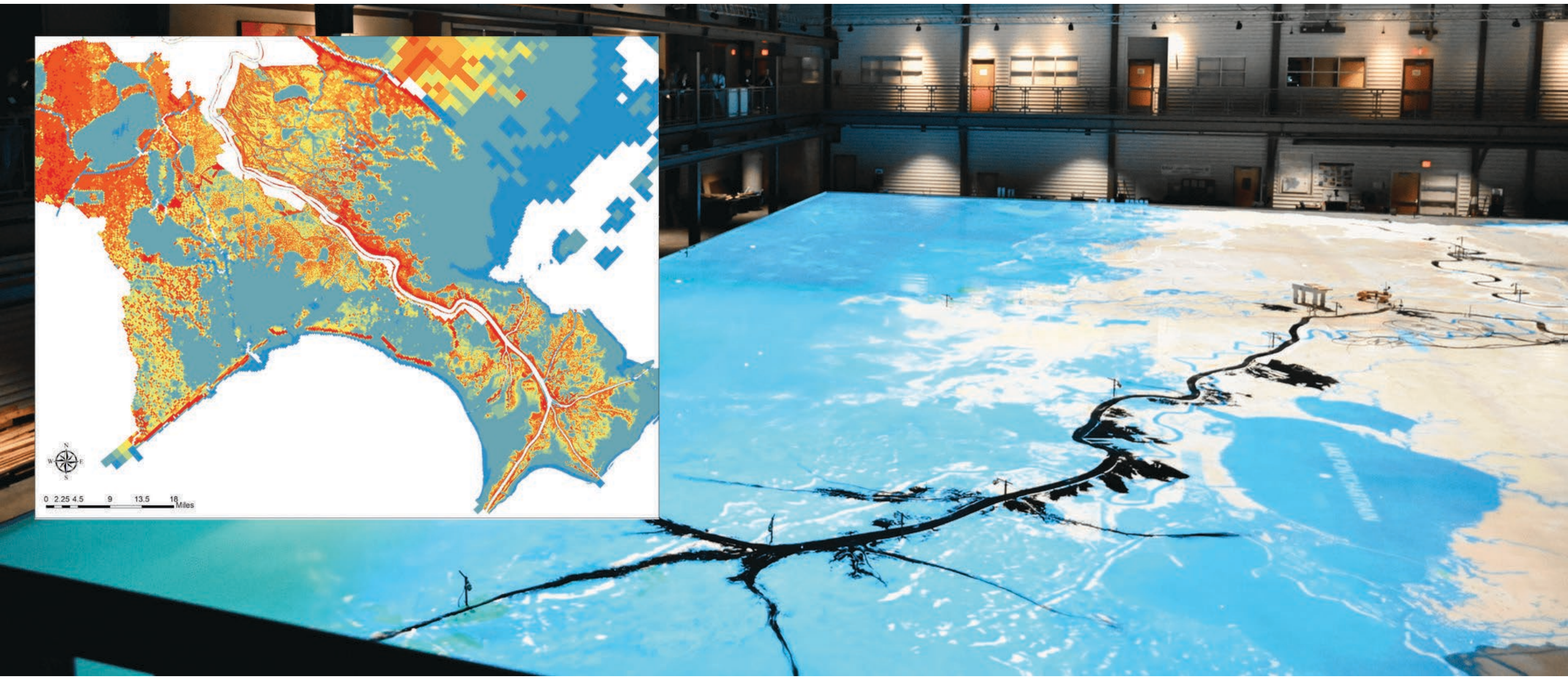

INTER-MODEL COMPARISONS BETWEEN PHYSICAL AND NUMERICAL MODELS

Comparisons of future projections between the numerical Basin Wide Model Version 4 and the Lower Mississippi River Physical Model

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Produced for and funded by the Coastal Protection and Restoration Authority

December 5, 2023

Report #P-00407-01

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CITATION

Bregman, M., Messina, F., Miner, M., Georgiou, I.Y., and Wilson, C.S., (2023). Inter-model comparison between physical and numerical models: Comparisons of future projections between the numerical Basin Wide Model Version 4 and the Lower Mississippi River Physical Model. Prepared for and funded by the Coastal Protection and Restoration Authority. Baton Rouge, LA.

PREFACE

This report was developed by The Water Institute (the Institute) for the Coastal Protection and Restoration Authority (CPRA) under Task Order 69 Lowermost Mississippi River Management Program (LMRMP).

CPRA has been using various tools to support coastal restoration projects. Among these tools, the Lower Mississippi River Physical Model (LMRPM) and the numerical Basin Wide model Version 4 have been used as part of the LMRMP to identify and test management strategies for the river. The report summarizes the comparison between these two models. Simulations with similar inputs and environmental conditions have been performed with both models, allowing for inter-model comparison. The comparison focused on simulations related to a future without any projects (sediment diversions) implemented on the landscape and included the same forecast window from 2020 to 2070. The simulations included the same sea level rise, Mississippi River hydrographs, and similar upstream sediment input. The analysis included the comparison of river discharge, stage, bed elevation, and dredging volumes between the two models, and where available, model results were also compared to observations within the river.

Geologists, geomorphologists, and engineers from the Institute, Louisiana State University, and CPRA contributed to this work and to the development of this report.

ACKNOWLEDGEMENTS

This analysis and report, and all related items of information were prepared by the authors through Task Order 69 (Lower Mississippi River Management Program) with the Louisiana Coastal Protection and Restoration Authority, who was funded under Award No. GNTCP18LA0035 from the Gulf Coast Ecosystem Restoration Council (RESTORE Council). The data, statements, findings, conclusions, and recommendations are those of the author[s] and do not necessarily reflect any determinations, views, or policies of the RESTORE Council. The authors thank Brendan Yuill and Kazi Sadid (US Army Corps of Engineers) for their contribution to the model comparison methodology and approach during the early stages of this work, and Louisiana State University Center for River Studies' graduate students Julia Mudd, and Emily Fertitta for sharing output from Physical Model experiments and for their assistance in interpretation of the physical model output.

James Pahl and Joseph Wes LeBlanc of CPRA provided guidance on the scope of work and project direction.

This report was reviewed by Alyssa Dausman, Chief Scientist of The Water Institute.

This report was reviewed, edited, and formatted by Charley Cameron of The Water Institute.

EXECUTIVE SUMMARY

Physical and numerical models are powerful tools for research in various disciplines. They both present advantages and disadvantages, and they can be used together to exploit the benefits of both approaches. Inter-model comparison is often used to compare different models, confirm and corroborate their results, and to verify projected trends. The work presented in this report focuses on inter-model comparison between the Lower Mississippi River Physical Model (LMRPM), a novel physical model with a movable bed of the Lower Mississippi River (LSU Center for River Studies, 2020), and the Basin Wide Model Version 4 (hereafter BWM; Bregman et al., 2020), a Delft3D-based numerical model (Deltares, 2017).

The management of the river has historically focused on different objectives (i.e., maintaining a navigable waterway, understanding sand dynamics and bar evolution, flood risk reduction) which all rely on river water and sediment. The goal of the LMRMP is to successfully manage both water and sediment resources to accomplish these objectives while also sustaining the coast, preserving environmental resources, and enhancing ecosystems health.

Both the BWM and the LMRPM cover the geographic extent of the LMR, receiving basins, and part of the Gulf of Mexico. Both models can be used to simulate the next 50 years of landscape evolution under Future Without Project (FWOP; i.e., the absence of restoration projects) or Future With Project alternatives. The models use the same sea level rise and subsidence rates, albeit with subsidence implemented differently. Additionally, they employ identical Mississippi River hydrographs at the upstream boundary. The similarities between the two models enabled the direct comparison of the model projections, and tests of the models corroborated similar patterns and trends. The comparison focused on in-river conditions and dynamics because the LMRPM was specifically designed to replicate the hydraulics and bulk non-cohesive sand transport in the Mississippi River (LSU Center for River Studies, 2020). River stage and flow, bed elevation, and dredging volumes were compared between the two models and, when available, with observational data from several locations along the river.

The relationship between stage and discharge was compared, at six locations, between the two models and with a target stage discharge curve developed with empirical data. Both models' stage-discharge relationships agreed well with those from a rating curve for the 2020 landscape at the stations located further upstream (e.g., Bonnet Carré Spillway and Carrollton). Downstream, at River Mile 40, the stage-discharge relationship is influenced by tides, flow loss through crevasses, and flow distribution through the bird's foot delta distributaries, a result that both models confirmed. For the 2070 landscape, the effect of sea level rise and subsidence was apparent in the projected stages for both the BWM and the LMRPM. The LMRPM consistently projected higher stages than those projected by the BWM. Over the period from 2020 to 2070, the LMRPM exhibited a decrease in variance while maintaining an almost constant stage-discharge relationship as the discharge increased. In contrast, the BWM did not show an asymptotic stage-discharge relationship; instead, the stage increased linearly with discharge. For this study, two identical experiments conducted with the LMRPM were analyzed, which revealed inconsistencies in the stage projections between the two experiments. Since both experiments had the same boundary conditions, the differences in stage projections between the two experiments can be attributed to repeatability and precision of stage measurements and the timing and location of dredging in the lower reaches of the model.

Bed elevations were collected at four locations in the LMRPM and were compared to bed elevations in the BWM. The numerical model bed elevations were extracted along four streamwise profiles and four cross sections in the channel, providing continuous bed elevation profiles with a 125-m spatial resolution. The numerical model results showed a relatively high standard deviation which could be explained by the relatively coarse grid resolution, hindering the ability of the model to fully resolve the river geomorphology including lateral bar geometry. The LMRPM showed deposition of the order of 1–4 m (3–13 ft) during the first decade at all analyzed locations, which suggested the model was still spinning up during that period, and showed variance of up to 7 m (23 ft) over one decade, a response that can be attributed to sand transported during river discharge flood peaks.

The dredging volumes projected by the BWM in the Mississippi River Ship Channel (MRSC) were generally less than half of the dredging volumes from historical records, however the volumes did show interannual variations that aligned with fluctuations in the annual river discharge. These dredging volumes amounted to approximately 25% of the sand load entering the model upstream and exhibited a 23% increase from the second to the fifth decade simulated. Despite this increase being 23%, bed level change analysis outside of the MRSC (or below the dredging threshold) suggests that the model shifted towards a more depositional behavior.

The dredging volumes projected by the LMRPM increased over time. In the first two decades dredging volume projections were lower than both the BWM and the historical records, indicating that the physical model was likely still reaching an equilibrium. During the remaining three decades, the LMRPM dredging volumes were greater than the BWM and comparable to historical records. In the LMRPM, the volume dredged from the MRSC amounted to approximately 50 to 60% of the sand load entering the model at the upstream boundary. The relatively large dredging volumes projected by the physical model could be explained by the large sand load imposed at the upstream boundary of the LMRPM, particularly during years with high discharge. Furthermore, the MRSC in the physical model is only 3.8 cm (1.5 inches) wide which may have posed physical limitations associated with dredging in such a narrow area. These physical limitations could also account for the relatively large variability in dredged sediment in the LMRPM. In certain years, the volumes differed by a factor of 2 between the two experiments, although the cumulative 50-year dredging volumes differed by only 12%.

The differences in the projected dredging volumes between the two models can be partially attributed to differences in the dredging depth and mainly to discrepancies in sand load entering the upstream boundary resulting from the use of different sand rating curves. Dredging volume results, similar to bed elevation results, suggest that both models were still evolving to reach a dynamic equilibrium in the first two decades of the simulation.

The comparison of projected dredging volumes with historical dredging records highlighted some limitations and opportunities. First, the model simulations evaluated in this study represent a future projection that includes the effect of sea level rise and subsidence that are not identical to those in the historical record. Second, historically, the dredged mass at Southwest Pass partially consists of fine material, which is not considered in the LRMPM and accounted for less than 1% of the dredged material in the BWM. Additionally, some of the dredged mass in the historical records was likely sourced from leakage from the Hopper Dredge Disposal Area (Brown & Luong, 2017), where previously dredged material was disposed of. For these reasons, the modeled dredged volumes were expected to be smaller than the measured volumes. Knowing the composition of the dredged material along the Mississippi River would help resolve these differences, provide better insight into river dynamics and dredging, and enable better model validation.

The comparison shows that both models show similar patterns and results and highlights the strengths and limitations of both models. The results show the importance of the model initialization phase, and for both models a longer initialization period is recommended. The use of different sand rating curves between the models was one of the factors that led to different dredging volume projections by each model over the 50-year simulated period. Sensitivity tests are recommended to test the influence of the sediment rating curves on the dredged volumes and to help better constrain sediment budgets in the LMR. Additional simulations performed with the BWM could be leveraged to better understand the correlations between sediment type, delta morphology, sea level rise, and dredging volumes, which continue to pose challenges. Experiments conducted with both numerical and physical models including the operation of the Mid-Barataria and Mid-Breton Sediment Diversion projects could also be compared to help gain additional insights on the ability of the models to project dynamic river responses to sediment diversions and elucidate on how these projects might impact downstream bed aggradation and corresponding requirements for dredging. In addition, other existing two- or three-dimensional models with higher resolution, which are more suitable to resolve in-river processes, could be leveraged for comparison with the LMRPM. In general, caution should be exercised when using either physical or numerical models, particularly when making absolute long-term projections. However, these models are powerful and informative tools, especially when employed to compare scenarios or alternatives, as they enable the testing of the impacts of different projects, environmental conditions, or management strategies.

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LIST OF ACRONYMS

Acronym	Term
BWM	Basin Wide model Version 4
CPRA	Coastal Protection and Restoration Authority
CRMS	Coastwide Reference Monitoring System
FWOP	Future Without Project
HDDA	Hopper Dredge Disposal Area
HOP	Head of Passes
LabVIEW	Laboratory Virtual Instrument Engineering Workbench
LMRMP	Lowermost Mississippi River Management Program
LMRPM	Lower Mississippi River Physical Model
LSU	Louisiana State University
MRSC	Mississippi River Ship Channel
RK	River Kilometer
RM	River Mile
RSLR	Relative Sea Level Rise
SWP	Southwest Pass
2D	Two-dimensional
USACE	U.S. Army Corps of Engineers
USGS	U.S. Environmental Protection Agency

UNIT TABLE

Abbreviation	Term
°C	Degrees Celsius
°F	Degrees Fahrenheit
cfs	Cubic feet per second
cm	Centimeter
ft	Feet
ft^2	Square feet
g/cm^3	Grams per cubic centimeter
in.	Inches
kg/m^3	Kilograms per cubic meter
$kg/m^2/s$	Kilograms per square meter per second
km	Kilometers
m	Meters
m^3/s	Cubic meters per year
m^2	Square meter
µm	Micrometer
MCY	Million cubic yards
mm/yr	Millimeters per year
mm/s	Millimeters per second
Pa	Pascal

1.0 INTRODUCTION

Physical and numerical models are essential tools in hydraulic engineering that help engineers understand fluid behavior, optimize designs, and make informed decisions for a wide range of water-related projects. Physical and numerical models have been used in research for decades, while physical models have been used for centuries to support planning, design, construction, and rehabilitation for major hydraulic engineering projects (Peña & Anta, 2021). Applications of physical models vary in size and complexity based on project need, the questions to be addressed, and available resources (Chow, 1959). Physical models are commonly used to study hydraulic structures and waterways involving complex flows (e.g., spillways, control structures, weirs, and flow extraction and flow distribution channels), with applications ranging from full-scale to scaled models (Muste et al., 2017). Numerical models, meanwhile, have gradually replaced various physical model applications with simultaneous technological advancements in computer technology, numerical methods, and computing costs, enabling more straightforward representation of complex flows and faster solutions of computational fluid dynamics processes. While computational methods now occupy an expanded role, physical modeling remains a valuable and irreplaceable aspect of hydraulic engineering practice. In recent years, physical models have received renewed attention due to advancements in low-cost sensor technology, including imaging techniques, high-speed hydro-acoustics and laser technology, sensor size, and process automation (Peña & Anta, 2021).

There are many advantages and disadvantages for using either one of these model types, some of which are summarized in Table 1. Regardless of their respective advantages and disadvantages, physical and numerical models are often used together to exploit the benefits of both approaches (Carmo, 2020; Sutherland & Barfuss, 2011). Examples include model nesting (i.e., using a numerical model to provide boundary conditions to a smaller physical model), using numerical models to inform the design and domain extent of a physical model, using physical model results to calibrate numerical models when it is challenging to collect real-world observations, and inter-model comparison to validate model results (Carmo, 2020; Sutherland & Barfuss, 2011). The work presented in this report focuses on an inter-model comparison between a physical and a numerical model. Inter-model comparison, in general, is used to compare results of the same simulations between different models, often testing numerical solution approaches, grid resolution and corresponding projections, convergence and accuracy, presence or absence of specific processes, or comparing a physical model with a numerical model. In this study, numerical and physical models were set up for the same geographic domain and environmental forcing, and once simulations were run, the model results were evaluated to verify that both models projected similar trends.

