Scenario Testing of the FRAME Tool on a 200 Mile Reach of the Lower Mississippi River

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Abstract

Understanding the likely future long-term evolution of the Lower Mississippi River (LMR) is a challenging mission for the USACE but one that remains a challenge for conventional river engineering models. A new type of model is currently in development, tasked with revealing uncertainty-bounded trends in sediment transport and channel morphology over annual, decadal and centennial time-scales. The FRAME (Future River Analysis & Management Evaluation) tool is being designed with river managers and planners in mind where results will offer exploratory insights into plausible river futures and their potential impacts. A unique attribute of the tool is its hybrid interfacing of traditional one-dimensional hydraulic and sediment transport modeling with geomorphic rules for characterizing the nature of morphological response.

A testbed model for a 200-mile reach of the LMR extending from the Arkansas River to just downstream of Vicksburg MS was the platform for expanding the FRAME tool's capabilities for long-term forecasting of river evolution under a range of possible future scenarios. A number of experimental runs using the LMR testbed reach were conducted to explore the ability of the testbed model to capture general morphologic trends. Experimental test runs using the LMR testbed reach included the following scenarios: 1) Flow and sediment diversions; 2) Impacts of varying bed material gradations; 3) Varying flow sequences using the FRAME tool flow multiplier to simulate potential climate change; 4) Geomorphic rules for dike filling, and 5) Effects of base level lowering. All of the FRAME testbed scenarios were run for 200 years and the cross sectional area trends compared to the Base condition to evaluate the relative impacts of the various scenarios. These experimental test runs confirmed that the FRAME tool is functioning with respect to the predicting broad scale morphologic trends along the LMR.

Introduction

The ability to consider a wide-range of future year scenarios in a morphological tool that can be run quickly and over annual, decadal, and centennial time scales, and bounded by levels of confidence on estimates, is one of the most critical deficiencies in our ability to design sustainable river systems within a regional sediment management framework. In 2016, researchers from ERDC-CHL brought together a team of experts from the University of

Portsmouth (Portsmouth, UK), Saint Louis University (St. Louis, MO), University of Nottingham (Nottingham, UK), and Mendrop Engineering Resources (Ridgeland, MS) to begin the development of an innovative geomorphic tool aimed at addressing this technological gap. The initial efforts of the project team successfully demonstrated to the proof-of-concept level that such an approach was possible, and a plan was advanced for the development of a tool for forecasting long-term sediment transport and morphological response. As a result of this effort, a new type of model is currently in development, tasked with revealing uncertainty-bounded trends in sediment transport and channel morphology over annual, decadal and centennial time-scales. The FRAME (Future River Analysis & Management Evaluation) tool is being designed with river managers and planners in mind where results will offer exploratory insights into plausible river futures and their potential impacts.

Presently, the project team was working with the Mississippi Valley Division (MVD) under the Mississippi River Geomorphology and Potamology (MRG&P) Program on the expansion of the FRAME tool focused on the Mississippi River. A testbed model for a 200-mile reach of the Mississippi River upstream of Vicksburg currently provides a platform for FRAME's development, testing and, critically, for realizing the multiple benefits that such a tool would deliver. While the LMR provides a prominent case where long-term forecasting of sediment transport and morphological response would be invaluable, such a tool would be transferable to other river settings and management programs seeking to mitigate against undesirable future outcomes.

Scenario Testing of Testbed Model on the LMR

A number of experimental runs using the LMR testbed reach were conducted to explore the ability of the testbed model to capture general morphologic trends. It is important to recognize that the testbed model is in the early developmental phases with somewhat limited functionalities. Therefore, the scenarios should not be viewed as definitive results, capturing actual spatial and temporal trends on the LMR, but, rather, are intended to test the model's capabilities to capture broad-scale morphologic trends.

Experimental test runs using the LMR testbed reach have included the following scenarios: 1) Calibration run; 2) Base run; 3) Diversion scenarios; 4) Impacts of bed material gradations; 5) Flow sequences using the flow multiplier to simulate potential climate change; 6) Geomorphic rule for dike filling, and 7) Effects a base level lowering. A description of each of these scenarios is described in the following sections.

