Application of FRAME Modeling to Evaluate Long-Term Morphological Changes in the Sabougla Creek Watershed

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Abstract

Previous studies of the Sabougla Creek Watershed, located in the north-central region of Mississippi, observed severe channel incision, bank erosion, and gully advancement in the upper portion of the basin caused by channel straightening in the early 1900s. These upstream erosion processes were also found to be contributing to excess sedimentation in the lower portion of the watershed. The Future River Analysis & Management Evaluation (FRAME) model, a new tool enabling long-term river morphology modeling over decadal and centennial scales, was used to simulate long-term changes in river shape and composition in the Sabougla Creek Watershed and investigate the impacts of potential channel modifications and various climate change scenarios. FRAME is a hybrid model integrating 1-D hydraulic and sediment transport modeling techniques with empirical methods for channel form adjustments. This study includes a 16-mile section of Sabougla Creek and a 4-mile section of the upstream tributary of Bellefontaine Creek. Initially, a baseline scenario was developed assuming no channel modifications or changes in historical flow-duration patterns. The FRAME model was then used to evaluate the impacts of erosion control measures and potential climate change scenarios. These types of channel modifications and changes in hydrologic patterns can provide a range of complex and sometimes unexpected responses, which makes this site a good candidate for applying the FRAME tool. For each of the different modeling scenarios, time series of simulation results for changes in cross-sectional area and bed material composition were compared to the baseline condition.

Introduction

Forecasting river morphological adjustments over annual, decadal, and centennial time scales is a challenging task given the uncertainties associated with multiple input parameters such as river flow sequences, bed material gradations, and roughness characteristics. These uncertainties cannot be easily addressed using deterministic modeling methods. Further, river morphological adjustments are significantly complex such that sediment transport processes alter channel form both vertically (bed elevation variations) and laterally (channel width variations). A new modeling tool is currently being created to address the uncertainty and complexity challenges associated with long-term forecasting of river morphology. The Future River Analysis and Management Evaluation (FRAME) tool is being developed by an international research consortium led by investigators at the US Army Corps of Engineers (USACE) Engineer Research and Development Center (ERDC) in Vicksburg, Mississippi. FRAME is an uncertainty-bounded hybrid model integrating 1-D hydraulic and sediment transport modeling techniques with empirical methods for associated channel form adjustments (Soar *et al.*, 2023). In coordination with the development of the FRAME tool, research is being conducted to translate sediment transport imbalances into morphological responses (Thorne *et al.*, 2023) and to develop user-friendly graphical interfaces and metrics that can facilitate management decision-making (Downs *et al.* 2023). The ultimate goal of the FRAME tool is to offer exploratory insights into plausible river futures and their potential impacts which can be used by river managers and planners.

Prior to this study, the FRAME tool had been initially applied to a relatively stable 70-mile reach of the Lower Mississippi River as a testbed study (Biedenharn *et al.*, 2023). The Sabougla Creek Watershed, located in the north-central region of Mississippi, was selected for additional FRAME modeling because of the smaller channel characteristics in contrast to the Mississippi River, known long-term channel instability, and availability of field survey and sediment data. The Sabougla Creek site also provided a platform for developing additional FRAME functionality such as incorporating multiple tributary inflows, variable bed material gradation inputs, defining cohesive bed material, and simulating cohesive scour.

The Sabougla Creek Watershed study includes a 16-mile section of the Sabougla Creek and a 4-mile section of the upstream tributary of Bellefontaine Creek. Previous studies of the Sabougla Creek Watershed observed severe channel incision, bank erosion, and gully advancement in the upper portion of the basin caused by channel straightening in the early 1900s (Little and Biedenharn, 2003). These upstream erosion processes were also found to be contributing to excess sedimentation in the lower portion of the watershed (Smith *et al.*, 2010). The objectives of this Sabougla Creek Watershed study were to 1) expand the functionality of FRAME tool to enable long-term forecasting of the Sabougla Creek Watershed, and 2) evaluate the potential impacts of erosion control measures and climate change over decade time scales.

Initially, a baseline scenario was developed with no channel modifications or changes in historical flow-duration patterns. The FRAME model was then used to evaluate the impacts of erosion control measures including bank stabilization and reduction in tributary sediment input and potential climate change scenarios. These types of channel modifications and changes in hydrologic patterns can provide a range of complex and sometimes unexpected responses. For each of the different modeling scenarios, the time series of simulation results for changes in bed elevation and bed material composition were compared to the baseline condition.