Table 1. Selected advantages and disadvantages of both physical and numerical models (from Sutherland & Barfuss, 2011)

Physical Models	Numerical Models
Advantages	
Allow for a natural reproduction of complex nonlinear physical phenomena that are not fully understood	Can be re-used in the future with minimal effort
It is intuitive and easy to visualize	Allow for testing of many configurations and options
Operates in a controlled environment	Results can be extracted from any point in the model and at any time (e.g., temporally and spatially continuous estimates)
It relies on actual physical forcings	Allows for adequate representation of many physical processes
It is well-established in the scientific community and, therefore, trusted.	Allows to control the complexity of the model by including or not specific phenomena
Disadvantages	
Subject to scaling effects	Prone to numerical instabilities
Labor intensive and time consuming	Results may not be intuitive
Expensive	Incapable of reproducing all phenomena due to simplified mathematical formulations
Extracting data can be difficult and it often requires novel and expensive instruments	Constrained by grid limitation and computations time (e.g., using 2D instead of 3D)
It requires a large, dedicated facility	Results might be influence by poor formulation of the initial or boundary conditions (e.g., because of lack of information)

The work presented in this report is part of the Louisiana Coastal Protection and Restoration Authority's (CPRA's) Lowermost Mississippi River Management Program (LMRMP), funded by the Gulf Coast Ecosystem Restoration Council. LMRMP is a large-scale effort designed to move the nation towards a holistic management of the lower reaches of the Mississippi River through the development and use of a science-based decision-making framework. Historically, the management of the Lowermost Mississippi River (LMR) has focused on objectives that have been addressed independently of one another. These objectives include maintaining a navigable waterway, improving understanding of some of the Mississippi River physical processes (e.g., sand dynamics and bed and bar evolution), reducing flood risk to communities, and restoring and protecting ecosystems. All these objectives rely on effective management of river water and sediment. At the same time, the demand for sediment resources for coastal wetland restoration is increasing, exemplified by projects such as sediment diversions or the mining of sand bars. Therefore, a holistic approach to management of both water and sediment is essential to accomplish the objectives listed above while also supporting the long-term sustainability of the coast, preserving environmental resources, enhancing the health of ecosystems, and ensuring that projects are not cost-prohibitive (Dalyander et al., 2022). The LMRMP approach focuses on the standard riverine elements, such as dredging and navigation, flood control, and ecosystem health, and considers additional elements such as delta restoration, storm impact risk reduction, and sediment diversion operations. These multiple elements are interdependent and part of a complex system.

LMRMP is composed of several subtasks that correspond to different technical elements. While each subtask has a specific focus, the efforts are correlated and designed to advance a science-based, holistic management philosophy. One of these subtasks focuses on an inter-model comparison between two specific models used by CPRA to support coastal restoration projects and to identify the best strategies to holistically manage the Mississippi River. Numerical and physical models are robust foundational tools for the holistic science-based decision-making framework developed under the LMRMP. The United States Army Corps of Engineers (USACE) and CPRA past conduct of the Mississippi River Hydrodynamic and Delta Management Study focused on developing a suite of models to evaluate the hydrodynamics, sediment transport, and salinity dynamics of the Lower Mississippi River (Meselhe et al., 2015; Georgiou et al., 2017; Brown et al., 2019). The Lower Mississippi River Physical Model (LMRPM), a novel physical model with a movable bed of the Lower Mississippi River that relies on experimental technology (LSU Center for River Studies, 2020), and the Basin Wide model Version 4 (BMW; Bregman et al., 2020), a Delft3D numerical model (Deltares, 2017), are among these tools.

The LMRPM is a 10,000 ft^2 physical model that replicates the topography and bathymetry of 14,000 mi^2 of southeastern Louisiana (LSU Center for River Studies 2020). It includes 195 miles of the Lower Mississippi River from Donaldsonville, Louisiana, to the Head of Passes (HOP), and many of the lakes and bays in southeast Louisiana that border the river and are tidally connected to the Gulf of Mexico. By replicating the hydraulics and sand transport of the Mississippi River, the LMRPM is a valuable tool for studying the effects of natural processes and anthropogenic influences (e.g., subsidence, climate change, sediment and freshwater diversions, and changes in lower river management and flows) on the river hydraulics and sand transport. The LMRPM is a replacement for a previous, smaller-scale physical model built to a scale of 1:500 in the vertical and 1:12,000 in the horizontal, with a distortion ratio of 1:24 (BCG Engineering and Consulting, 2015). The existing LMRPM has, in comparison, a scale of 1:400 in the vertical and 1:6,000 in the horizontal, resulting in a comparatively lower distortion ratio of 1:15, which ensures a sufficiently high Reynold's number for sediment transport and design discharges (Brady et al., 2021). The newer LMRPM is thus twice as wide, and covers a much larger portion of south Louisiana than just the river and delta distributaries (BCG Engineering and Consulting, 2015). The model is located at the Louisiana State University (LSU) Center for River Studies on the Baton Rouge Water Campus (Figure 1). The scaling used in the model allows for the replication of hydraulics and sand transport processes along the LMR reach, enabling the model to be used for quantitative experimentation. A detailed description of the LMRPM and how it operates can be found in LSU Center for River Studies (2020)

The BWM is a two-dimensional (2D), depth-averaged numerical model developed by the Water Institute (the Institute) for CPRA using the Delft3D software (Bregman et al., 2020). It includes hydrodynamic, morphodynamic, vegetation and nutrient dynamics, and has been used to evaluate long-term morphological changes in Barataria and Breton Sound basins and in the bird's foot delta and to study the effect of restoration projects, such as sediment diversions (Messina et al., 2019, 2021). The vegetation and nutrient dynamics models are part of the modeling framework that evolves the landscape; however, these model components were not considered in the analysis presented in this report.

The BWM was developed to evaluate the response of deltaic and coastal systems to flow and sediment re-introduction from the Mississippi River to the receiving basins, evaluate with and without project conditions across climate change scenarios (i.e., sea level rise), and quantify the impact of restoration projects on the landscape (i.e., sediment diversions, marsh creation, ridge restoration, etc.). In particular, the BWM was used by CPRA and the Institute to simulate landscape evolution over the next 50 years under a Future Without Project (FWOP) alternative (i.e., absence of restoration projects on the landscape; Messina et al., 2021). The LMRPM was used to study the impacts of Mississippi River floods, sediment diversion openings, and the effect of relative sea level rise on the river hydraulics and corresponding bedload sand transport and dredging activities. The same FWOP simulation was performed via two identical experiments with the LMRPM (Brady et al., 2021), and the results of these experiments provided the opportunity for inter-model comparison, which was performed and is summarized in this report. A significant advantage of performing this comparison using numerical modeling output relative to observational datasets is that numerical models provide comprehensive, spatially distributed data fields at time periods of interest, which in turn provides the means to compare the LMRPM performance at many points over flexible time intervals. Cross-comparison allows for either the LMRPM or a numerical model to be used to calibrate the other for certain applications (e.g., observed land building in the LMRPM may be used to calibrate future numerical models). The BWM and LMRPM simulations used for the inter-model comparison employed the same sea level rise, subsidence rates, and identical river hydrographs. Both models include sediment diversion outlets and their corresponding receiving basins, and their capabilities extend beyond processes occurring in the Mississippi River channel and the modern delta distributaries. In spite of these capabilities, the inter-model comparison described herein focuses on in-river changes within the main stem of the Mississippi River. The Mississippi River stage, bed elevation, and dredging volumes were compared between the two models and with empirical datasets at several locations along the river.

The primary objectives of this study included quantifying the projections by each of these models regardless of differences in their scales, resulting limitations, and corresponding uncertainties, evaluating their respective performance, and identifying learning opportunities that improve understanding of the LMR system.

Figure 1. A picture of the Lower Mississippi River Physical Model located in Baton Rouge, LA.

2.0 MODEL DESCRIPTION

This section includes a brief description of the two models used for cross-comparison activity. References to specific reports that describe the two models and their application in detail are included.

2.1 MODEL DOMAIN

The BWM and LMRPM both represent the LMR, starting at Reserve (River Mile [RM] 137, just upstream of the Bonnet Carré Spillway) and at Donaldsonville (RM 175), respectively. Both models include the river downstream of these locations through HOP and part of the northern Gulf of Mexico (Figure 2).

The areas of interest in the BWM are the Barataria and Breton Sound basins and the Mississippi River Delta, but the model domain also includes Lake Pontchartrain, Chandeleur Sound, the coast of Mississippi and parts of the coast of Alabama including Mobile Bay to the east, and the lower part of the Mississippi River and the continental shelf to the south to include the Mississippi River plume to adequately capture water exchange between the lower basins, the delta, and the shelf (Figure 2; Bregman et al., 2020). The resolution of the model grid varies throughout the geographic domain (i.e., from 45 m in Breton Sound to 5 km in the Gulf of Mexico). The grid resolution within the Mississippi River, which is the focus of this inter-model comparison, is 125 m. Details on the BWM calibration and validation efforts can be found in Bregman et al. (2020).

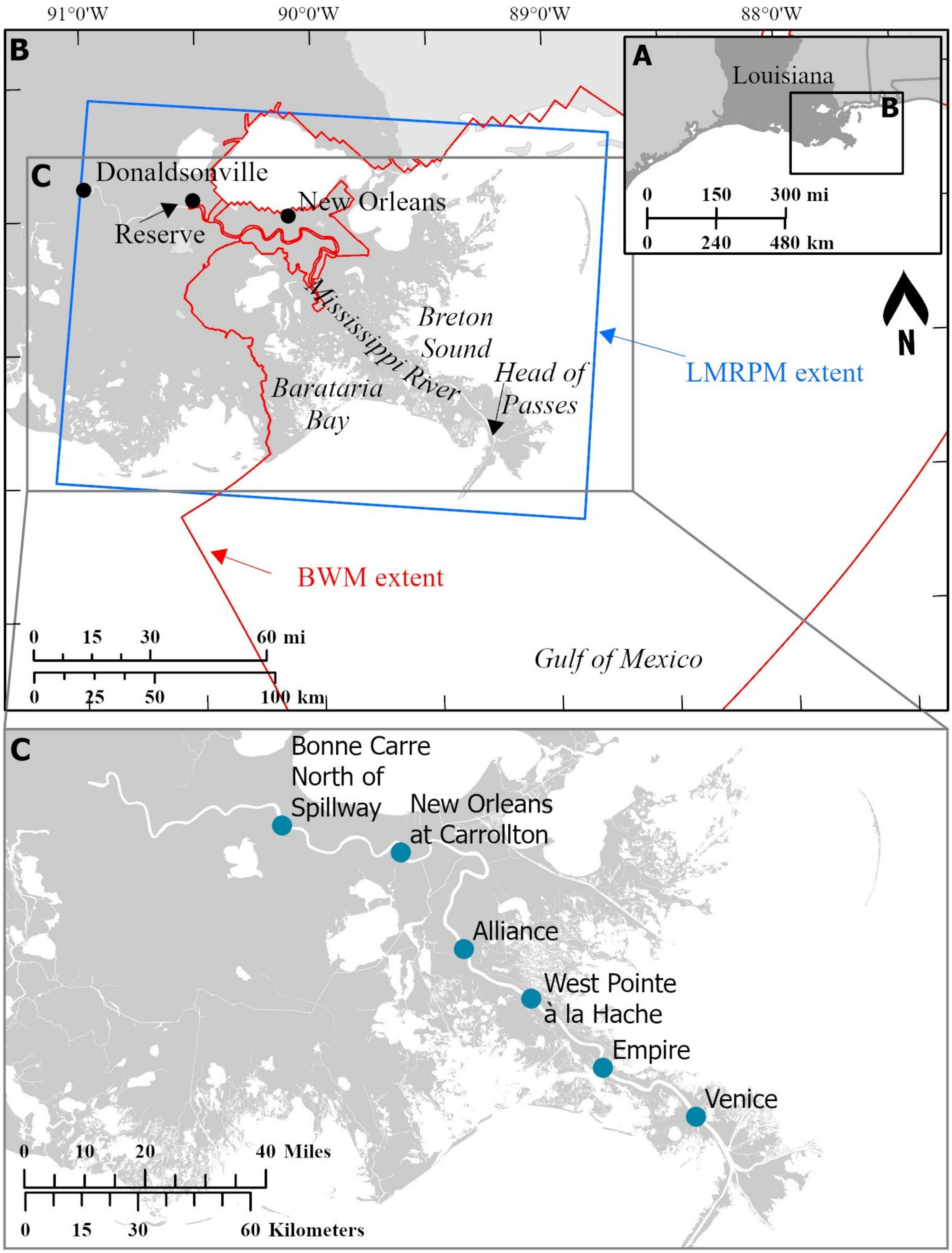

Figure 2. Geographic extent of the area of interest. BWM and LMRPM domain is displayed in panel B. USACE stations used for the stage and discharge analysis are shown in panel C.

2.2 MODEL CALIBRATION AND VALIDATION

The BWM used in this report was previously calibrated and validated as described in Bregman et al. (2020). The calibration effort focused on the mainstem of the Mississippi River channel, the Mississippi River Delta, Barataria and Breton basins, and a portion of Lake Pontchartrain. Within the Mississippi River channel, model output including water level, water discharge, and flow distribution through modern delta distributaries and crevasses were compared to field measurements, when available, or rating curve-based projections. In the receiving basins, water level, temperature, and salinity were also compared to observations. Field observations for 2016 were used for model calibration in the receiving basins, and were assembled from USACE, the United States Geological Survey (USGS), and the Coastwide Reference Monitoring System (CRMS) programs to calibrate river and basin hydrodynamics (Bregman et al., 2020). Sediment transport and morphology were calibrated using observational datasets from 2009–2011 in the Mississippi River, and from 2014 in the receiving basins. The following components were calibrated:

- suspended sediment load (for fine sediment and sand) in the Mississippi River (2009–2011),
- total suspended load in the Caernarvon Outfall Channel (using sediment observations at the site by USGS from 2007–2011),
- volumetric erosion/deposition of sediment in the West Bay receiving basin (estimated based on USACE New Orleans District and CPRA multi-beam bathymetry data for the diversion channel and single beam bathymetry data for receiving area from 2009–2011), and
- the spatial extent of inorganic sedimentation in the Big Mar Lake adjacent to the Caernarvon Diversion (using aerial photographs, differential RTK-GPS, and single-beam bathymetry from years 2013 to 2014; (Meselhe et al., 2015; Bregman et al., 2020).

2.3 SIMULATION PERIOD AND MODEL OPERATIONS

Two identical experiments (i.e., Series 6 and 8, also referred to as Test 1 and Test 2, respectively) were performed with the LMRPM to investigate the river hydrodynamics and sediment dynamic projections for the future 50 years (2020–2070) without restoration projects. Execution of each 50-year experiment took approximately 50 hours of simulation time, excluding preparations, measurements, and dredging activities performed throughout the simulation period. For additional information and details on the two identical experiments (Series 6 and 8) performed with the LMRPM, the reader is directed to Brady et al. (2021) and LSU Center for River Studies (2020). Simulations performed with the BWM for the 50-year production run differed slightly from the LMRPM:

- Five, one-decade long morphodynamical simulations were performed with Delft3D using morphological upscaling methods (MORFAC; Deltares, 2017). The landscape, including topography, bathymetry, and vegetation coverage was updated at the end of each decade to include marsh organic matter accretion due to the presence of vegetation. The bed elevation estimated by the BWM at the end of each decade was compared with the bed elevation measured in the LMRPM. The dredging volumes projected by these simulations were compared with the dredging volumes estimated with the LMRPM.

- Six one-year long hydrodynamic simulations were performed each time the landscape was updated every 10 years. These simulations include atmospheric forcing, salinity, and temperature and are not numerically accelerated (i.e., upscaled). The river stage and flow projected by these simulations was compared with the results from the LMRPM.

The BWM production run used for this comparison was performed as part of the Mid-Breton Environmental Impact Statement and corresponds to the "V4PR1_FSP_morph" from Messina et al. (2021). In this production run, the proposed sediment diversions were not included on the landscape (i.e., FWOP) and anthropogenic intervention on any newly formed crevasses in the Mississippi River spoil banks were reversed, mimicking channel maintenance approaches employed by the USACE. Before starting the simulations for a new decade, the crevasses that formed in the previously simulated decade were repaired by editing the model topography and bathymetry. This approach was performed to emulate potential future action and intervention by USACE New Orleans District if crevassing could compromise the Mississippi River channel or natural levee/bank.