The spatial extent of the LMR testbed reach extends from RM 576, just downstream of the Arkansas River, to RM 389 near St. Joseph LA (Figure 1). To assist in the examination of morphologic trends for the various scenarios, the testbed reach was divided into five sub-reaches with outputs averaged over the sub-reach lengths (Figure 1). Avatar cross section spacing for all reaches was approximately five miles. Reaches 2, 3, and 4 were the focus for examination of morphologic trends for the calibration and various scenarios (Soar, et al., 2023). Each of these reaches was approximately 40 miles in length. Reaches 1 and 5 are downstream and upstream boundary reaches, respectively, of approximately 20 miles in length, and were not considered in the morphologic trend assessments for the scenarios.

The primary metric used to evaluate the morphologic trends for the various FRAME scenarios was the change in cross sectional area. All of the FRAME testbed scenarios discussed herein were runs for 200 years and the cross sectional area trends are compared to the Base condition. All scenario graphs represent the percent difference between the scenario results and the Base condition results for each year. Thus, it must be emphasized that all discussion of trends of aggradation or degradation reflect trends that are relative to the Base condition. To assist with visualizing the relative impacts of the various scenarios, all scenario results are plotted to the same y-axis scale between plus 20% and negative 20%.

Model Setup and Calibration

As previously mentioned, FRAME is in its infancy and the testbed results discussed herein are not intended to reflect detailed Mississippi River trends, but rather are aimed at highlighting some of FRAME's capabilities, and limitations, with a view towards future enhancements. Consequently, a detailed calibration of the model looking at water surface trends and detailed geometry changes was not attempted. Rather, the model was calibrated to ensure that broad-scale morphologic trends were generally captured.

For the calibration runs, the FRAME model was run from 1983 to 2013 using flow duration curves for each year and the Toffaleti sediment transport function. Manning n values for the main channel and overbank areas ranged from 0.027 to 0.032, and 0.12 to 0.2, respectively.

Figure 2 shows the percent change in cross sectional area relative to the starting year (1983) for Reaches 2, 3 and 4 for the 30 year period. Note that positive percent values indicate a decrease in cross sectional area which would reflect an aggradational trend, while negative values indicate an increase in cross sectional area, reflecting a degradational trend. As shown in Figure 2, all three reaches are relatively stable during this period with perhaps a slight aggradational trend. This generally agrees with the observed trends for the study reach. Based on these results, it appears that the FRAME model is generally capturing the broad scale morphologic trends of the testbed reach.

