 39 through Figure 43, data series for D7.5 and D1 overlaying D15 and prototype results further indicate scaling roughness can be a crucial part to accurately modeling water surfaces in scale models. According to section 2.9, the roughness scale factor may not be accurately computed using equation 22 for flows in hydraulically smooth or transition regimes. To investigate this, Figure 2 has been expanded into Figure 69 using model results for the cross section at Harvey.

<table>
<thead>
<tr>
<th>Discharge (cfs)</th>
<th>P (ft)</th>
<th>E(H)</th>
<th>E(L)</th>
<th>Distortion</th>
<th>fpw</th>
<th>Re_p</th>
<th>Re_M</th>
</tr>
</thead>
<tbody>
<tr>
<td>476640</td>
<td>#N/A</td>
<td>400</td>
<td>6000</td>
<td>15</td>
<td>1.5</td>
<td>9.40E+07</td>
<td>5.59E+03</td>
</tr>
<tr>
<td>1080000</td>
<td>#N/A</td>
<td>400</td>
<td>6000</td>
<td>15</td>
<td>1.5</td>
<td>1.50E+08</td>
<td>1.18E+04</td>
</tr>
<tr>
<td>417600</td>
<td>#N/A</td>
<td>400</td>
<td>3000</td>
<td>7.5</td>
<td>1.3125</td>
<td>9.40E+07</td>
<td>7.01E+03</td>
</tr>
<tr>
<td>1060800</td>
<td>#N/A</td>
<td>400</td>
<td>3000</td>
<td>7.5</td>
<td>1.3125</td>
<td>1.50E+08</td>
<td>1.70E+04</td>
</tr>
<tr>
<td>386240</td>
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<td>8.78E+03</td>
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<tr>
<td>1127465.6</td>
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<td>400</td>
<td>1</td>
<td>1</td>
<td>1.50E+08</td>
<td>2.47E+04</td>
</tr>
</tbody>
</table>

Figure 69 Roughness Scaling based on Model and Prototype Reynolds Numbers

Some important distinctions need to be made when comparing Figure 2 and Figure 69. The ESSPM feasibility report assumed a typical cross section and depth calculate Reynolds numbers. A HEC-RAS based modelling approach was used to produce the results for Figure 69, with a fixed cross section under dynamic conditions. The viscosity was set to 1.0 x 10^-5 ft^2/s. The Reynolds number and Moody Diagram, see in Figure 70 can be used to classify the flow; all distortion scales fall between the transition to rough-turbulent regime.

Figure 70 Moody Diagram (Munson, 2005)
It will be a challenge to reproduce prototype roughness in the ESSPM, especially considering that it’s a mobile bed model. Figure 54 through Figure 57 give some detail about the tiny deviations observed in the model; friction slopes deviations from a 1:15 ratio can indicate where one model is gaining/losing energy with respect to the other. HEC-RAS attributes all energy loss to roughness or expansion/contraction coefficients (which have been held constant), further stressing the significant role roughness plays. Minor internal rounding may also contribute to some small deviations in the model.

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 the sediment in suspension. Because hydraulic radius is a function of depth, distorted models can only achieve similarity at a single depth (Novák & Čabelka, 1981). In models having wide channels (e.g. Mississippi) and no vertical distortion, the height/width ratio will only see a small deviation, so approximate similarity could be assumed. The ESSPM is vertically distorted as seen in Figure 8, causing a range of hydraulic radii, as depicted in Figure 58 through Figure 62. The sudden drop in hydraulic radius ratio at Bonnet Carre Spillway (RM 129.2) can be attributed to high flows accessing a large overbank, affecting the wetted perimeter more than the area. Figure 63 through Figure 67 indicates low to medium, and at certain locations, high flow rates, may not trigger adequate turbulence for sediment transport. Areas with a broad overbank, such as river miles 135-128 cause a loss in energy. Channel only output would likely increase the Reynolds numbers as areas in the overbank contribute to reduced velocities. Incipient motion is dictated through Shields scaling, meaning that even if computed Reynolds numbers fall below the targeted threshold it could still be possible for the model to transport sediment, especially finer particles. For acceleration of bed load movement, it is advisable to use sediment material of a specific gravity lower than in the prototype (Ivicsics, 1975); the ESSPM has a low density plastic with a specific gravity of approximately 1.05.