Results for each decade were generated with both models and compared in this study.

2.4 MODEL INPUT AND FORCING

This section describes the main boundary conditions and forcing used in the BWM and in the LMRPM 50-year FWOP simulations/experiments. More detailed information can be found in Messina et al. (2021), for the BWM, and in Brandy et al. (2021), for the LMRPM.

2.4.1 Hydrodynamics

Mississippi River discharge for both models used the daily-averaged discharge at the USACE Tarbert Landing station (#01100Q) from 1964–2013, forward-projected to represent 2020–2070. For the LMRPM, the discharge values were converted into the physical model flows using model scaling information (Brady et al., 2021). The 50-year hydrograph used in the models is shown in Figure 3.

In the BWM, additional flow from tributaries in the Pontchartrain Basin, Mississippi Sound, and the Bonnet Carré Spillway were included; their hydrographs were calculated using available stream gauges variously from USGS, USACE, and rating curves previously developed for ungauged tributaries as described in Messina et al. (2021). For all these tributaries, the year 2014 hydrograph was selected and used in the boundary conditions[1].

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[1] Messina F., Bregman M., Georgiou I.Y., Appendix to H&H comments from Mid-Breton submitted to the Modeling Working Group, April 2020, Task Order 77

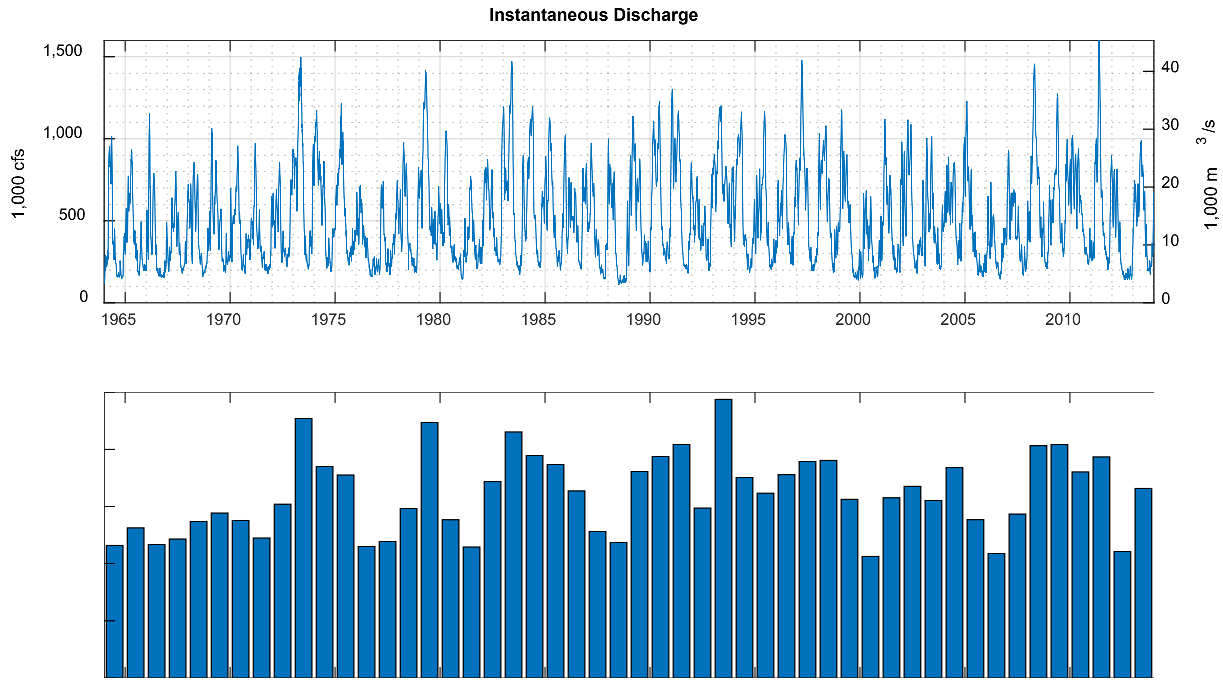

Figure 3. Mississippi River instantaneous discharge (top graph) and total annual discharge (lower graph) observed at USACE Tarbert Landing station (#01100Q) between 1964 and 2013.

2.4.2 Sediment Transport and Rating Curves

The BWM utilizes sediment transport formulae that account for bedload and suspended load (van Rijn et al., 2004). For this analysis only sand transport and corresponding sand flux (bedload and suspended load) were considered in the comparison between the two models, because the physical model does not consider fine sediment transport. Sand transport was previously simulated using a single representative grain-size fraction of 175 µm in grain diameter (Bregman et al., 2020), which approximately represents the spatially averaged median grain size (D_{50}) of the Lower Mississippi River bed sediment within the model domain (the D_{50} typically varies between 100 µm to 250 µm dependent on location; Gaines & Priestas, 2015). In the BWM, the suspended sand concentrations at the upstream boundary were estimated using water discharge records at Baton Rouge (USGS station 07374000) and a traditional sand rating curve previously developed by the Institute using the methodology described in Allison et al. (2012) and boat-based USGS measurements for the period 2008 to 2012 (Meselhe et al., 2016):

$$\text{Suspended Sand Load (metric tons/day)} = \mathrm{a} * [1 - \exp(-\mathrm{b} * Q_w)] + \mathrm{c} * [1 - \exp(-\mathrm{d} * Q_w)] \qquad \text{Eqn. 1}$$

where a = -2.145×10^5; b = 2.855×10^{-6}; c = 3.261×10^9; and d = 1.242×10^{-10}; and Q_w is the main stem water discharge at Baton Rouge (in m^3/s), and coefficients a through d, are regression constants originating from the development and revision of the rating curve (Allison et al., 2012; Meselhe et al., 2015)

A graphic representation of the sand rating curve used in the BWM is provided in Figure 4. Additional information on sand transport modeling in the BWM can be found in Bregman et al. (2020).

Fine sediment transport, erosion, and deposition (i.e., clay and silt) was based on Partheniades-Krone sediment transport formulations (Partheniades, 1965). For fine sediment load, a rating curve that includes "hysteresis behavior" (a temporal offset in the sediment concentration peak relative to the flow peak) was used, previously developed at Belle Chasse by Liang et al. (2016). First, the total sediment load was calculated using the hysteresis rating curve, developed using empirical sediment observations (both in-situ turbidity and isokinetic samples; Allison et al., 2012) and water discharge at Belle Chasse (USGS station 07374525; RM 76). Then, to determine the fine load, the sand fraction (as projected using the traditional sand rating curve developed by the Institute from boat-based USGS measurements for the period 2008 to 2012; (Allison et al., 2012; Meselhe et al., 2015)) at Belle Chasse was subtracted from the total sediment load, resulting in an estimated fine load curve that retained the hysteresis behavior and shape. Lastly, the fine sediment load was proportioned into 75% silt and 25% clay, based on sediment data collected as part of the Louisiana Coastal Area Program – Mississippi River Hydrodynamic and Delta Management Study (Allison & Pratt, 2013b, 2013a). The reader is directed to Liang et al (2016) and Bregman et al. (2020) for more details on the methods and procedures.

The LMRPM used one sediment class: sand. The material chosen to comprise the movable bed was a ground unexpanded polystyrene with a specific gravity of 1.05 g/cm^3, which is a widely used lightweight sediment in physical modeling (Frostick et al., 2011). BCG Engineering and Consulting (2015) assumed a real-world specific density of 2.65 g/cm^3 and a sand grain diameter of 162 µm. The model grain size distribution was scaled based on similarity of the Froude number, critical particle Reynolds number, and critical Shields parameter (BCG Engineering and Consulting, 2015), and is summarized in Table 2. Sediment concentrations at the upstream model boundary near Donaldsonville were determined from HEC-6T model results (Thomas, 2014) that were used to determine the relationship between sediment discharge (or sediment concentration) and water discharge (orange line in Figure 4). The sediment concentrations imposed at the upstream HEC-6T model boundary near Tarbert Landing were are derived from a regression curve (yellow line in Figure 4, Copeland et al., 2020) that is based on measurements taken at Tarbert Landing. Hooper (2019) used the HEC-6T results by Thomas (2014) to determine the scaled sediment rating curve for the LMRPM.

Because of the use of different sand rating curves in the two models, there was a notable difference between sand loads entering the model domain at the upstream model boundaries. Figure 5 shows the annual sand load input into both models over the entire 50-year simulation period.

Table 2. Comparison of sediment characteristics in the "real" Mississipi River system and in the LMRPM (BCG Engineering & Consulting, Inc., 2015). Adapted from LSU Center for River Studies (2020).

Type	D_{10} (mm)	D_{50} (mm)	D_{90} (mm)
Mississippi River	0.08	0.12–0.14	0.25
LMRPM	0.25	0.40–0.45	0.80

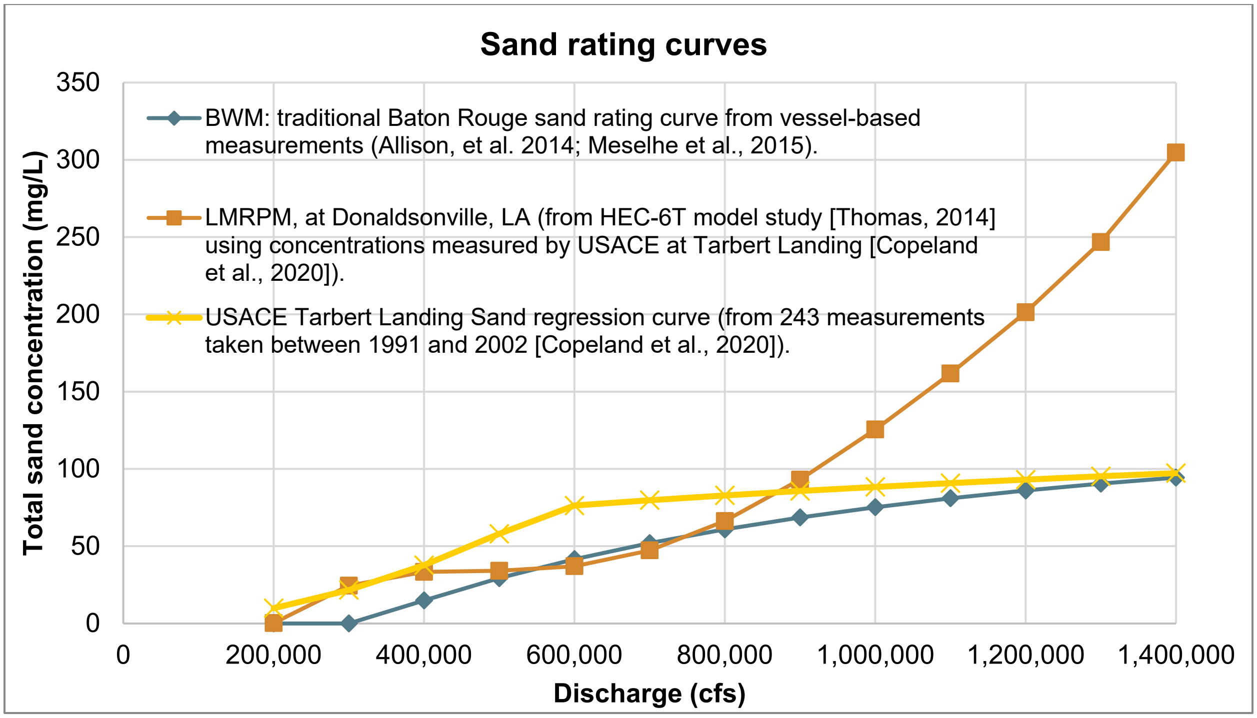

Figure 4. Sand rating curves used to calculate sand load at the upstream boundary of the LMRPM, in orange, (Copeland et al., 2020; Thomas, 2014) and of the BWM, in green (Allison et al., 2012, 2014; Meselhe et al., 2015). The USACE Tarbert landing sand regression curve, in yellow, is also included as a reference (Copeland et al., 2020). For the BWM, the sand rating curve (green) was applied as shown at Reserve.

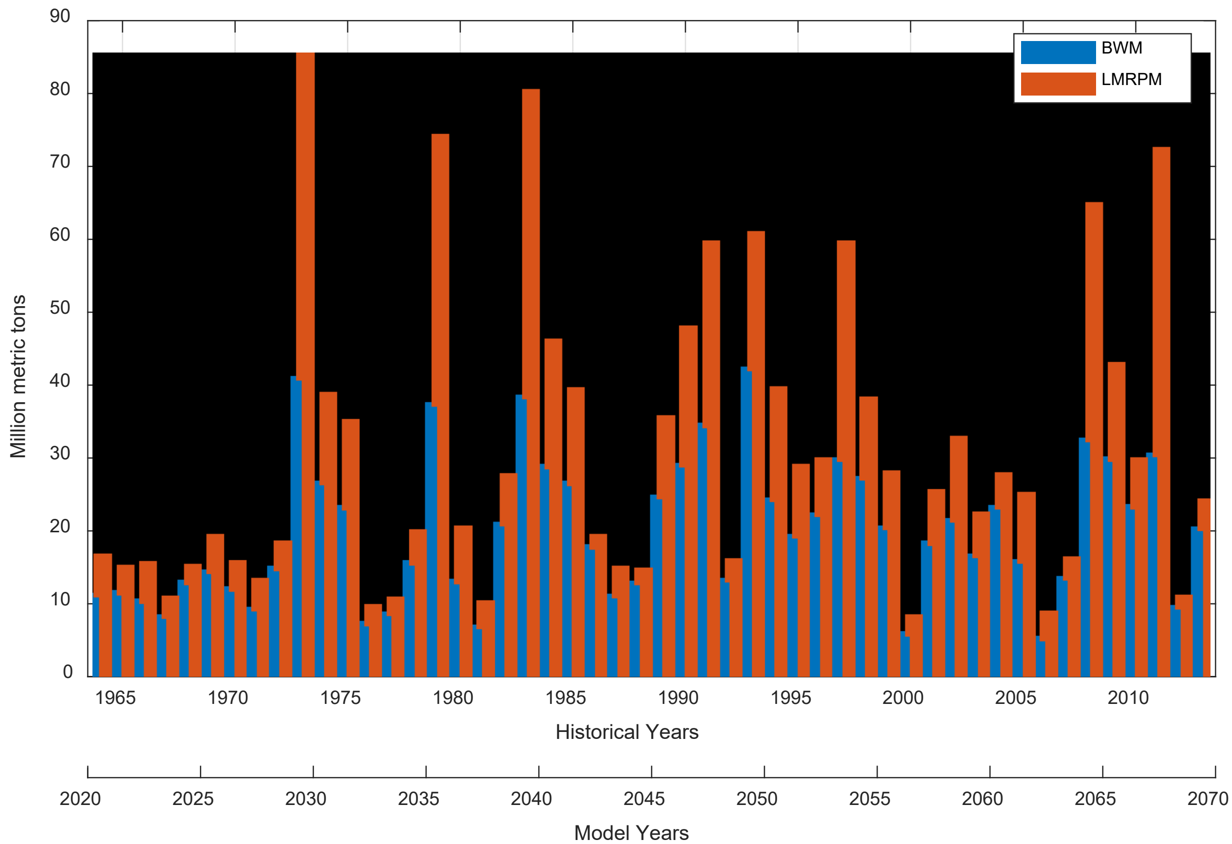

Figure 5. Comparison of annual sand load at the upstream boundary of the LMRPM (in orange) and of the BWM (in blue), based on the rating curves in presented in Figure 4, and the Mississippi River discharge between 1964 and 2013 (Figure 3).

2.4.3 Morphology

Bed stratigraphy and soil properties (e.g., critical shear stress, bulk density) were defined in the BWM based on interpretation of observational datasets, expert opinion, and published studies of similar environments (Allison et al., 2015; Meselhe et al., 2015). The stratigraphy (layering of sediment) that comprises the bed and the underlying sediment in the model domain was simplified into five layers of variable thicknesses (Bregman et al., 2020). The bed composition and stratigraphy of the Mississippi River reach of the model were derived from a calibrated and validated regional-scale model of the Lower Mississippi River previously developed and informed by field observations including cores, and contains a substrate characterized by a sand river bed underlain by lenses of sand, clay, and silt (Meselhe et al., 2015). A MORFAC value of 40 was used for the BWM's morphological simulations to shorten computational time. The MORFAC approach was implemented and validated by Lesser et al. (2000; 2004), investigated for its validity and limitations by Ranasinghe et al. (2011), and has since been successfully used in coastal and deltaic applications by Roelvink (2006) and Li et al. (2018). These studies demonstrate that the application of acceleration methods does not significantly affect the simulated evolution of deltaic environments. For the BWM, it was found that a MORFAC of 40 did not produce a significant bias in the results (Sadid et al., 2018).