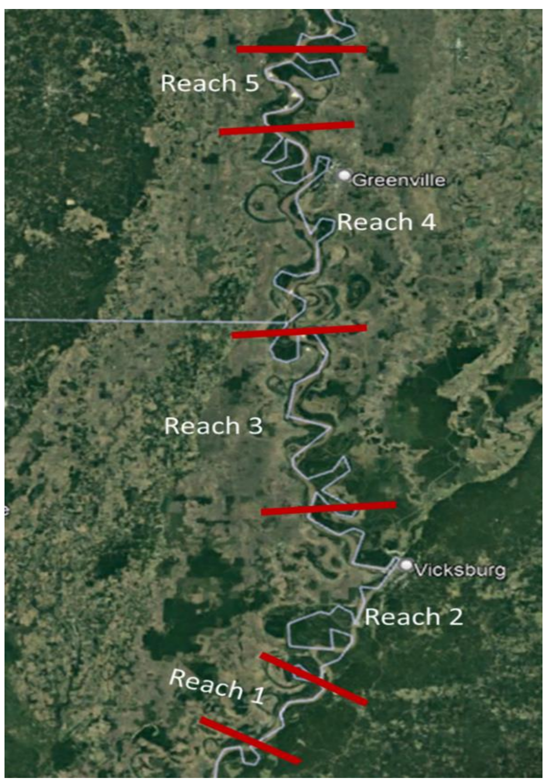

Figure 1. FRAME study reaches for the LMR

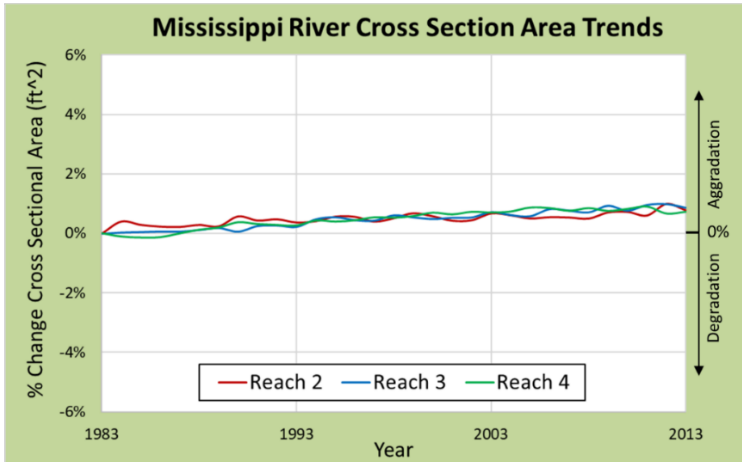

Figure 2. Cross sectional area trends for Reaches 2, 3, and 4, for the 1983 - 2013 calibration period

Base Condition Run

The base condition was developed by running the calibrated FRAME model for 200 years replicating the flow duration curves from 1963 to 2013. Figure 3 shows the percent change in the cross sectional area relative to the initial condition (year zero) for the 200 year period. As shown in Figure 3, all three reaches are slightly aggradational for the first 50 to 60 years, after which they are relatively stable for the remainder of the period of record.

It is important to note, that upstream and downstream boundary conditions are always an important component when modeling a river. However, when attempting to model really long time periods, like 200 years, these boundary inputs become critical. For example, the relative stability in Figure 3 after the first 60 years or so is, at least, partially a function of the fixed upstream and downstream boundary conditions. If this model were extended over a longer reach, say upstream to Cairo, and downstream to Baton Rouge, these trends would be much different, as they would reflect the complex channel adjustments that would be occurring in these upstream and downstream reaches.

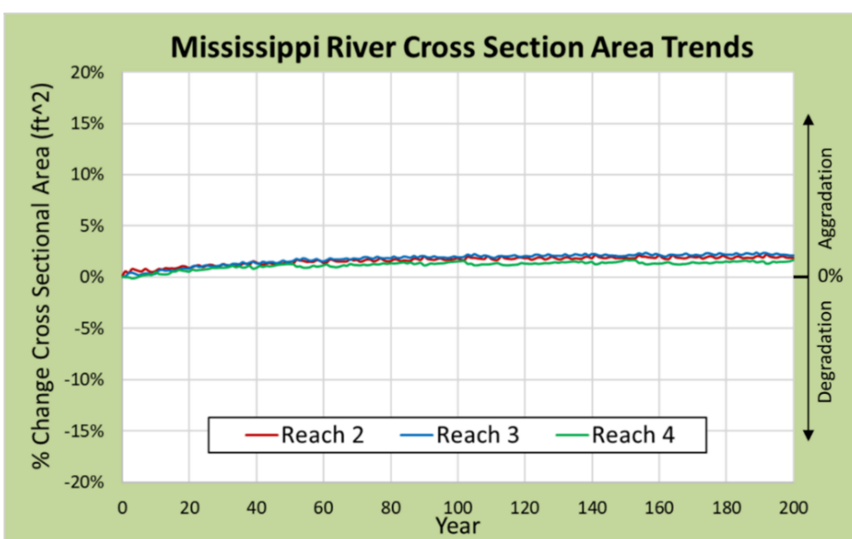

Figure 3. Base condition percent change in cross sectional area relative to starting year (Reaches 2, 3, and 4)

Diversion Scenarios

The Diversion tool within FRAME was used to test the ability of the model to capture the effects of a flow diversion. Three diversion scenarios were tested and described in this section.