Study Site: Sabougla Creek

The Sabougla Creek watershed, shown in Figure 1, outlets into the Yalobusha River and has a total drainage area of 126 mi^2 that includes Sabougla Creek and several tributaries. The tributaries included in this study are labeled in Figure 1 and listed in Table 1 with their respective drainage areas. Key considerations for the site include the following: 1) channel straightening occurred in the early 1900s, 2) channel instability in the form of bed degradation and bank instability was observed in a previous study (Little and Biedenharn, 2003) (see Figure 2), 3) excess sedimentation in the downstream section of the reach was also observed, 3) the upstream section of the study reach, Bellefontaine Creek, has many clay outcrops (see Figure 2), and 4) the downstream section of Sabougla Creek is influenced by backwater from Grenada Reservoir. This study includes a 16-mile section of Sabougla Creek and a 4-mile section of the upstream tributary of Bellefontaine Creek. As shown in Figure 2, the study site was divided into eight reaches with Reach 1 through Reach 6 in Sabougla Creek and Reach 7 and Reach 8 in Bellefontaine Creek. Reach divisions were based on tributary locations and maintaining similar reach lengths. The resulting average reach length was 2.5 mi.

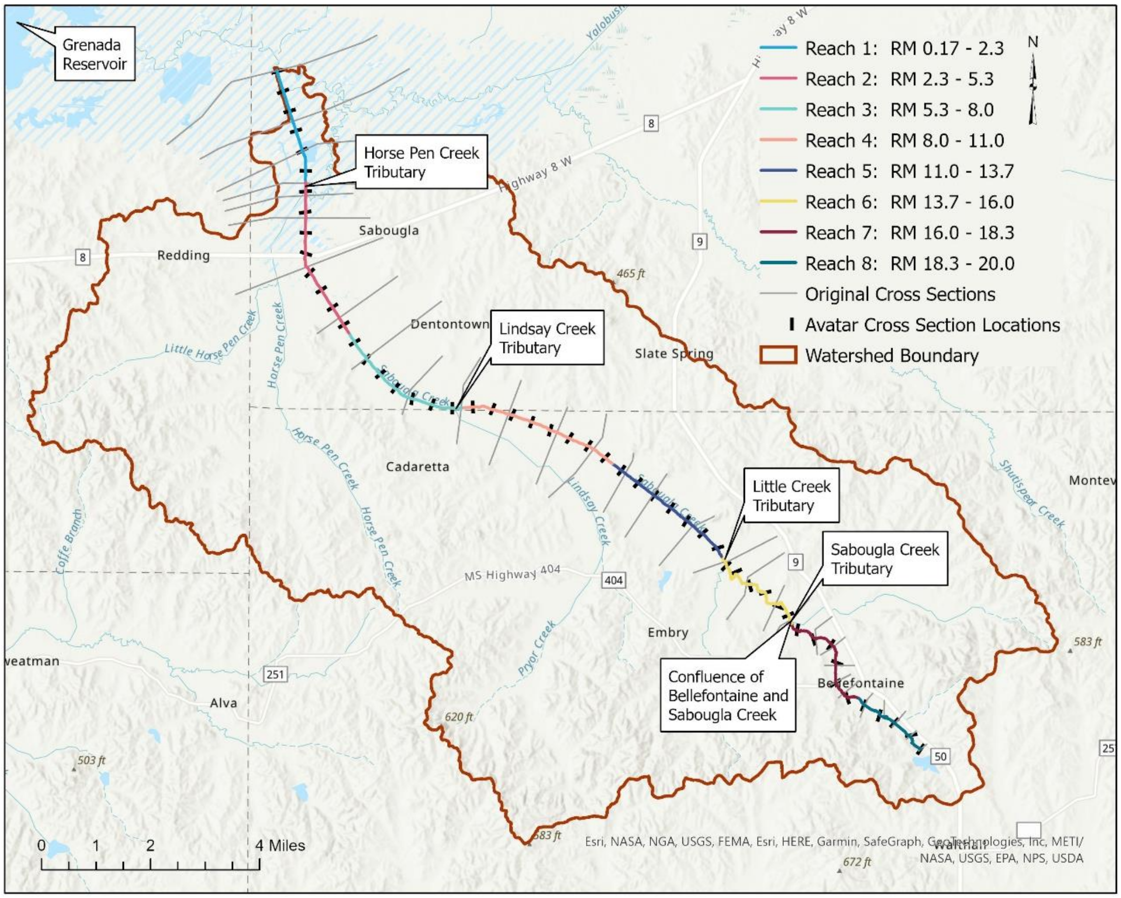

Figure 1. Reach definitions and cross-section locations for the Sabougla FRAME numerical model. Reaches 1 to 6 are along Sabougla Creek and Reaches 7 and 9 are along Bellefontaine Creek.

Table 1. River Stations and drainage areas for locations of interest within the Sabougla Creek Watershed.