Due to the LMRPM's representation of the topography and bathymetry using non-erodible high-density foam panels, the LMRPM was pre-loaded with sediment and was initialized by running 18 average hydrographs and five real hydrographs to establish base conditions before conducting a 50-year simulation (Brady et al., 2021). The utilization of single sediment fraction implies the absence of imposed or natural stratification within the bed sediment. The best replication of real-world overall morphology was found when using a sediment time scale of 6600 seconds, which indicates that it takes approximately 1 hour in the LMRPM to simulate a full year (Hooper, 2019).

2.4.4 Relative Sea Level Rise

Both models used the used the 'Medium' sea level rise scenario (i.e., 1.5 m by 2100) from the 2017 Coastal Master Plan (Pahl, 2017) for this comparative analysis. Spatially variable subsidence was included in the BWM according to the 2012 Coastal Master Plan's 'Moderate' scenario (Appendix C in CPRA, 2017). Because it is not possible to lower the bed of the LMRPM, subsidence was incorporated by implementing relative sea level rise (RSLR, i.e., sea level rise coupled with subsidence) while keeping the bed at the same level. The subsidence imposed in LMRPM for the RSLR calculation is the medium rate at HOP (RM 0), based on the 2012 Coastal Master Plan (Olivier, 2016). While the BWM accounts for spatially variable subsidence, the RSLR implemented in the LMRPM considered a uniform subsidence value informed by subsidence at the HOP.

2.5 NAVIGATION DREDGING

The BWM simulates navigation channel maintenance dredging in the Lower Mississippi River Ship Channel (MRSC; Figure 6) to maintain a navigable depth of 13.7 m (45 ft) below NAVD88. Specifically, the model was programmed to dredge at four reaches in the Mississippi River domain that undergo regular dredging: Fairview Crossing, New Orleans Harbor, HOP, and Southwest Pass (SWP). Dredging in the BWM is represented by the removal of all sediment deposited above the specified channel depth. Additionally, when dredging is required, the model over dredges by an additional 0.5 m. The sediment volume that was dredged is subsequently eliminated from the model domain (i.e., it is not placed anywhere within the model domain, but it is recorded and documented). The MRSC dredging operation was performed every 30 days.

Dredging activities in the LMRPM consist of maintaining the lowermost part of the river channel to a depth of 38 mm (model scale) to mimic USACE dredging to a real-world equivalent depth of 15.24 m (50 ft), at a frequency of every other year in the first 25 years, and annually in the latter 25 years. The narrow width of the MRSC, which measures 229 m (750 ft) wide in the real world, translates to a width of 3.8 cm in the LMRPM, which can inadvertently lead to potential dredging outside of MRSC footprint (Brady et al., 2021). In addition to the regular navigation dredging in the MRSC between Venice and SWP jetties, in the LMRPM was also necessary to dredge other bird's foot delta distributaries (i.e., Grand Pass, Baptiste Colette, Cubits Gap, Pass a Loutre, and South Pass; Figure 6; Brady et al., 2021) on an as-needed basis to prevent blockages caused by sedimentation. The channels of these distributaries were dredged to a real-world equivalent depth of 6–7.6 m (20–25 ft) every 4 years in the LMRPM. Some additional dredging is conducted at the Bonnet Carré Spillway. Approximately two-thirds of the dredging in the LMRPM occurs between Venice and the SWP jetties, while the remaining one-third takes place within the delta distributaries. However, these additional dredging activities outside of the MRSC were not included in the projected dredging statistics developed for this model comparison. Annual dredging volumes were provided for both identical experiments (i.e., Series 6 and 8). The dredging volumes between the two experiments conducted with the LMRPM display a significant degree of variability. In some years, the dredging volumes differed by more than a factor of 2 between the two experiments. Additionally, the second experiment (Series 8) exhibits more dredging during the first half of the simulation, whereas the first experiment (Series 6) shows more dredging during the second half. Despite these differences, the cumulative 50-year dredging volumes only differ by 12%.

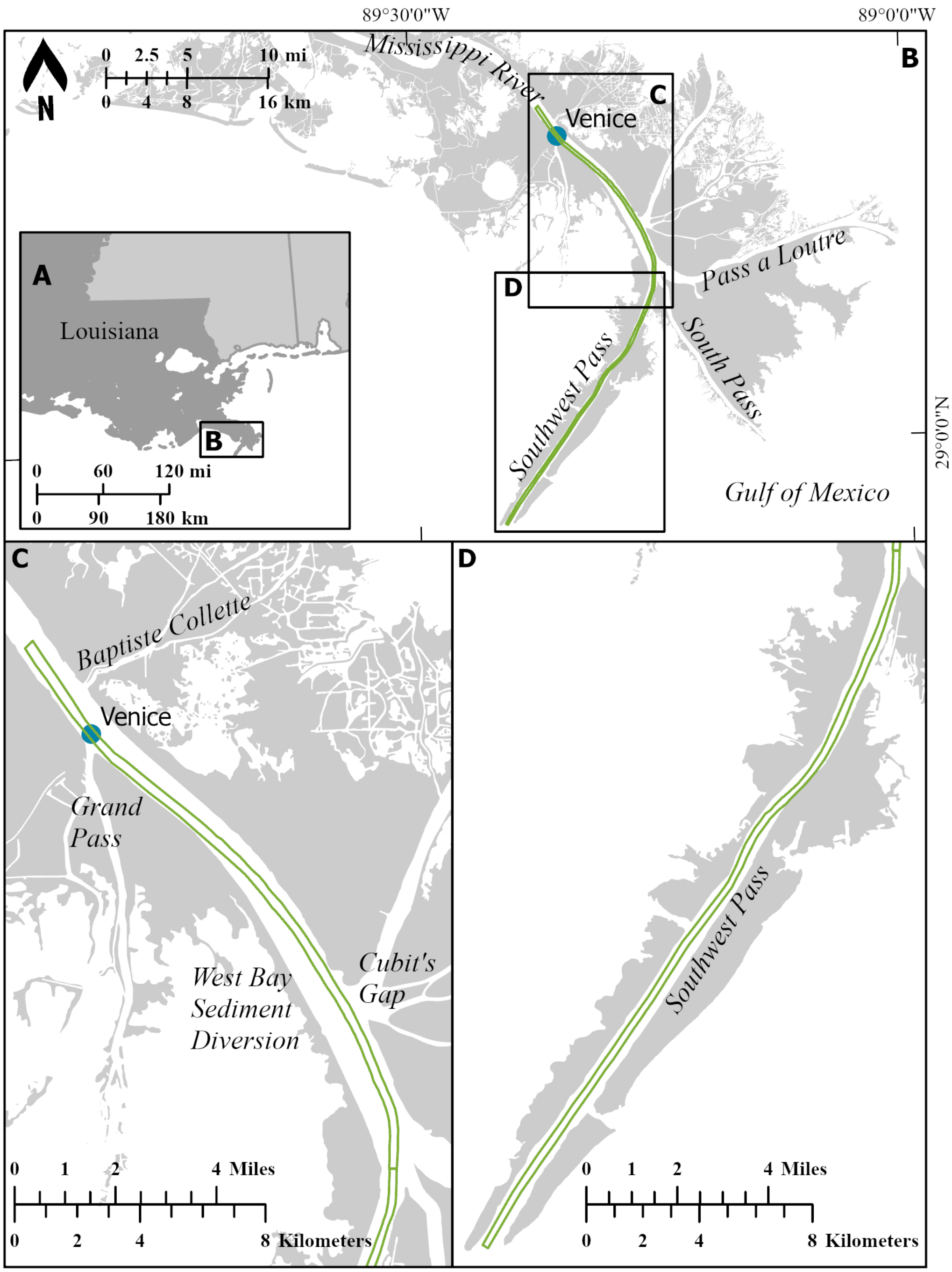

Figure 6. Lowermost part of the Mississippi River and its main distributaries. The green polygon indicates the MRSC where maintenance dredging takes place.

3.0 METHODOLOGY

3.1 STAGE AND FLOW

The BWM output is saved at each grid cell every three hours. Selected observation points and cross sections were implemented in the model corresponding to existing gauges or points of interest. At these locations, the model results were saved every hour. When possible, these locations were selected to compare in-river stage and flow discharge with the LMRPM.

To monitor and record stage in the river projected by the LMRPM, 16 ultrasonic water level sensors were located along the Mississippi River channel at the same corresponding locations as actual gauges on the prototype. These sensors measure river stages throughout each year. This data, along with headbox discharge, was collected automatically by Laboratory Virtual Instrument Engineering Workbench (LabVIEW)[2] approximately every 6 seconds throughout each year, which correspond to 14.6 hours in the "real world" time. The LMRPM stage and flow results were provided, on a decadal basis, for eight locations along the Mississippi River. Six of these locations correspond to existing observation points and cross sections in the BWM: Bonnet Carré North of Spillway, New Orleans at Carrollton, Alliance, West Point à La Hache, Empire, and Venice (Figure 2C). Stage-discharge curves at these six locations were compared between the two models. Additionally, for the 2020 landscape, target stage discharge curves using historical observations were created to compare with the models as a second validation check; these target stage-discharge curves are only valid for the first decade because they only reflect historical sea level with little to no acceleration (LSU Center for River Studies, 2020).

For this comparison, the results of the six one-year hydrodynamic simulations performed with the BWM were used.

3.2 BED ELEVATION

Bed elevation measurements in the LMRPM were taken every other year at four cross-sections near each of the following locations: Reserve (at RM 138, RM 137.5, RM 137, and RM 136.5), New Orleans at Carrollton (at RM 107, RM 106.5, RM 106, and RM 105.5), Alliance (at RM 65, RM 64.5, RM 64, and RM 63.5), Empire (at RM 26.5, RM 25, RM 25.5, and RM 25), and Venice (at RM8, RM7.5, RM7, RM6.5). Each year, the average of the three previous years was retained for analysis (i.e., for year 10, it was an average of year 6, year 8, and year 10). Two measurements per cross section were collected: one closer to the east side of the channel (i.e., "East" measurement) and one further west (i.e., "West" measurement). The East and West measurement locations varied based on the cross sections. Table 3 lists the four cross sections used for each one of the four locations, and the East and West measurement distance from the east side of the river channel.

[2]System-design platform and development environment for a visual programming language from National Instruments

The BWM bed elevation results were extracted from the model output files providing bed elevation results at selected streamwise transects incorporating all grid cells along the transect. The extracted bed elevation was compared with the LMRPM bed elevation every 10 years. The bed elevation projected by the BWM was extracted along several profiles:

- Four streamwise profiles starting at HOP going up to RM 108 at four different distances across the river. These four profiles were used to calculate average, maximum, and minimum bed elevation across the river from HOP to RM 108. These values were compared with the average bed elevation measurements from the LMRPM;
- Four bank-to-bank cross sections across the river (see right-hand column in Table 3). The average bed elevation at the two grid cells closer to the LMRPM measurements was calculated, together with the standard deviation. These values were compared with the corresponding LMRPM bed elevation average and standard deviation at the four corresponding cross sections (Table 3).

Table 3. Cross section locations where the bed elevation measurements were taken in the LMRPM. East and West locations are provided as mm from the east side of the river channel in the physical model. Horizontal scale of the LMRPM is 1:6,000. The cross-section RM used in the BWM for the comparison is also provided.

Location	LMRPM			BWM
	Cross section RM	East Measurement (mm from the east side of the channel)	West Measurement (mm from the east side of the channel)	RM
New Orleans at Carrollton	107	10	12.5	106
	106.5	8	11.5	
	106	10.5	13	
	105.5	9	11	
Alliance	65	7.5	10	64
	64.5	8	10	
	64	7.5	11	
	63.5	7	11	
Empire	26.5	7	10	26
	26	8	10	
	25.5	7.5	9	
	25	6.5	9	
Venice	8	11	-	7
	7.5	8.5	11	
	7	7	11	
	6.5	8	11	

3.3 NAVIGATION DREDGING VOLUMES

The comparison of dredging volumes between the two models included dredging in the MRSC between Venice and the SWP jetties. The analysis omitted the dredging volumes at Fairview Crossing and New Orleans Harbor in the BWM, and any dredging in the LMRPM within the delta distributaries (i.e., Grand Pass, Baptiste Colette, Cubits Gap, South Pass, and West Bay Sediment Diversion; Figure 6). The LMRPM results encompass two experiments, and the dredging volumes between these experiments were averaged for the analysis presented in this study.

For the dredging analysis, additional comparisons were conducted using historical records of dredged volumes in the MRSC spanning the period from 1970 to 2019, as documented by Sharp et al. (2013), and Esposito et al. (2021). While these real-world records reflect historical data rather than simulated future conditions that incorporate sea level rise and subsidence, they are useful for evaluating and validating model projections. The historical records provide a baseline comparison as they represent similar hydrographic conditions, enabling an assessment of the accuracy and reliability of the model outputs.

The comparison of dredging volumes between the two models is considered justified, even though the LMRPM only considers sand while the BWM incorporates both sand and fines, because the fine sediments in the BWM constitute less than 1% of the dredged sediment. The dredging volumes between the two models were compared under the same sediment property assumptions. The accuracy of the sand mass data provided for the LMRPM was confirmed by comparing the values at the upstream boundary with those calculated using Thomas' (2014) sand rating curve at Donaldsonville (Figure 4) and the Mississippi River discharge timeseries (Figure 3). Because dredging contracting and activity are commonly reported in volumes, a dry bed density of 1,590 kg/m^3 was assumed for the LMRPM, which matches the dry bed density used for sand in the BWM. The historical dredging records, which are included in the comparison, were presented as volumes in Esposito et al. (2021).

4.0 RESULTS

4.1 STAGE AND FLOW

The results for the 2020 landscape show that both models aligned well with the target stage discharge curve at Bonnet Carré Spillway and Carrollton (Figure 7 and Figure 8). From Alliance downstream, LMRPM slightly overestimated stage for all discharge values, while the numerical model agreed with the target stage for discharges below 20,000 m^3/s (700,000 cfs) but overestimated stage for higher flows (Figure 9 to Figure 12). The BWM exhibited larger variance in the projected stage at lower discharges (<13,000 m^3/s or ~450,000 cfs) with the average being close to the target stage. At higher flows, generally above 13,000 m^3/s (~450,000 cfs), the stage variance in the model projection was lower (Figure 7 to Figure 12). There appears to be more variance in the physical model at higher flows (Figure 7 to Figure 12) compared to the numerical model.

For later decades (e.g. year 2060 for reference) both models (BWM and LMRPM) projected higher river stages than the target stage, as expected, because of the increase in Gulf of Mexico sea levels above the baseline sea level experienced over the historical record due to RSLR (Figure 13 to Figure 18). For the 2060 landscape, LMRPM stage projections were 1.5–3 m (5–10 ft) higher than the BWM results, with Test 1 being consistently higher than Test 2 (Figure 13 to Figure 18). At higher flows, and specifically when discharge in the river exceeds ~25,000 m^3/s (~900,000 cfs), the LMRPM stage-discharge projections exhibited lower variance and asymptotic behavior, similar to stage discharge projections for 2020. Stage-discharge projections by the BWM above the same threshold (~25,000 m^3/s; ~900,000 cfs) similarly exhibited lower variance compared to the physical model but showed a linear response continuously increasing as a function of flow.