Diversion Scenario 1: For Diversion Scenario 1, a flow diversion was placed at RM 460 which is at the downstream end of Reach 3. The diversion was set to begin operation in Year 30. For this scenario, the diversion of water for all flows was set at 0.3, and the sediment concentration multiplier (SCM) was set to '0'. Thus, 30% of all flows will be diverted after Year 30, but no sediment will be diverted with the flow.

As shown in Figure 4, there was an immediate decrease in cross sectional area in Reach 2 after the diversion became operational in year 30. As this reach is immediately downstream of the diversion this aggradational trend would be expected. The most dramatic rate of aggradation occurred in the first 20 to 30 years following the diversion. In fact, by about Year 60, there had been about a 12% loss in area. Between Years 60 and 140, the rate of aggradation decreased, losing only about another 7% of area. After Year 150, there is little change in the area (about 1% decrease). The initial effects of the diversion on Reach 3 are minimal, with perhaps a slight degradational trend, for about the first 10 to 20 years following the diversion. However, after this, Reach 3 begins a long term aggradational trend. The loss of area between Years 50 and 150 in Reach 3 was about 5%. After this, the rate of aggradation continues, but at a reduced rate. Following the diversion, Reach 4 exhibits a slight erosional response that continues for about 30 years, after which a slight aggradational trend continues for the period of record. The total loss of area between Years 60 and 200 is slightly less than 3%.

Diversion Scenario 2: Diversion Scenario 2 was identical to Diversion Scenario 1, except that the SCM was set to '1', which sets the sediment concentration of the diverted flow equal to the sediment concentration of the flow just upstream of the diversion. The results for this scenario are shown in Figure 5. As shown in Figure 5, Reach 2 follows a somewhat similar trend to the Diversion 1 scenario, although at a much reduced rate. By Year 60, Reach 2 had only experienced about a 6% loss in area as compared to about 12% for the Diversion 1 scenario. The total loss of area for Reach 2 was slightly less than 12% while for the Diversion 1 scenario, the loss was about 20%. The response to the diversion in Reach 3 was an initial period of erosion that lasted for about 25 to 30 years, and resulted in an increase in area of slightly more than 3%. After this, there was a rather subtle, aggradational period for the next 140 years, although the net loss of area (about 3%) was significantly less than was observed for the Diversion 1 scenario. Reach 4 experienced a slight degradational trend following the diversion that existed for about 30 years. After that the reach was relatively stable, with only about a 1% loss in area over the remaining period or record.

Diversion Scenario 3: Scenario 2 showed that even with a SCM set to 1, the reach downstream of the diversion was still aggradational. Therefore, a series of runs were examined to determine what the SCM needed to be to produce a response that would match the base condition response in Reach 2. As shown in Figure 6, setting the SCM to 2.0 produced a channel response that approximately matched the Base condition. However, it should be noted that diverting this much sediment also triggered a dramatic degradational response in Reach 3 and Reach 4, which was a significant contributor to the Reach 2 response.