As a whole, ESSPM can be considered semi quantitative in nature in that it reproduces some variables (such as stage or velocity) with high accuracy while having limited or little potential for matching other hydraulic parameters. Moreover, if the user’s only desire is accurately model stage, the model could be considered quantitative in nature. Instead, if the ultimate goal was to reproduce flow structures observed in the prototype, the model would be inadequate due to obvious changes present in a narrowed bathymetry. 1-D numerical model results indicate the quantitative parameters in the model can be accurately reproduced. Higher order modeling is needed to provide quantitative results and insight for what would otherwise be qualitative parameters, i.e. flow structure.

One major limitation of HEC-RAS is evident in Figure 44 to Figure 57; the oscillating downstream boundary condition has caused variable results (velocity, friction slope, Froude number) for D15, D1, and D7.5 to increasing spread apart with downstream progression. This outcome is unavoidable because the boundary condition at D7.5, D1, and Prototype had to be interpolated between measurements taken at model scale. HEC-RAS cannot output variable results (other than water surface) more frequently than 1 minute; boundary condition input time for D7.5 and D1 is less than a minute, meaning results tend oscillate. Output for prototype scale is smoother due to the boundary condition input time being larger than variable output time.
Results upstream converge; the proximity of RM 138.8 to the smooth input flow upstream (RM 142) may play a role. Additional limitations are evident in future physical model sediment test as the ESSPM has been unevenly deepened within certain cross sections to accommodate placing a layer of sediment; HEC-RAS only allows for placing sediment in even thickness.

One of the biggest advantages of one-dimensional numerical modeling of large scale physical models is the short simulation times, as summarized in Figure 71.

<table>
<thead>
<tr>
<th></th>
<th>D15</th>
<th>D7.5</th>
<th>D1</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Complete Process</strong></td>
<td>1.61 sec</td>
<td>4.95 sec</td>
<td>4.56 sec</td>
<td>0.77 sec</td>
</tr>
<tr>
<td><strong>Preprocessing Geometry</strong></td>
<td>0.69 sec</td>
<td>0.80 sec</td>
<td>0.63 sec</td>
<td>0.61 sec</td>
</tr>
<tr>
<td><strong>Unsteady Flow Computations</strong></td>
<td>1.63 sec</td>
<td>8.72 sec</td>
<td>15.53 sec</td>
<td>2 min 59.45 sec</td>
</tr>
<tr>
<td><strong>Writing to DSS</strong></td>
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<td>0.67 sec</td>
<td>0.89 sec</td>
<td>37.16 sec</td>
</tr>
<tr>
<td><strong>Post-Processing</strong></td>
<td>5.53 sec</td>
<td>24.52 sec</td>
<td>44.34 sec</td>
<td>9 min 35.97 sec</td>
</tr>
<tr>
<td><strong>Complete Process</strong></td>
<td>8.44 sec</td>
<td>34.77 sec</td>
<td>1 min 1.44 sec</td>
<td>13 min 13.20 sec</td>
</tr>
</tbody>
</table>

**Figure 71 Summary of HEC-RAS Computational Run Time**

At prototype scale, it takes 13 minutes to model six months of data. When compared to two and three dimensional models, computations over this domain size would be impossible on a single machine.

There are multiple opportunities for expanding upon this work. First, the roughness ratio at each distortion scale should be rechecked using model output. Models with a roughness already scaled should have a ratio of nearly 1. Once ESSPM’s full domain has been constructed, a new 1-D numerical model should be developed and coupled to predicted hydraulic parameters under sediment and non-sediment conditions. A fast numerical model would be useful to design and investigate long term changes in river management such as new diversions and deeper channels before approving a geometry change for deeper physical model testing. It would be useful to perform similar studies on the impact that varying distortion has on large domain systems. Evidence suggests low roughness is needed at D7.5 and D1; it would interesting to study the flow structures and patterns under such circumstances with 2D and 3D numerical models. Further investigation with the physical model should try to pinpoint the roughness most representative of synthetic sediment bed and smooth painted walls.
Work Cited


Vita

Benjamin Joseph Hartman, a native of Baton Rouge, Louisiana, received his bachelor’s degree at Louisiana State University in 2012. An interest in Louisiana’s unique coastal systems motivated him to continue his education by entering the LSU graduate school to pursue a Master’s Degree in Coastal and Ecological Engineering. After two years of continual study, he accepted a position as a consulting engineer in Houma, Louisiana. He would continue thesis work at night and eventually complete the necessary requirements; he anticipates receiving a master’s degree in December 2015. His plans for future professional development will likely include pursuing an MBA and becoming a registered professional engineer.