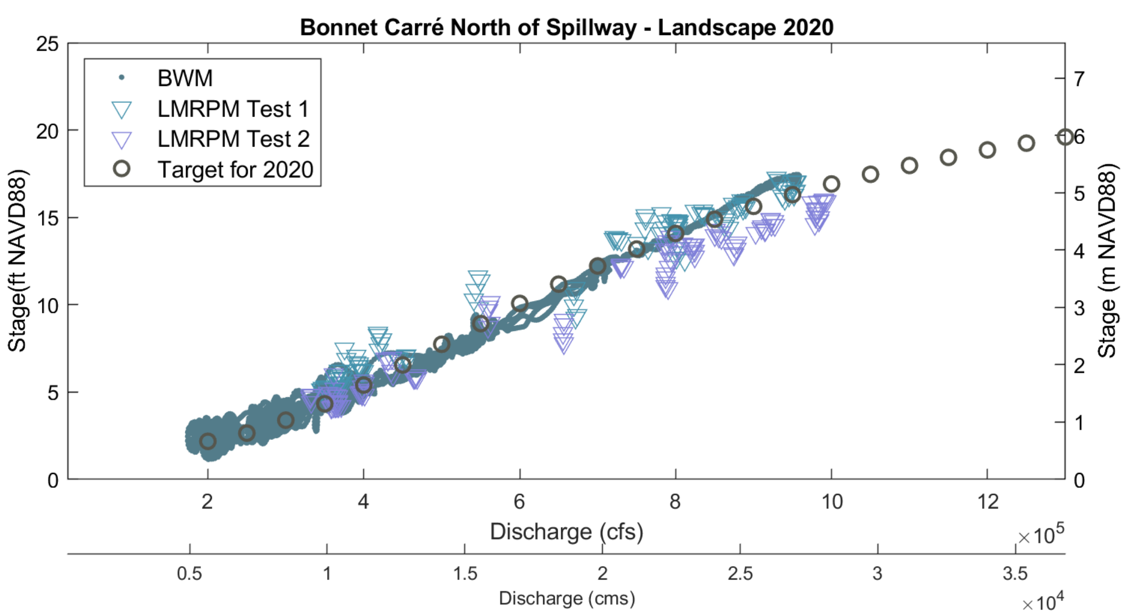

Figure 7. Relationship between stage and discharge at Bonnet Carré North of Spillway in 2020 for the BWM FWOP alternative (green dots), LMRPM Test 1 results (green triangles), LMRPM Test 2 results (purple triangles) and the target stage discharge curve (black dots)

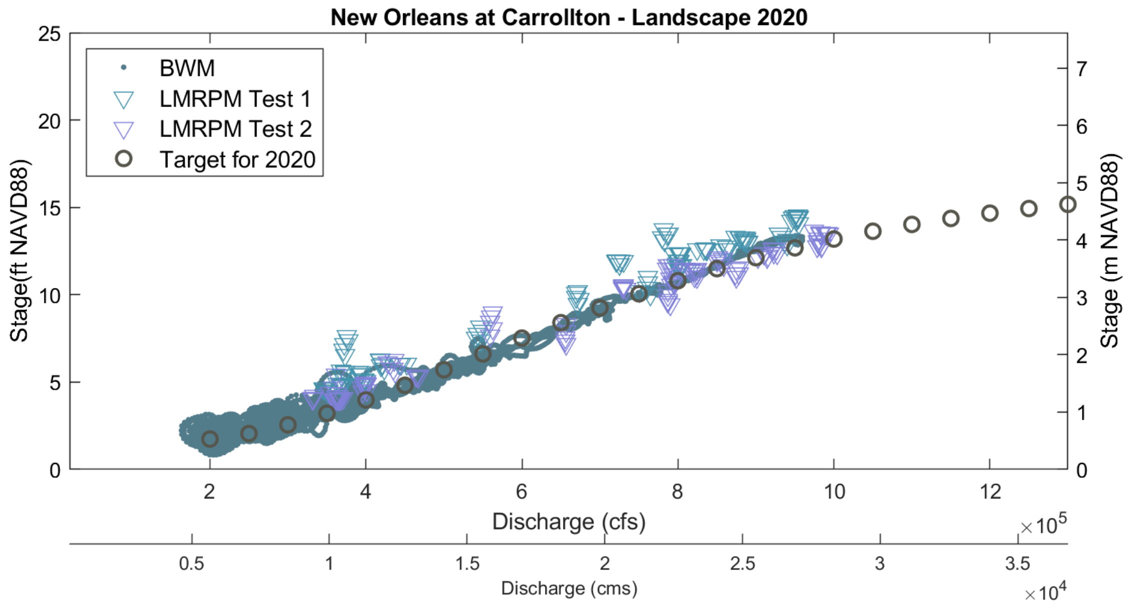

Figure 8. Relationship between stage and discharge at New Orleans at Carrollton in 2020 for the BWM FWOP alternative (green dots), LMRPM Test 1 results (green triangles), LMRPM Test 2 results (purple triangles) and the target stage discharge curve (black dots)

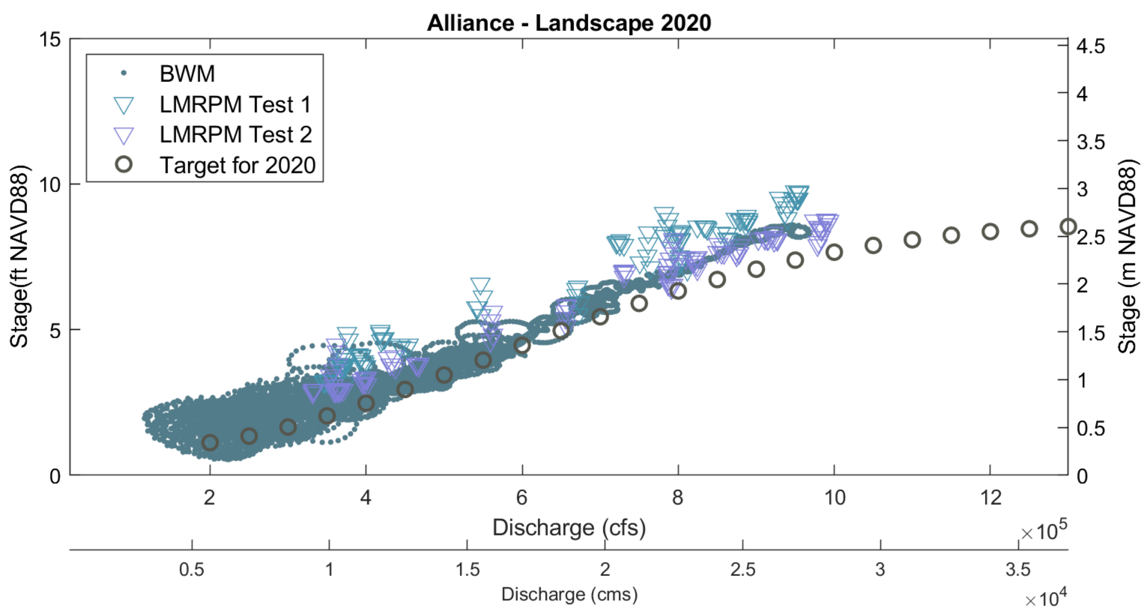

Figure 9. Relationship between stage and discharge at Alliance in 2020 for the BWM FWOP alternative (green dots), LMRPM Test 1 results (green triangles), LMRPM Test 2 results (purple triangles) and the target stage discharge curve (black dots)

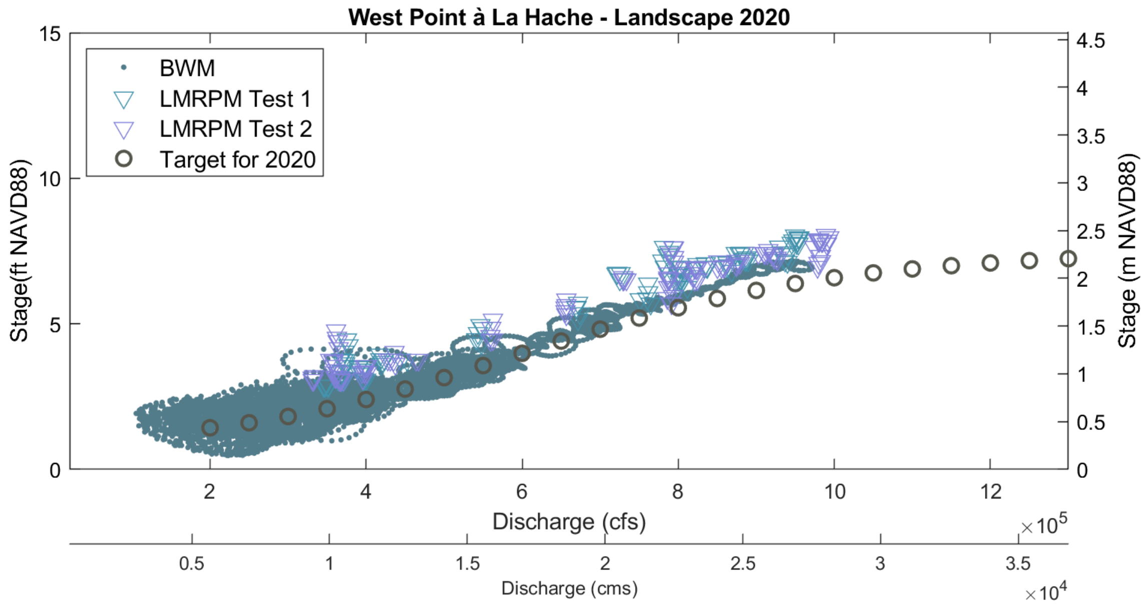

Figure 10. Relationship between stage and discharge at West Point à La Hache in 2020 for the BWM FWOP alternative (green dots), LMRPM Test 1 results (green triangles), LMRPM Test 2 results (purple triangles) and the target stage discharge curve (black dots)

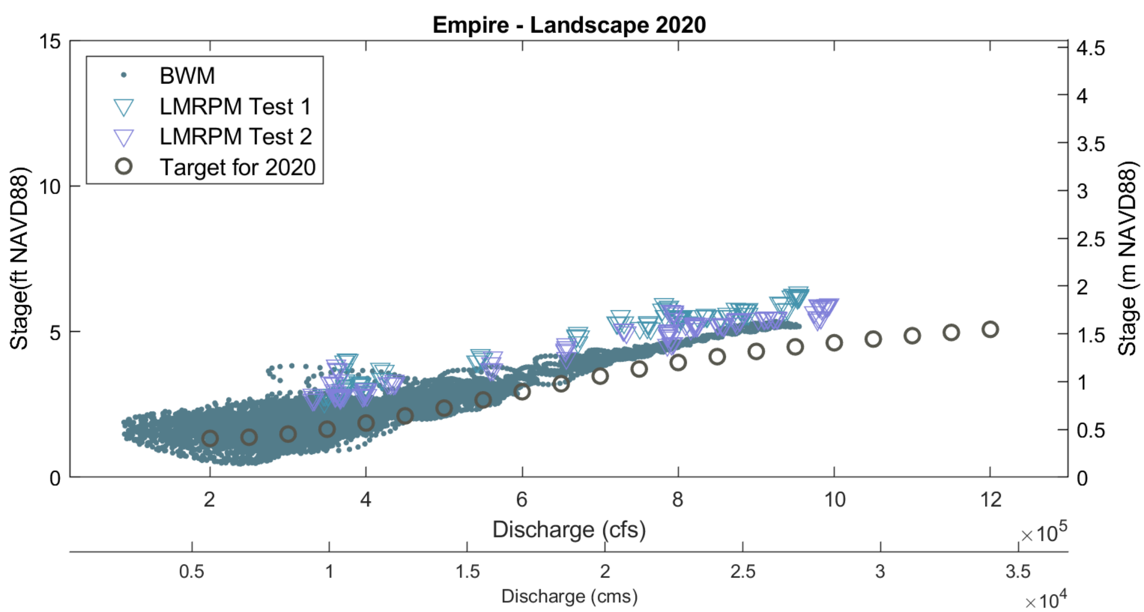

Figure 11. Relationship between stage and discharge at Empire in 2020 for the BWM FWOP alternative (green dots), LMRPM Test 1 results (green triangles), LMRPM Test 2 results (purple triangles) and the target stage discharge curve (black dots)

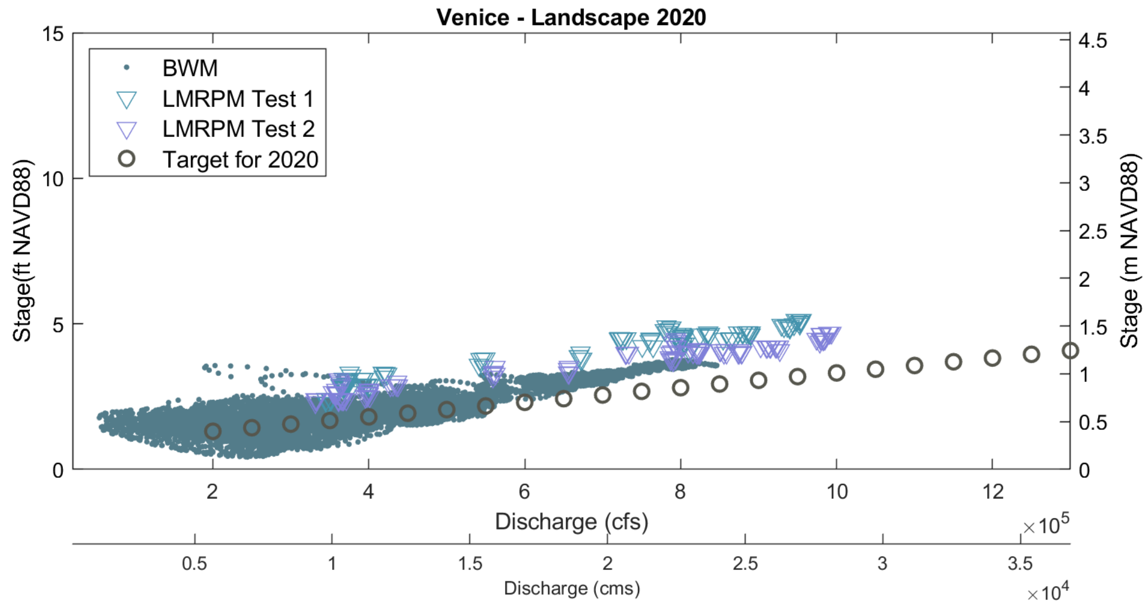

Figure 12. Relationship between stage and discharge at Venice in 2020 for the BWM FWOP alternative (green dots), LMRPM Test 1 results (green triangles), LMRPM Test 2 results (purple triangles) and the target stage discharge curve (black dots)

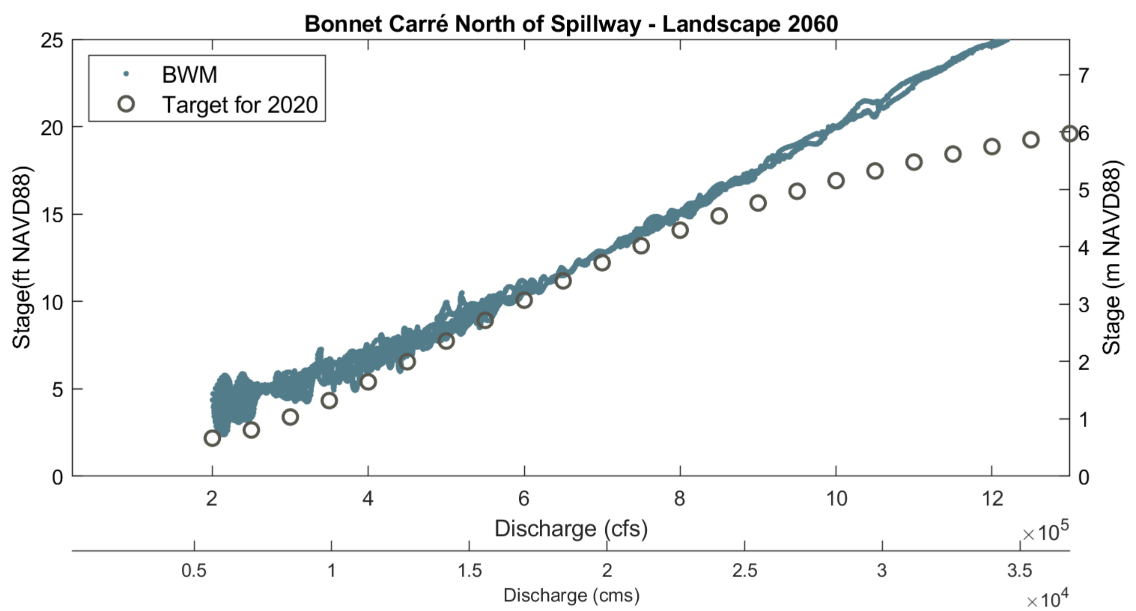

Figure 13. Relationship between stage and discharge at Bonnet Carré North of Spillway in 2060 for the BWM FWOP alternative (green dots) and the 2020 target stage discharge curve (black dots) included to show the effect of SLR. LMRPM results were not available.