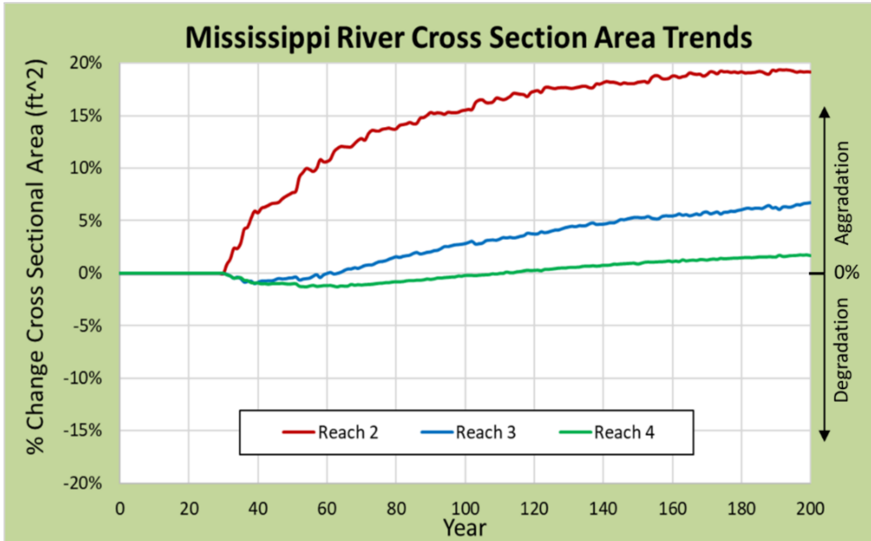

Figure 4. Diversion Scenario 1. Thirty percent water diverted at downstream end of Reach 3 after Year 30 with an SCM of 0.

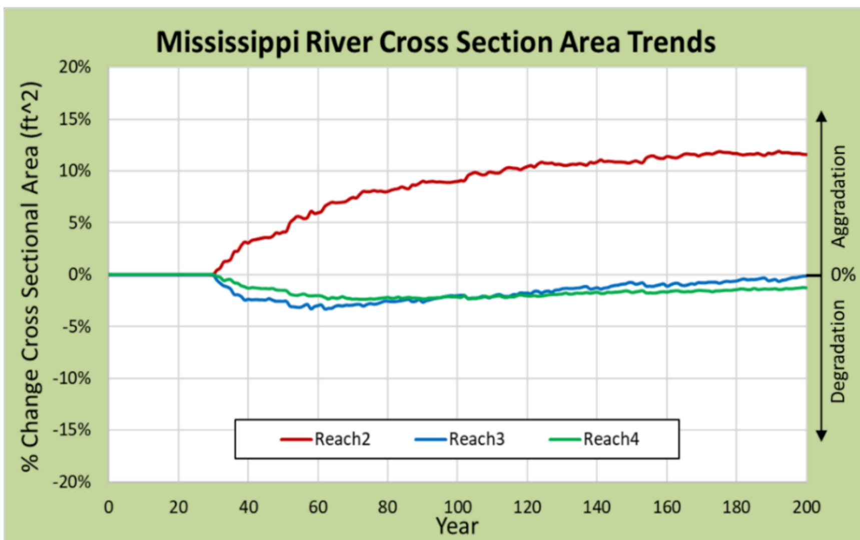

Figure 5. Diversion Scenario 2. Thirty percent water diverted at downstream end of Reach 3 after Year 30 with an SCM of 1.0.

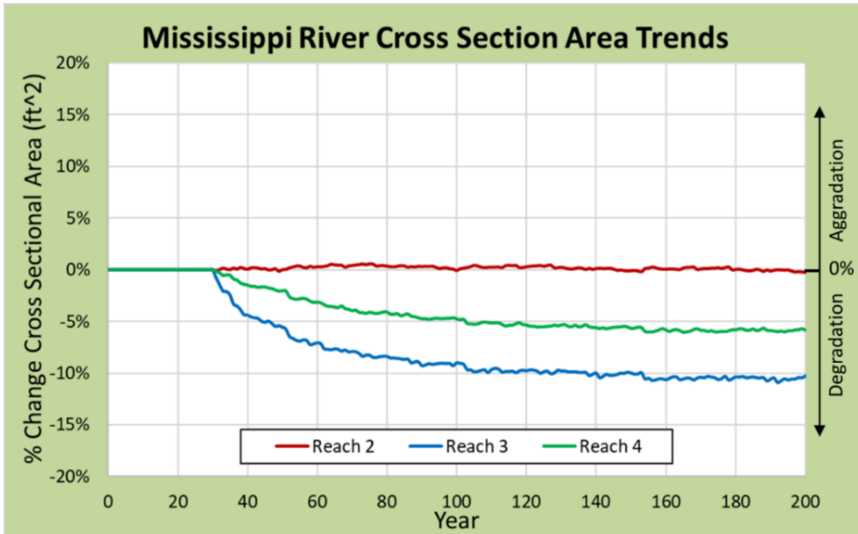

Figure 6. Diversion Scenario 3. Thirty percent water diverted at downstream end of Reach 3 after Year 30 with an SCM of 2.0.