Name	Drainage Area (mi²)	Main Channel Drainage Area US of Tributary (mi²)	River Station (ft)	River Mile (mi)
Downstream-most XS of Sabougla Creek	126	n/a	920	0.17
Little Horse Pen Creek Trib.	29.3	94.9	12,916	2.45
Lindsay Creek Trib.	22.5	51.8	41,460	7.85
Little Creek Trib.	7.21	23.3	73,095	13.84
Sabougla Creek Trib.	10.9	9.76	84,165	15.94
Upstream-most XS of Bellefontaine	1.99	n/a	105,524	19.99

Figure 2. Left photo (taken in 2003) –Bellefontaine Creek in Reach 7 showing bank erosion, right photo (taken in 2003) –Bellefontaine Creek in Reach 8 showing clay outcrops. (photos by D. Biedenharn)

FRAME Modeling Methods

This section provides a brief overview of the FRAME computational methods. More detailed information is provided in Soar et al. (2023). FRAME is a hybrid model that integrates 1-D hydraulic and sediment transport modeling techniques with empirical methods for associated channel form adjustments. FRAME modeling methods are designed to maintain a simplified approach for the following reasons: 1) multiple uncertainties of model input parameters render significant precision in process calculations not valuable, and 2) complex analysis processes are computationally intensive and the tool is intended to quickly evaluate multiple scenarios with varying inputs.

For hydraulic calculations, the standard step numerical method (Chow, 1950) is employed with simplified cross sections, termed avatars, for which the right overbank area, main channel, and left overbank area are represented as rectangles. Avatar cross sections are developed to maintain the same hydraulic conveyance as the natural channel at bankfull conditions. Specifically, the bankfull channel width is set to the natural channel bankfull width and the channel depth is modified to establish equal conveyance. A similar approach is used for the left and right overbank areas. However, the depth is set equal to the natural channel overbank maximum depth and the overbank width is modified to establish equal hydraulic conveyance.

Avatars generated from a set of natural cross sections are then interpolated and averaged to develop equally-spaced avatar cross sections for the simulations.

To calculate channel form and bed material composition changes over time for cross sections with non-cohesive material, the following calculations are conducted for each time step:

1. Hydraulic conditions and sediment transport capacity rates by grain size fraction are computed for each flow rate in the specified annualized flow-duration curve. FRAME has multiple sediment transport equation options for modeling. A bed material load calibration factor as a multiplier to the computed sediment transport capacity is used to enable model calibration.
2. Flow rate proportions from the annualized flow-duration curve are applied to each time step duration to determine the duration of each unique flow rate. Load fluxes between avatar cross-section control volumes are computed based on the duration of each flow rate in the timestep. A sediment supply adjustment factor greater than one can be added to each cross section to simulate sediment supply from bank erosion. The analysis is done by grain size and ultimately determines the total volume of sediment that will be deposited or removed from the cross-section control volumes.
3. Cross-section bed elevation changes are then computed using the Exner equation with a wedge-shaped volume of removal or deposition.
4. Bed composition changes are computed using a simple two-layer mixing method which includes a dynamic active layer at the surface of the channel bed and an underlying layer of undefined depth with the composition of the initial bed material layer. The active layer thickness is set to 15% of the bankfull flow depth.

FRAME allows users to specify a cohesive layer of bed material for any cross section. The depth of cohesive scour, ΔE_i, at each cross section, i, is computed using the following equation (Soar *et al.*, 2023):

$$\Delta E_i = \frac{E_h \Delta t}{86400(\omega_h - P_{SP0}\omega_h)} \sum_{j=1}^{N_J} F_j . \max\{(C_{E,i}\omega_j - P_{SP0}\omega_h), 0\}$$

where:

E_h = calibration erosion rate (ft/day) at a reference specific stream power, ω_h;
Δt = time step duration (sec);
ω_h = reference specific stream power for an arbitrarily high-intensity condition (ft-lb/sec.ft^2);
j = discharge class index (dimensionless);
F_j = frequency of occurrence of the jth discharge class (dimensionless);
$C_{E,i}$ = local erodibility calibration factor (dimensionless);
ω_j = specific stream power for the jth discharge class (ft-lb/sec.ft^2);
P_{SP0} = user-defined index for calibration ($0 < P_{SP0} < 1$) (dimensionless);

If an exposed cohesive layer is subjected to sedimentation, a new layer of granular material is defined on top of the cohesive layer and must be eroded through the non-cohesive erosion process before any additional cohesive scour can occur.

Sabougla Model Simulations

Four 100-yr forecasting scenarios were modeled in this study: 1) a baseline condition (BC), 2) a bank stabilization erosion control scenario (BSEC), 3) a tributary erosion control scenario

(TEC), and a climate change scenario (CC). Table 3 provides a summary of the variations in model scenario configurations. The BSEC scenario simulated the implementation of bank stabilization measures from River Mile (RM) 12.4 to 15.4 reducing the local sediment supply adjustment factor from 1.1 to 1.0. The TEC scenario simulated reduced sediment input from tributaries by reducing the tributary sediment concentration multiplier from 1 to 0.75 for the Sabougla Creek Tributary which represents the portion of Sabougla Creek upstream of the confluence with Bellefontaine Creek. The CC scenario demonstrated how potential impacts from climate change could be simulated by increasing the flow-duration curve multiplier linearly from 1 to 1.5 over the 100-year period. The linear multiplier was used for demonstration purposes; accordingly, more research should be conducted to determine suitable representative climate change future conditions. This section provides additional details of the model setup parameters.