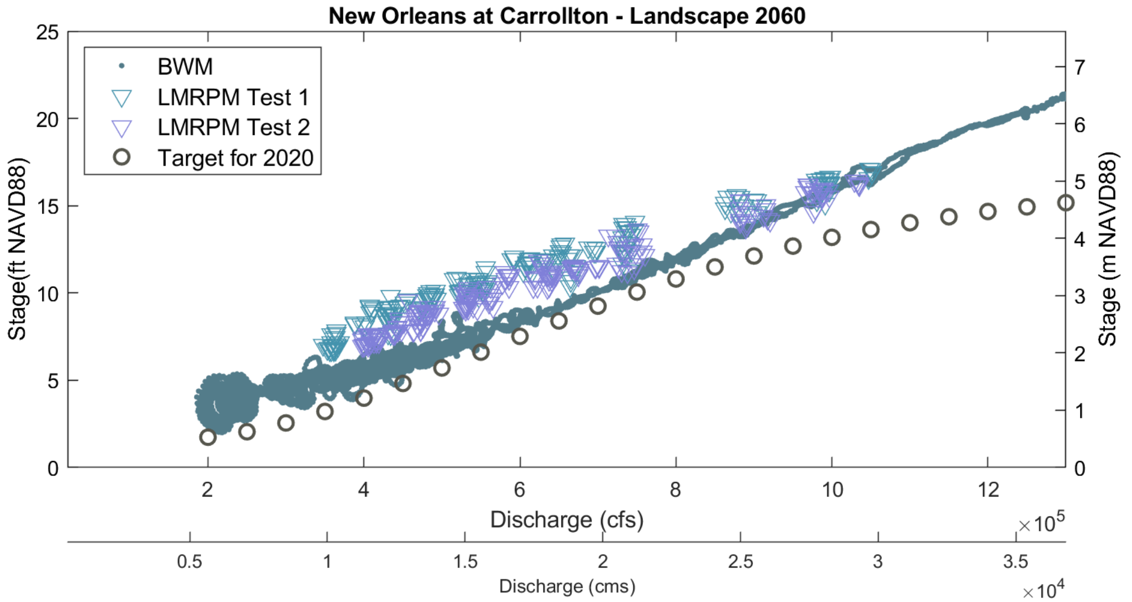

Figure 14. Relationship between stage and discharge at New Orleans at Carrollton in 2060 for the BWM FWOP alternative (green dots), LMRPM Test 1 results (green triangles), LMRPM Test 2 results (purple triangles) and the 2020 target stage discharge curve (black dots) included to show the effect of SLR.

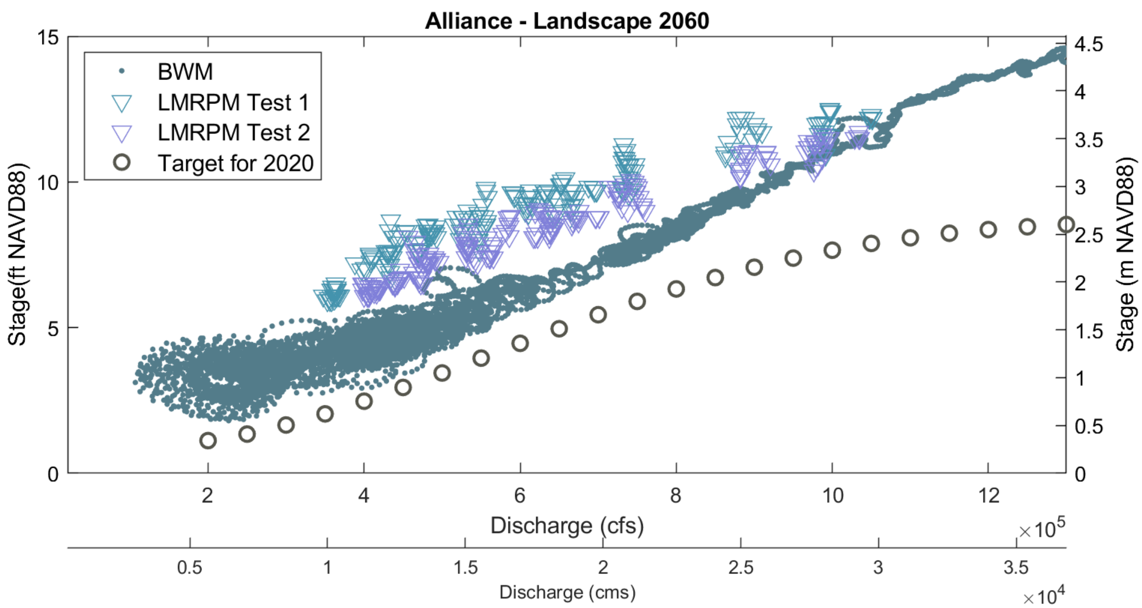

Figure 15. Relationship between stage and discharge at Alliance in 2060 for the BWM FWOP alternative (green dots), LMRPM Test 1 results (green triangles), LMRPM Test 2 results (purple triangles) and the 2020 target stage discharge curve (black dots) included to show the effect of SLR

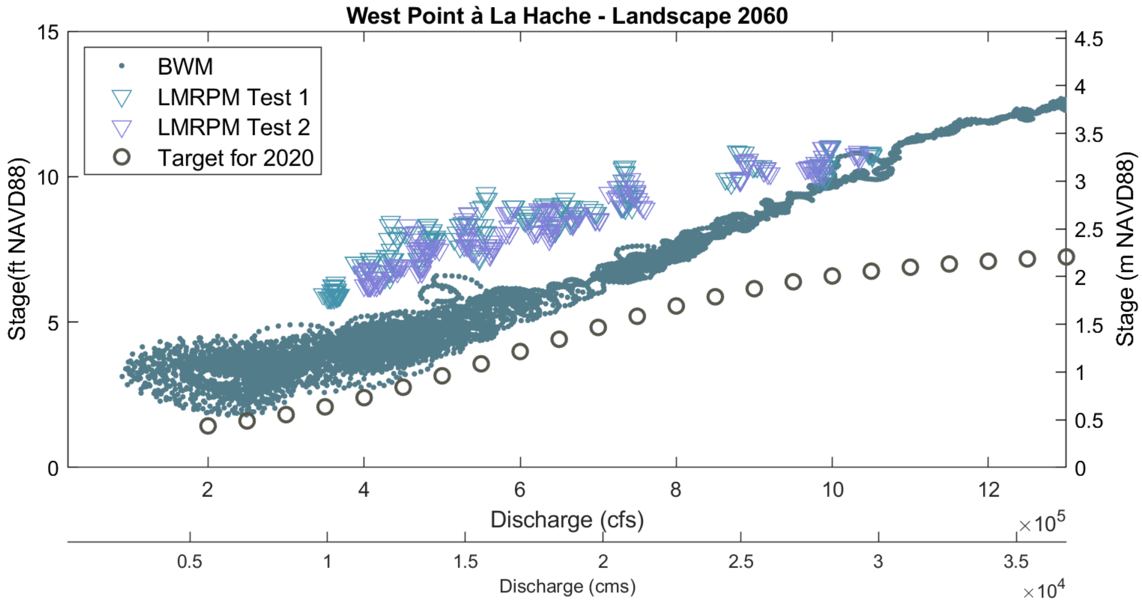

Figure 16. Relationship between stage and discharge at West Point à La Hache in 2060 for the BWM FWOP alternative (green dots), LMRPM Test 1 results (green triangles), LMRPM Test 2 results (purple triangles) and the 2020 target stage discharge curve (black dots) included to show the effect of SLR

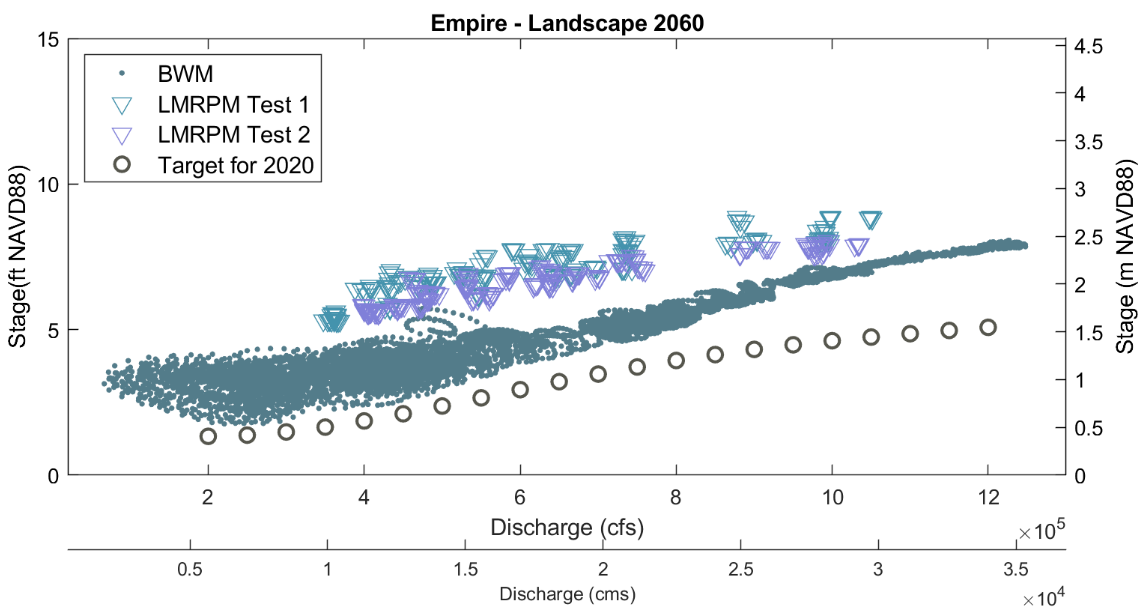

Figure 17. Relationship between stage and discharge at Empire in 2060 for the BWM FWOP alternative (green dots), LMRPM Test 1 results (green triangles), LMRPM Test 2 results (purple triangles) and the 2020 target stage discharge curve (black dots) included to show the effect of SLR

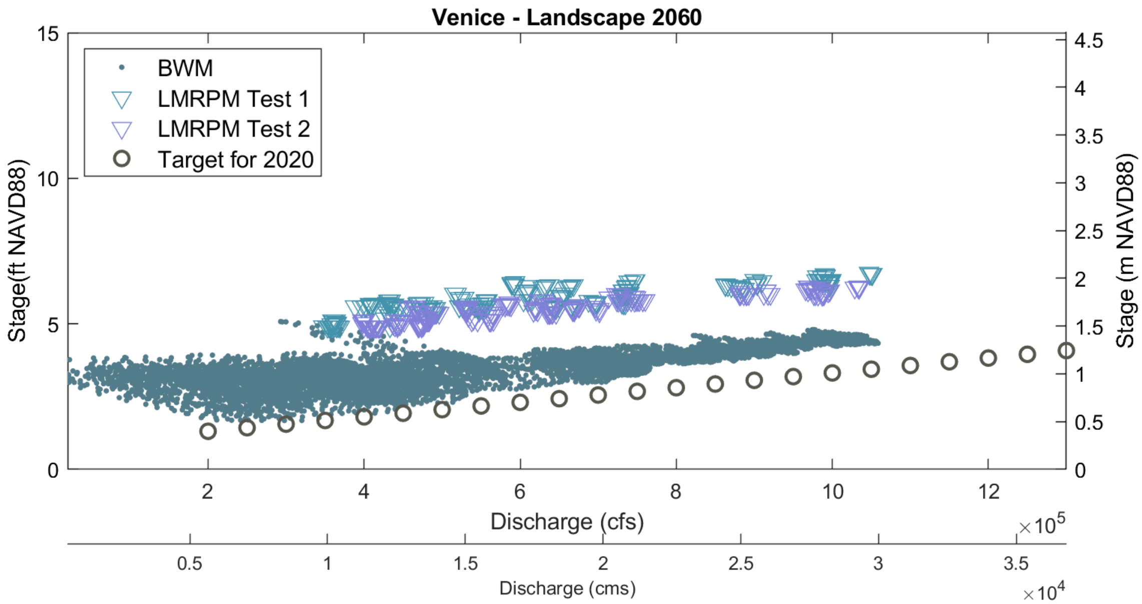

Figure 18. Relationship between stage and discharge at Venice in 2060 for the BWM FWOP alternative (green dots), LMRPM Test 1 results (green triangles), LMRPM Test 2 results (purple triangles) and the 2020 target stage discharge curve (black dots) included to show the effect of SLR

4.2 BED ELEVATION

The comparison of bed elevation between the LMRPM and the BWM focused on the four locations at which the LMRPM measurements were taken.

At RM 106, the BWM projected almost no change in the first three decades (2030–2050) and less than one meter aggradation (<1 m; 3 ft shallower) in the last two decades (2050–2070; Table 4). LMRPM exhibited channel degradation for the same period (2030–2060), followed by channel aggradation (~2 m; 6 ft) during the last decade (Table 4). Little and Biedenharn (2014) showed that this reach of the river has been in dynamic equilibrium between 1970 and 2000, in line with the BMW projections. As indicated by the standard deviation in the BWM, the variance was about half that of the LMRPM data.

At RM 64, the BWM projected a stable bed as evidenced by bed elevation exhibiting little change (~0.5 m/decade) for the simulation period (2020–2070), while the LMRPM showed a large bed aggradation and degradation response (up to 8 m [26 ft] variability across decades), without obvious trends over time (Table 4). Despite low decadal variability, as shown by the average bed elevation for each decade, the annual bed elevation trends (as indicated by the standard deviation) in the BWM were the largest projected at this location and up to 8.5 m (28 ft). Little and Biedenharn (2014) showed a trending aggradation in this reach of the river between 1970 and 2000.

At RM 26, the LMRPM showed bed elevation always 3–7 m (10–23 ft) lower (deeper channel) than the numerical model. The projections by the LMRPM showed a consistent channel aggradation trend from 2030 to 2070 (Table 4). Both models showed a similar decadal variability in bed elevation as evidenced by the standard deviation. The LMRPM showed apparent trends in channel aggradation since the riverbed elevation was rising over time (~4 m [13 ft] in 40 years) from 2030 to 2070, while the BWM showed no apparent trends over time. Little and Biedenharn (2014) confirmed historical aggradation in this reach from 1970 to 2000.

At RM 7 the LMRPM projected riverbed elevation was approximately 2 m lower than the riverbed elevation projected by the BWM in 2030. However, the channel aggraded over time and then became shallower (2–4 m; 6–13 ft) in subsequent decades (Table 4). The BWM showed channel degradation of the order of 0.6 m (2 ft) after the first decade, followed by sediment deposition and resulting channel aggradation over time. Similarly, Little end Biedenharn (2014) showed aggradation. Both models have a similar decadal variability as evidenced by similar standard deviation (Table 4).

The riverbed elevations projected by the BWM showed a variance in the transverse direction (across the river) as well as a variance along the river in the streamwise direction as follows (Figure 19 and Figure 20): from ~3 m (10ft) around RM 60 and RM 106 to ~37 m (121 ft) at RM 50. The LMRPM showed a variance of ~4 m (13ft) around RM 8 and RM 106, and ~15 m (49 ft) at RM 68 (Figure 19 and Figure 20). The BWM did not show a significant bed elevation difference between 2030 and 2060 (Figure 19 and Figure 20).

Table 4. Average (and standard deviation in parenthesis) bed elevation for the BWM and for the LMRPM at RM 106 (New Orleans at Carrollton), RM 64 (Alliance), RM 26 (Empire) and RM 7 (Venice). The LMRPM results were averaged between Test 1 and Test 2 and among the four cross sections specified for each location in Table 3. The BWM results were taken at the specified cross section, using the two grid cells closer to the East and West locations where the LMRPM results were taken (Table 3)

Decade	RM 106			RM 64		
	Averaged Bed Elevation (m NAVD88)			Averaged Bed Elevation (m NAVD88)		
	LMRPM	BWM	LRMPM - BWM	LMRPM	BWM	LRMPM - BWM
2030	-14.6 (2.3)	-19.2(1.1)	4.6	-23.3 (6.6)	-21.7 (8.5)	-1.7
2040	-15.1 (2.1)	-19.2 (1.1)	4.2	-19.9 (6.9)	-21.7 (8.5)	1.8
2050	-16.7 (2.9)	-19.1 (1.4)	2.4	-26.0 (5.0)	-21.8 (8.5)	-4.2
2060	-19.1 (4.5)	-18.4 (2.5)	-0.7	-27.7 (3.4)	-21.9 (8.5)	-5.8
2070	-17.0 (3.3)	-18.4 (2.7)	1.3	-20.9 (4.6)	-22.0 (8.5)	1.1
Decade	RM 26			RM 7		
	Averaged Bed Elevation (m NAVD88)			Averaged Bed Elevation (m NAVD88)		
	LMRPM	BWM	LRMPM - BWM	LMRPM	BWM	LRMPM - BWM
2030	-30.8 (5.9)	-23.9 (4.8)	-6.9	-21.7 (5.0)	-19.4 (4.5)	-2.2
2040	-30.0 (4.5)	-22.6 (6.9)	-7.4	-16.2 (5.3)	-20.0 (4.1)	3.8
2050	-28.0 (4.2)	-23.9 (5.2)	-4.1	-15.8 (5.4)	-19.1 (4.2)	3.2
2060	-28.4 (5.4)	-24.0 (5.3)	-4.4	-16.9 (3.8)	-19.7 (3.8)	2.8
2070	-26.7 (5.7)	-23.4 (6.3)	-3.3	-16.7 (3.6)	-18.6 (3.9)	1.9

Figure 19. Bed elevation profile along the Mississippi River, from HOP to River Kilometer 175 (RM 108), close to Avondale, Louisiana. Gray line shows the average bed elevation across the river projected by the BWM for 2030, the light blue shaded area shows the variation across the river (maximum and minimum values) in the BWM for landscape 2030, green triangles show the LMRPM observations (average and standard deviation) for 2030.