Bed Material Scenarios

One of the most widespread and important uses of bed material data is as input data for sediment transport models. On a large, predominantly sand bed river such as the LMR within the testbed reach, it is easy to assume that the sand sizes and distributions are relatively stable. However, Thorne et al, (2017) documented that extreme variability exist in the bed material gradations both in space and through time, and this variability can significantly affect sediment transport calculations. It was therefore considered important to test the sensitivity of the FRAME results to bed material variability. To accomplish this, an alternate gradation curve (herein referred to as the BM2 Scenario) was developed and applied to Reaches 4 and 5. As shown in Figure 7, the BM2 gradation has about the same D50 as the Base gradation (D50 about 0.34mm), while the D16 is slightly coarser (0.28mm vs 0.21mm) and the D84 is slightly finer (0.44mm vs 0.56mm).

The BM2 scenario results are shown in Figure 8. As shown in Figure 8, the effects in Reach 4 are minimal, with only a very slight increase in area. However, the impacts to Reaches 2 and 3 are more dramatic. Within the first approximate 60 years, Reaches 2 and 3 experienced about a 5% increase in area. After this, the degradational trends lessens such that by Year 200, the area had only increased another 2%. This exercise shows that relatively minor variations in the bed material gradations can significantly affect the modeled channel response.

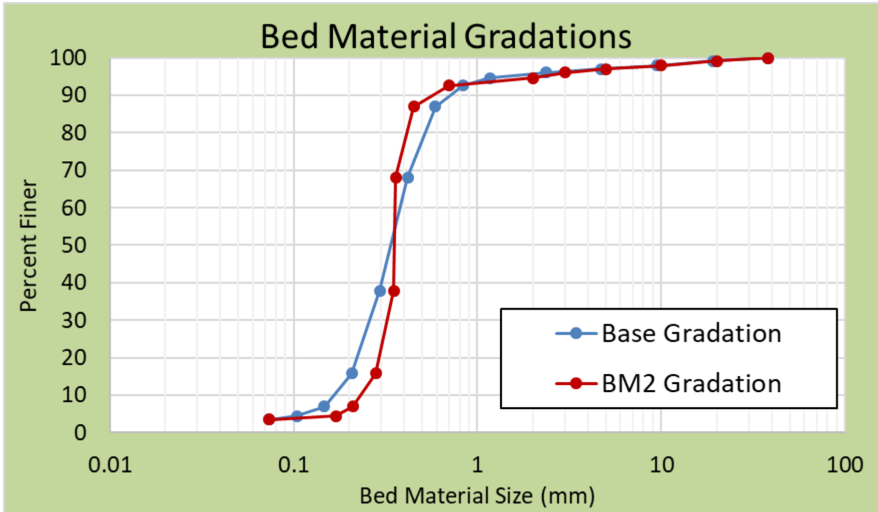