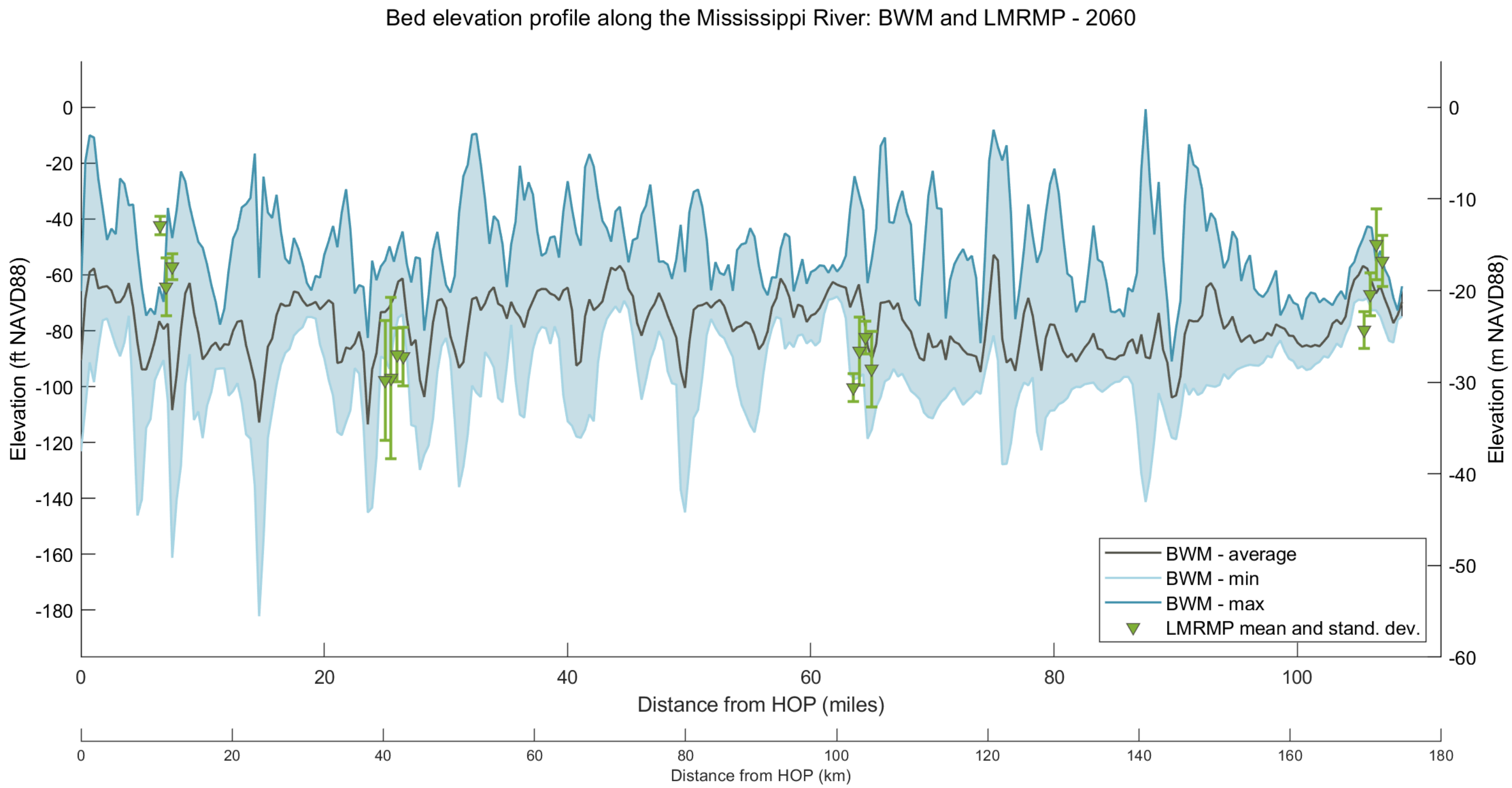

Figure 20. Bed elevation profile along the Mississippi River, from HOP to River Kilometer 175 (RM 108), close to Avondale, Louisiana. Gray line shows the average bed elevation across the river projected by the BWM for 2060, the light blue shaded area shows the variation across the river (maximum and minimum values) in the BWM for landscape 2060, green triangles show the LMRPM observations (average and standard deviation) for 2060.

4.3 NAVIGATION DREDGING VOLUMES

The BWM dredging volumes showed interannual variation but did not exhibit a strong temporal trend over the entire 50-year simulation period (Figure 21), and simulated volumes were smaller than the dredging volumes from historical records (Esposito et al., 2021). The highest dredged volumes occurred during the first decade (2020–2029; Table 5A). However, a gradual increase in dredged volume was evident from the second decade to the fifth decade, with an increase from 28.8 million m^3 to 35.5 million m^3 (37.7 MCY to 46.4 MCY), representing a 23% increase. Bed volume change that was not being dredged (outside of the MRSC or below the dredging threshold) was tracked to account for overall channel aggregation or degradation patterns (Table 5B). Examination of the bed volume change demonstrated that the area became increasingly depositional. This depositional response followed initial degradational behavior in the first two decades, which could indicate that the model was reaching its dynamic equilibrium. A clear upward trend over time is evident from the net volume change (Table 5C), representing the change in sediment volume regardless of whether the sediment was dredged or deposited.

The volume of dredged material from the MRSC between Venice and SWP jetties (i.e., SWP reach) in the BWM was approximately 25% of the sand load entering the model at the upstream boundary and gradually increased over time (Figure 22). However, the first decade appeared to be an outlier, with the dredged volumes equating to approximately 50% of the sand load entering the upstream boundary, likely due to the initial over-mobilization of sand upstream of the MRSC channel while the model reached dynamic equilibrium. The BWM has an insufficient resolution around the SWP jetties where grid cells are relatively coarse (1875 m) compared to the width of the MRSC (229 m or 750 ft). Consequently, none of the grid cell centers fall within the dredging polygon, which resulted in no dredging at the jetties, thereby causing significant local aggradation. However, throughout the 50-year simulation period, the water budget indicated that SWP continues to capture 40–50% of the discharge at the delta, suggesting that SWP remained an active distributary and continued to capture a high portion of the river discharge.

The LMRPM results showed a substantial increase in dredging volumes over time (Table 5). Volumes in the first two decades were smaller than the BWM and the historical records. However, dredging volumes were larger than the BWM and comparable to historical records in the remaining three decades (Figure 21). LMRPM results projected that it was not until year 12 (1975) that a significant volume of sediment reached the MRSC along the SWP reach (Brady et al., 2021), where navigation dredging occurs typically. Moreover, for the first 26 years of the experiment (1964–1989), projected dredging in the model occurred every other year. However, the model was dredged yearly to maintain the channel clear in the remaining 24 years (1990–2013). It should be noted that, to enhance visual comparison of the results, the two-year dredging volumes were split and plotted on a yearly basis. After year 26 (1989), the LMRPM was dredged up to RM 15 (i.e., 5 miles upstream of Venice; Brady et al., 2021). From the third decade onward, the volume of dredged material from the MRSC in the SWP reach was approximately 50 to 60% of the sand load entering the model at the upstream boundary (Figure 23).

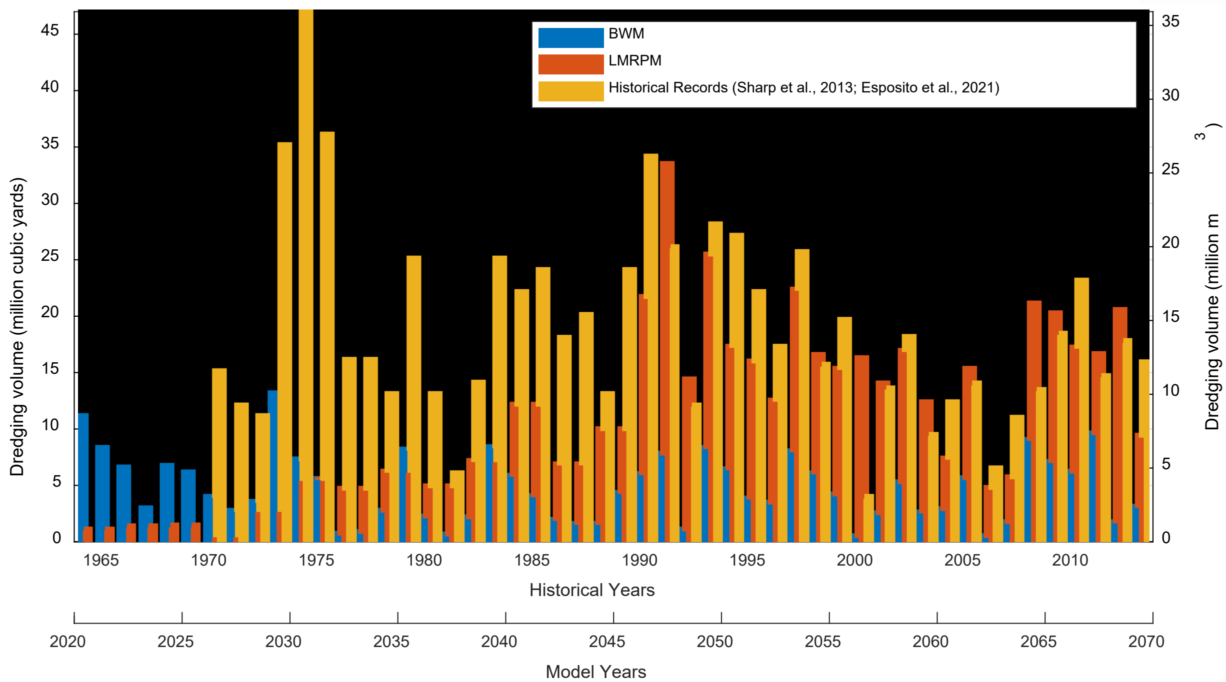

Figure 21. Comparison of projected annual dredging volumes in the MRSC between Venice and SWP jetties, known as the "SWP reach", for the 50-year FWOP simulations using the BWM (in blue) and the LMRPM (in orange). Historical records starting in the year 1970, as reported by Sharp et al. (2013) and Esposito et al. (2021), are displayed in yellow. The LMRPM volumes were estimated based on the average of two FWOP experiments (series 6 and 8) and assuming a typical dry bulk density of 1590 kg/m³ for sand. LMRPM was dredged every other year in the first 25 years.To enhance visual comparison of the results, the two-year dredging volumes were split and plotted on a yearly basis. The horizontal axis shows the hydrograph years (1964–2013) that were used in both models to simulate a period of 50 years into the future (2020-2070).

Table 5. Dredged volumes and volume change (million m^3 per decade) in the Mississippi River reach between Venice and the SWP jetties, for BWM and LMRPM. Row [A] represents the volumes dredged from the MRSC, as also presented on annual timescales in Figure 21. Row [B] indicates the deposition (positive) or erosion (negative) volumes across the entire river reach, including parts of the model domain outside of the MRSC. Positive volumes, for example, indicate deposition occurring outside of the MRSC or within the MRSC but below the dredging threshold. Row [C] represents the net volume change calculated by summing rows [A] and [B], representing the change in sediment volume regardless of whether the sediment was dredged or deposited.

Model	**Model years**	**2020-2029**	**2030-2039**	**2040-2049**	**2050-2059**	**2060-2069**
	Historical years	1964-1973	1974-1983	1984-1993	1994-2003	2004-2013
	Volumes in million m^3					
BWM	[A] Dredged volume from MRSC	49.1	28.8	31.8	32.0	35.5
	[B] Bed volume change (across the entire river channel)	-54.6	-13.6	4.4	4.5	12.4
	[C] Net volume change (bed volume change + dredged volume)	-5.4	15.2	36.2	36.5	48.0
LMRPM	Dredged volume from MRSC	10.2	42.8	116.0	121.3	104.9

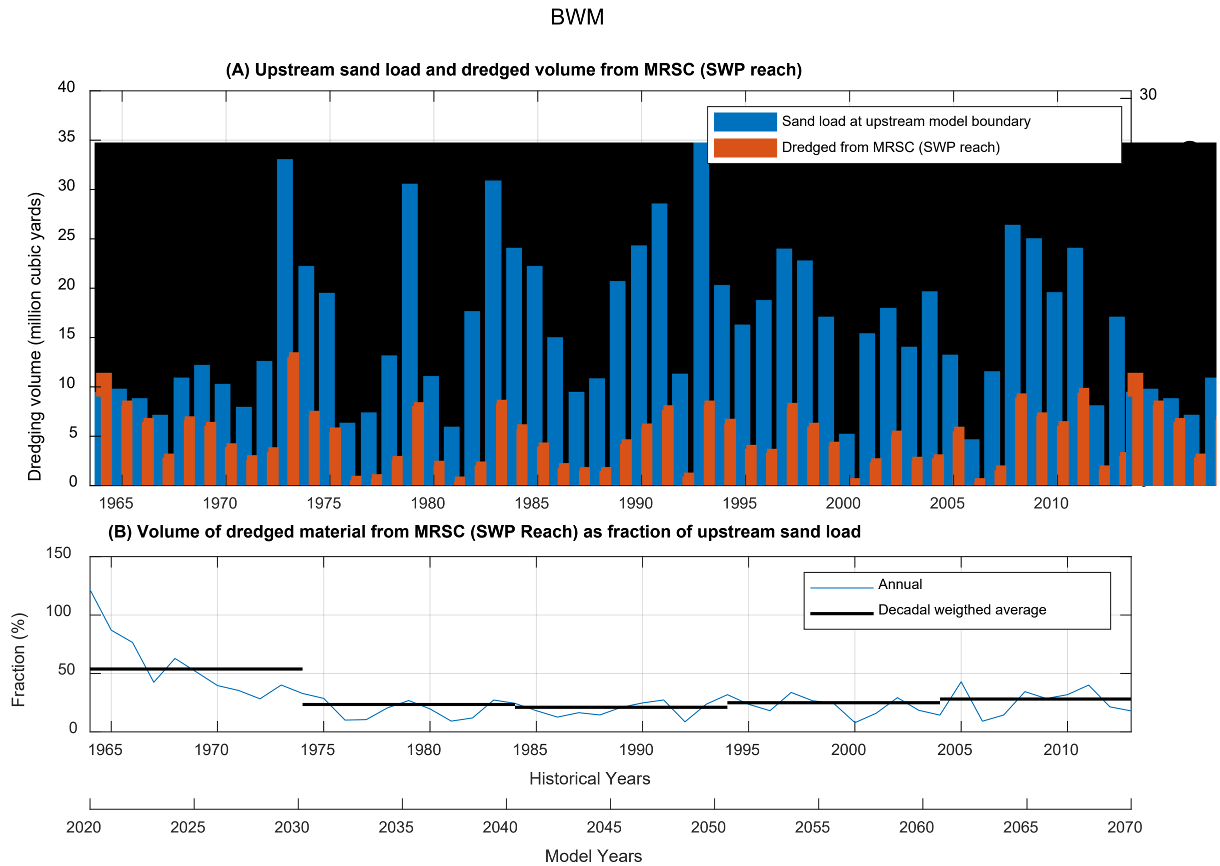

Figure 22. BWM: comparison of upstream sand load and dredged volume from the MRSC in the SWP Reach (A), annual and decadal ratio between upstream sand load and dredged volume (B).

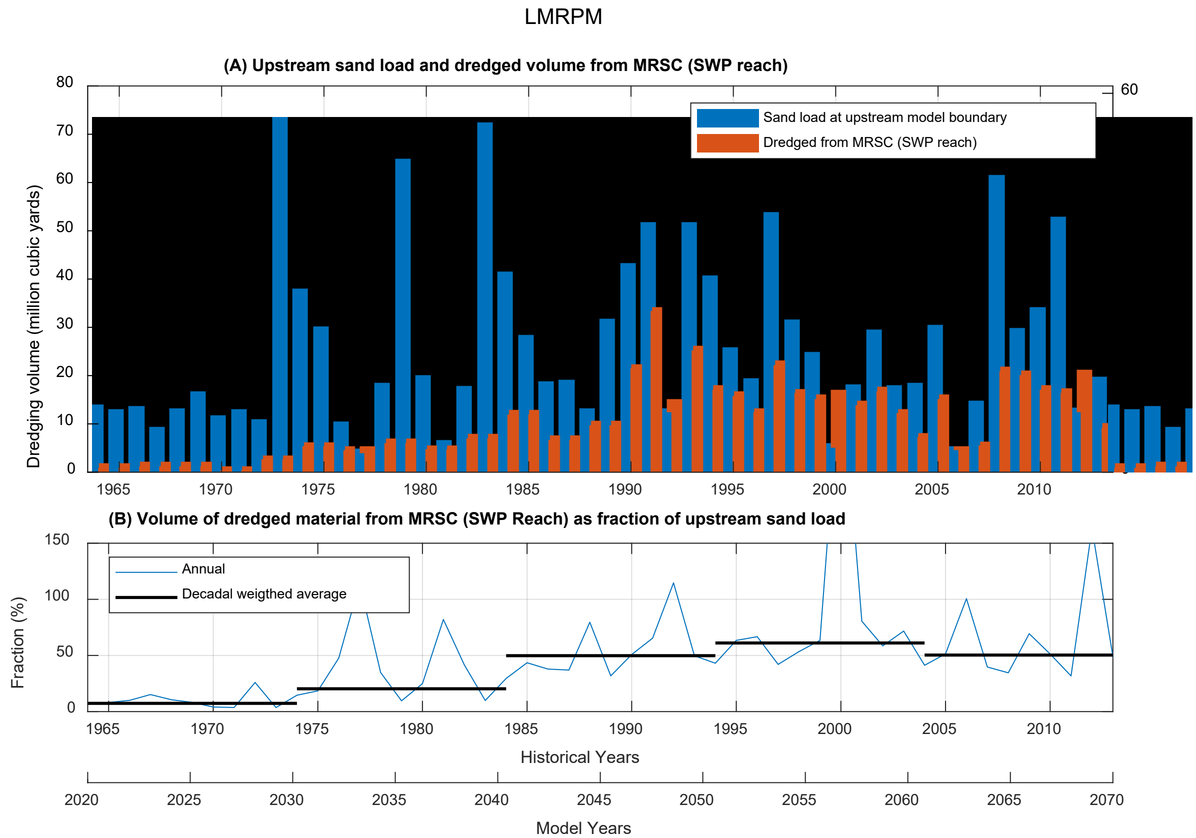

Figure 23. LMRPM: comparison of upstream sand load and dredged volume from the MRSC in the SWP Reach (A), annual and decadal ratio between upstream sand load and dredged volume (B).

5.0 DISCUSSION AND CONCLUSION

5.1 STAGE AND FLOW

The projected stage-discharge relationships by both models agreed with the target stage discharge curve for the 2020 landscape, especially at Bonnet Carré Spillway and Carrollton. The stage-discharge relationship downstream of the Bohemia Spillway (~RM 40) is influenced by tides and the flow distribution through the crevasses and distributaries at the bird's foot delta. The significant stage variation (> 1.2 m [4 ft]) observed at West Point a La Hache, Empire and Venice is likely linked to tidal modulation.

For later decades, both models (BWM and LMRPM) projected higher stages than the target stage-discharge curve, mainly due to differences in the RSLR between projections and the historical record. Both models are simplifications of the natural system and, as such, are not capable of reproducing all physical phenomena and surface processes. For instance, the model grid resolution in the BWM and scaling in the LMRPM likely prevent the models from fully resolving small cuts in the riverbank or small waterways that extract flow in the real system. The models therefore likely underestimate discharge in these outlets. Additionally, neither model includes interactions and groundwater exchange with the underlying aquifer system. For later decades (i.e., 2060), the LMRPM stage projections were consistently higher (1.5 to 3 m [5 to 10 ft]) than those projected by the BWM. This result could be related to increased deposition in the physical model following higher sand load during high flow years, which correlated well with the projected dredging volumes. Additionally, some of the stage differences observed between the two models could be explained by the implementation of RSLR by adjusting the water level alone and being unable to apply spatially variable subsidence in the LMRPM. Vertical and horizontal distortion in the LMRPM could have also played a role in the model response to RSLR. Lastly, the consistent bias between the two tests (Test 1 and 2) performed with the LMRPM could be explained by slight differences in the initial bed level condition (Brady et al., 2021), which demonstrated that the LMRPM projections are sensitive to the initial riverbed elevation. In later decades (i.e., 2060), the BWM stage projections did not show asymptotic behavior, as clearly underlined by the 2020 target stage-discharge curve and, to some extent by the LMRPM results. In contrast, the BWM stage projections exhibited linear response and continued to increase as a function of discharge. This deviation could be attributed to the model's assumption of spatially variable, but temporally constant roughness or bottom friction, which does not account for the influence of a changing water depth on flow velocity and sediment transport.

5.2 BED ELEVATION

The bed elevation comparison highlighted limitations of both modelling approaches: specifically, the grid resolution in the numerical models and the challenging conditions for obtaining measurements in physical models (Table 1; LSU Center for River Studies, 2020).

The LMRPM results were limited to four locations throughout the model domain, at which eight measurements were taken (i.e., East and West at four separate, nearby cross sections). The BWM bed elevation results were extracted along four streamwise profiles and four cross sections across the channel, providing continuous elevation at a 125-m spatial resolution.

The higher standard deviation in the BWM results (i.e., 8.5 m at RM 64, see Table 4) could be attributed to the relatively coarse grid resolution within the river. The two grid cells used for the calculations reported in Table 4 are 125 m apart, while the LMRPM values were obtained 3 mm apart, corresponding to an 18 m distance in the real world. This suggests that the BWM is not the appropriate tool with which to examine bedforms with wavelengths of less than 125 m, as it is hindered by the river's coarse grid resolution, which does not resolve sub-grid scale features. Furthermore, over the 50-year simulation, the BWM tended to migrate and smooth submerged morphologic features within the river instead of growing and decaying these features through sand sequestration and release and corresponding inflation and deflation cycles.

Neither of the models showed a clear trend of bed elevation over time. However, while the BWM may underestimate bed level variation over time, the LMRPM showed a 7 m (23 ft) bed level difference over one decade (e.g., RM 64, 2060–2070). The significant differences in the LMRPM results could be related to deposition due to high sand load during high flow and/or manual interference during data collection. In addition, the LMRPM showed 1–4 m (3–13 ft) of deposition during the first decade at all analyzed river miles, suggesting a spin-up of the model during that phase.

5.3 NAVIGATION DREDGING VOLUMES

The comparison of model results with historical records (Esposito et al., 2021) showed that the BWM tends to underestimate dredging, while the LMRPM exhibits a close agreement with the historical records from 1990 onward. The differences between projected dredging volumes in the BWM and the LMRPM can be partially attributed to variations in dredging depths. For instance, the BWM was configured to maintain a navigable depth of 13.7 m (45 ft), whereas the LMRPM was dredged to a depth of 15.2 m (50 ft). It is noted that model results, despite being based on historical hydrographs, pertain to the future (2020–2070) and encompass future environmental conditions. Therefore, unlike historical records, these projections consider potential factors that could contribute to increased dredging requirements, such as future projections of sea level rise and subsidence. Furthermore, according to data presented by Esposito et al. (2021), the amount of dredged mass in the MRSC in the SWP reach exceeds the mass of suspended sediment that passes through Belle Chasse. Various explanations are offered including potential deficiencies in available sand rating curves. The report also points out that fine sediments might be present in the dredged material from the SWP reach. However, these fine sediments are not taken into consideration in the LMRPM, and they constituted less than 1% of the dredged material in the BWM. This implies that the dredged mass documented in historical records possibly leans towards the higher end in comparison to the model results, due to the inclusion of fine sediments. Additionally, some of the dredged mass in the historical records is likely sourced from leakage from the Hopper Dredge Disposal Area (Brown & Luong, 2017), where previously dredged material was disposed. Therefore, given the disparities between the models and historical records, it is expected that the simulated dredging volumes would be lower in comparison to the measured dredging volumes. One possible explanation for the similarity in volumes between the LMRPM and historical records in the last 25 years could be the relatively large sand load imposed at the upstream boundary of the LMRPM, particularly during years with high discharges (Figure 5). This could contribute to the relatively large dredging volumes observed in the LMRPM. Another explanation for the relatively large dredging volumes in the LMRPM is the narrow width of the MRSC, which is only 229 m (750 ft) wide translating to a width of 3.8 cm (1.5

inches) in the model. Dredging in the LMRPM might have inadvertently occurred over a wider footprint due to the practical and physical limitations associated with dredging such a narrow area.
Compared to historical records, the lower projections for dredging volumes in the BWM could be partly attributed by the model limitation to reproduce physical processes that lead to sedimentation of fluvial clay (which is enhanced by the presence of a salt wedge during lower flows; [Ayres, 2015; Galler & Allison, 2008; Georgiou et al., 2017]) in areas where dredging occurs. As a result, in the BWM, less than 1% of the dredged material consists of fluvial clay, while in reality, the clay content of the dredged material is likely much higher. This outcome could be the result of the model calibration process, which is primarily aimed to accurately represent sediment deposition in receiving basins rather than focusing on the river channel. Model results also indicated deposition occurring in certain parts of the river channel within the SWP reach but outside the MRSC (Table 5). These deposits could enter the MRSC over time through subaqueous landslides; however, these processes are punctuated and non-linear and are not resolved in numerical models like Delft3D. Additionally, other recent modeling studies conducted by the Institute heightened the limitation of the Van Rijn sediment transport formulae, possibly leading to overestimating suspended sand transport in the Mississippi River during periods of high discharges (Georgiou et al., 2023). This overestimation could result in exaggerated sand transport estimates in the areas where navigation dredging occurs, leading to reduced deposition rates in the MRSC and consequently smaller dredging volumes. This behavior might not be exclusive to Delft3D models utilizing the Van Rijn sediment transport formulae. In the HEC-6T model, used to determine the sand load at the upstream LMRPM boundary near Donaldsonville, sand concentrations for discharges exceeding 25,000 m^3/s (~900,000 cfs) were significantly higher than the measured concentrations at Tarbert Landing, which were utilized as an upstream boundary condition in the same HEC-6T model (Thomas, 2014) used to prepare input to the LMRPM. These potential deficiencies in sand rating curves may also contribute to the discrepancies in dredging volumes between the BWM and historical records.

Model results suggested that the LMR becomes increasingly depositional over time (Table 5). A complicating factor in drawing firm conclusions arises from the tendency of both models to approach a dynamic equilibrium within the first part of the 50-year simulation period. This behavior was evident in the first decade for the BWM (Figure 22), and the first two decades for the LMRPM (Figure 23), despite the fact that both models were spun-up or prepared prior to the 50-year simulation period (i.e., preloaded in the case of the LMRPM, or initialized in the case of the BWM). The BWM showed relatively large dredging volumes in the first decade that were likely caused by scouring along the SWP reach, resulting in high sediment mobilization, and consequently deposition and dredging. For the remaining decades, the BWM confirmed the hypothesis (and theoretical expectation) of an increasingly depositional system. Model results showed an increasing depositional trend over time, as evidenced by increasing deposition of sediment that was either dredged from the MRSC or deposited in regions of the SWP reach outside of the MRSC. The LMRPM started out with a deficit of sediment, as evidenced by dredging volumes in the first two decades that were much smaller than both the BWM and the historical records. From results of the remaining three decades, it was more difficult to conclude whether the LMRPM projects that the

LMR will become increasingly depositional, because dredging volumes remain relatively constant throughout this period and even exhibit a slight decrease between the fourth and fifth decade.

5.4 RECOMMENDATIONS FOR FUTURE RESEARCH

The comparisons presented in this report highlighted the strengths and limitations for each of the modeling approaches and present an opportunity to offer recommendations for future research.

- Results presented in this report highlighted the significance of the model initialization phase. During the first decade, the BWM bed level underwent an initial adjustment leading to significant erosion in the river channel downstream of Fort St. Philip, which is an indication that the model is undergoing a prolonged spin-up phase. The LMRPM dredging volume and bed elevation results showed that the physical model also reached equilibrium during the first two decades, evidenced by low dredging volumes. For both models, it is recommended to consider using a longer initialization period, with flood years rather than average flow hydrographs included. Additionally, it is recommended that models are tested with simulation periods of comparable durations to the final production runs. This would provide a better understanding of when initialization (or spin-up) effects have subsided and allow for identifying potential issues that may not be obvious during shorter simulations.
- The use of different sand rating curves in the two models is one of the factors that caused dredging volumes to be nearly double for the LMRPM compared to those for the BWM. The upstream sand load in the LMRPM was determined using a sediment rating curve derived from a HEC-6T model (Thomas, 2014). This HEC-6T model projects significantly higher sand concentrations at large discharges compared to the measured concentrations at Belle Chasse. Therefore, efforts to quantify the influence of sand rating curves on model results and the consequences on long-term morphology and resulting dredging volumes are recommended to reduce uncertainty.
- Both physical and numerical models should be used carefully when making absolute long-term projections. They are, however, powerful tools for comparing different scenarios or alternatives. Moreover, comparing different model projections is essential to validate projected trends and patterns.
- Another recommendation is to expand the analysis performed in this study to incorporate additional experiments conducted in both models, specifically those where operational sediment diversions (i.e., Mid Barataria and Mid Breton) were tested. Performing a comparison of these experiments will provide more insight on the ability of the models to project river responses to sediment diversions and elucidate on how upstream projects altering streamflow might impact downstream bed aggradation and the subsequent requirements for dredging.
- The fine sediment composition of dredged material from the SWP reach remains unclear. Previous studies have suggested that fine sediment fractions are likely present, although quantitative estimates are still lacking (Thorne et al., 2017; Esposito et al., 2021). The LMRPM does not account for or consider fine sediments and the dredged material in the BWM primarily consists of sand (>99%), suggesting that both models are not accurately projecting the dredged sediment type. In addition to dredged volumes, it is recommended that the composition of

dredged sediment along the Mississippi River be documented and analyzed to better validate model behavior, improve model projections of river morphology and changes in dredging, and improve the reliability of tools used for river management strategies.

- The correlation between dredging volumes and SLR in BWM remains unresolved. The modeled eustatic sea level rise between 2020 and 2070 is 0.68 m (2.2 ft), which is approximately 5% of the depth of the MRSC. While the rise in sea level could directly lead to an increase of dredging volumes, it is recommended indirect effects of SLR be analyzed, such as the formation and evolution of crevasses along the eastern riverbank near the modern delta. These crevasses extract water and sediment from the river, and thus could influence future dredging activities, and analysis to evaluate the degree to which they could impact sedimentation and dredging is necessary. In the BWM simulations analyzed in this study, newly formed crevasses were repaired and not allowed to evolve, so as to maintain a fair comparison with the LMRPM. However, additional simulations where crevasses are allowed to form and evolve offer an alternate simulation to further inform dredging activities and could be leveraged to test the hypothesis that secondary SLR effects driving delta morphology such as crevassing, are potentially more impactful to dredging than the primary effects (i.e., an increase in depth).
- Additional models with enhanced capacity to resolve in-river processes could provide better insights into future dredging trends under existing and a future with projects. There are additional existing river models that were specifically built to resolve morphology within the Mississippi River channel (e.g. Georgiou et al., 2023; McCorquodale et al., 2017; Reins, 2018). Compared to the BWM, these models are better suited for supplementary analysis due to their simplified setup, quicker execution, and potential to offer a more accurate representation of physics in the Mississippi River. One approach is to adopt 3D models (instead of the depth-averaged approach of the BWM) or retain use of depth-averaged models but incorporate more sediment fractions, which would help discern the composition of deposited and dredged sediment.
- Analyzing additional output from the LMRPM simulations is essential to comparing the models at various locations to improve the understanding of spatial geomorphic variability in the river. For example, when comparing simulations with sediment diversion in operations, it would be essential to gather bed elevation measurements at additional locations downstream of the diversions to better constrain shoaling patterns.

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