Figure 7. Bed material gradations change in Reaches 4 and 5

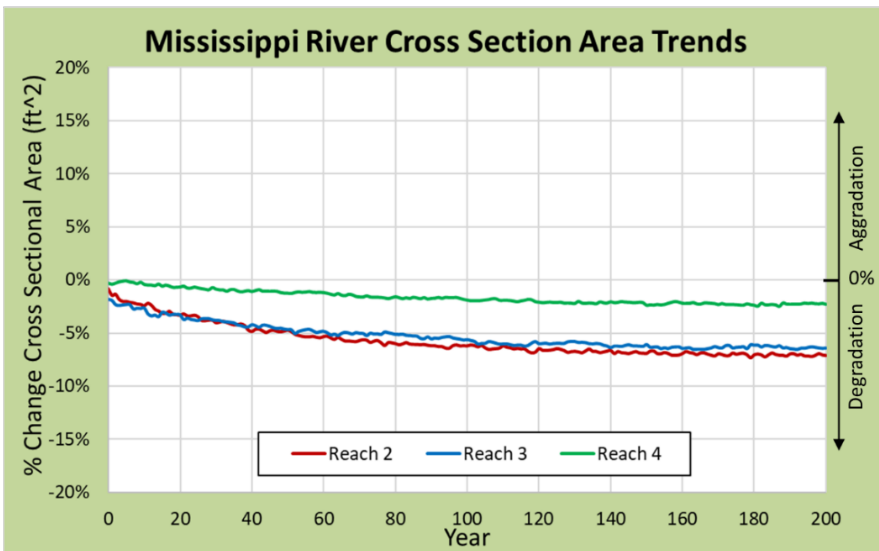

Figure 8. Bed material results for the BM2 scenario.

Climate Change Scenarios

The ability to account for long-term climate change is an important functionality for the FRAME model. A climate change scenario was developed by modifying the flow duration curves for the Base condition using the flow multiplier function in FRAME. Table 1 shows the flow multipliers used for the 200 year simulation. It should be noted that these flow multipliers are not based on any published climate change model results, but rather were simply selected to illustrate how a climate change scenario might be applied.

The results for the climate change scenario are shown in Figure 9. As shown in Figure 9, the most dramatic impact occurs in Reach 4. Between about Year 35 and 100, the area increases almost 3%. After this, the reach is relatively stable. The impacts in Reach 3 are similar to Reach 4, but at a reduced rate, with the increase in area being only about 1%. Interestingly, Reach 2 exhibits very little difference between the climate change and base condition. Again it may be worth emphasizing that the boundary conditions in the model may be affecting the observed response.

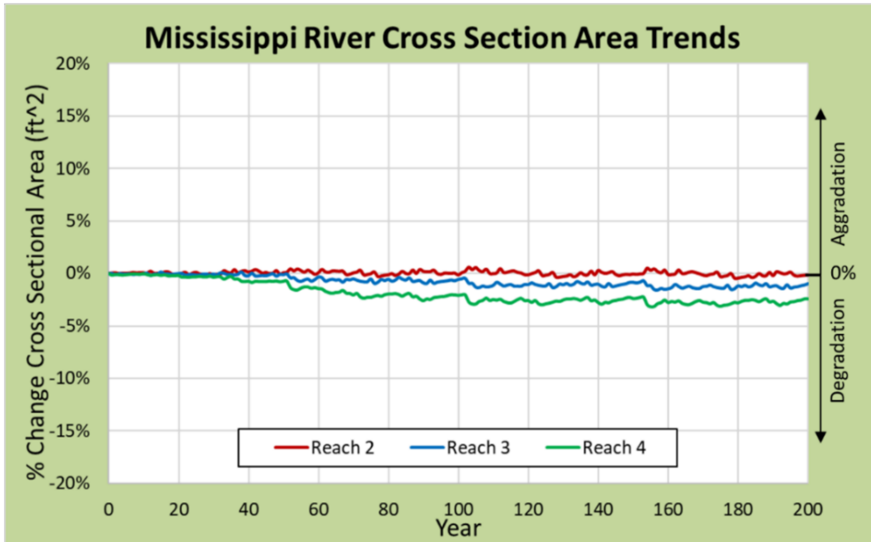

Figure 9. Climate change scenario results

Table 1 Flow multipliers for the climate change scenario

Time Period	Flow Multiplier
0 to 10	1
11 to 20	1.05
21 to 30	1.1
31 to 40	1.15
41 to 50	1.2
51 to 60	1.25
61 to 70	1.3
71 to 200	1.35

Geomorphic Rule for Dike Filling

One of the unique capabilities that is envisioned for the FRAME tool is the coupling of geomorphic rules with the hydraulic and sediment transport engine to drive the morphologic response of the stream. An example of how a simple geomorphic rule might work is presented using the dike field designer function in FRAME. For this example, a dike was placed at RM 475 which is in the center of Reach 3. Capturing the detailed channel response to the dikes is problematic due to the limitations of the rectangular avatar cross sections. Therefore, the focus of this exercise is to highlight how a geomorphic rule can be integrated into the FRAME model. Two scenarios were run to illustrate how different geomorphic rules would affect the time to fill the dike fields. The “Trapping Efficiency” factor for dike fields determines the proportion of incoming total bed material load that is directed into the sediment reservoir (representing the dike field) rather than passing downstream during a given time step. The larger the trapping efficiency, the more bed material that is diverted into the dike field, which should affect the filling time. For this test, the only factor changed was the trapping efficiency, with Dike Scenario

1 and Dike Scenario 2 being set to 0.005 and 0.1, respectively. For this test, it took 38 years for the dike field in Scenario 1 to be filled to capacity, while it only took two years for Scenario 2. While this is a simple example, it does provide some insight into how more complex geomorphic rules might be used in the future.

Base Level Lowering

The ability of FRAME to capture the effects of a base level lowering was tested by lowering the downstream cross section by about 5 feet. The downstream cross section was also fixed for the period of record. The results of a five foot base level lowering are shown in Figure 10. As shown in Figure 10, all three reaches exhibit a degradation response, with the effects being diminished in the upstream direction. By about Year 100, Reach 2 had about a 7% increase in area, while Reaches 3 and 4 only had increases of about 4.5% and 2%, respectively. After about Year 100, there were only minor changes in area for all three reaches.

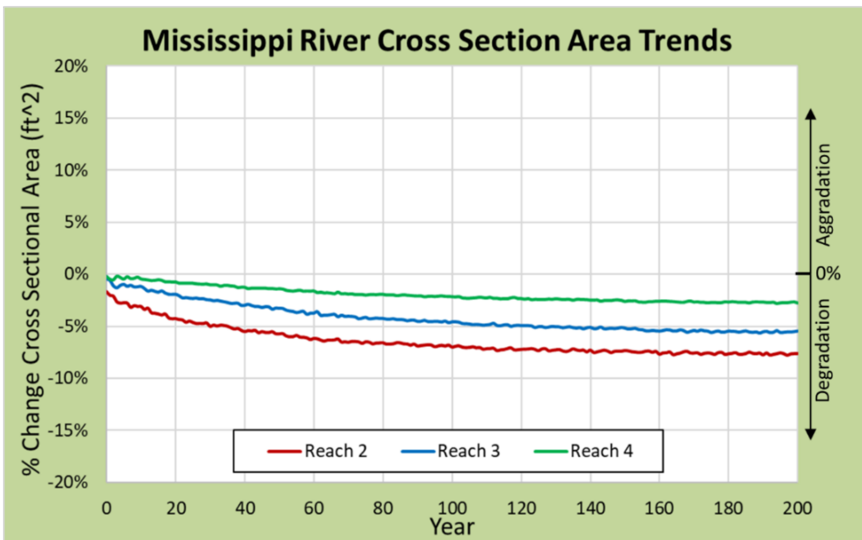

Figure 10. Base level lowering scenario results.

Summary

Although the existing FRAME tool has only limited functionality, the successful application to the LMR confirms that the model is functioning with respect to the predicting broad scale morphologic trends and has the capability to capture channel changes resulted from stream and watershed alterations. However, the testbed model work effort represents only the first step in the tool development and it is now recognized that further complementary research is needed to expand FRAME's ability to investigate long-term morphological adjustment for channel stabilization and restoration projects. In particular, it will be important to simulate the modes and stages of channel evolution that are characteristic of river types that are quite different to the laterally-constrained LMR.

References

Soar, P.J., D.S. Biedenharn, A.C. Cox, T.A. Dahl, C.H. Haring, C.D. Little, and C.R. Thorne, 2023, "Future River Analysis & Management Evaluation (FRAME): A new forecasting tool for long-term morphological response in river channels," SEDHYD Conference, St. Louis, MO.

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