Table 2. Summary of variations in model scenario configurations.

			Tributary Sediment Concentration Multiplier				Local Sediment Supply Adjustment Factor	
Scenario Name	**Scenario ID**	**Flow Duration Curve Multiplier**	**Sabougla Creek Trib.**	**Little Creek Trib.**	**Lindsay Creek Trib.**	**Little Horse Pen Creek Trib.**	**RM 1 to 12.4 and RM 15.4 to 20.0**	**RM 12.4 to 15.4**
Baseline Condition	BC	1	1	1	0.75	1	1	1.1
Bank Stabilization	BSEC	1	1	1	0.75	1	1	1
Tributary Erosion Control	TEC2	1	0.75	1	0.75	1	1	1.1
Climate Change	CC	variable*	1	1	0.75	1	1	1.1

*Increased linearly from 1.0 to 1.5 over the 100-year period.

Avatar Cross Sections

Two digital elevation models (DEMs) were downloaded from the Mississippi Automated Resource Information System (MARIS) (https://maris.mississippi.edu): 1) the USGS/NRCS Central MS Lidar Project 2014 bare earth DEM product, and 2) the Corps of Engineers Delta Phase II Lidar Project bare earth DEM product. These DEMs were merged to develop a continuous surface for the study area. As shown in Figure 1, a 20-mile long profile line and 31 cross sections (average spacing of approximately 3500 ft) were digitized for the study area. The lidar DEMS worked well to represent the channel conditions for most of the study section, however, portions of the 12 downstream-most cross sections were submerged during the time of lidar collection which resulted in capturing the water surface elevation instead of the bathymetric portion. Cross section data from a 2003-2004 survey, used in the Smith (2010) study, were used to modify these 12 downstream cross sections to obtain an accurate representation of the channel cross sections.

Avatar cross sections were developed for each of the 31 DEM cross sections. Figure 2 provides examples of the Sabougla Creek avatars over the entire cross section and Figure 3 shows a closeup view of the main channel area. The preliminary avatar cross sections were then interpolated and averaged to develop equally-spaced avatar cross sections. This resulted in 53 avatar cross sections with approximately 2000-ft spacing. The average bankfull channel width for the DEM cross sections was 127 ft; therefore, a 2000-ft spacing of avatar cross sections corresponds to approximately 15 times the channel width. Figure 1 illustrates the locations of the 53 equally-spaced avatars which were used as inputs into the FRAME model.

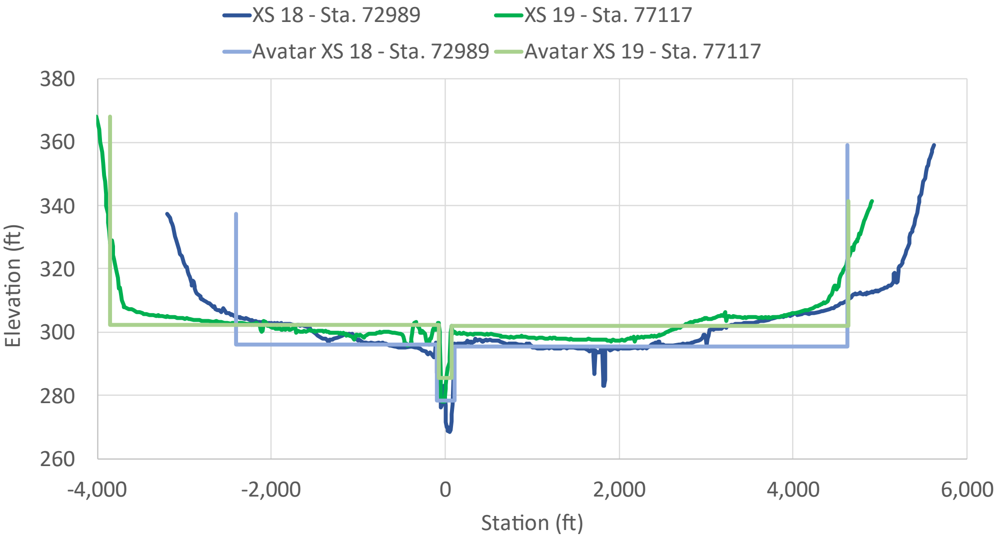

Figure 3. Example of Sabougla Creek entire cross sections and associated avatars

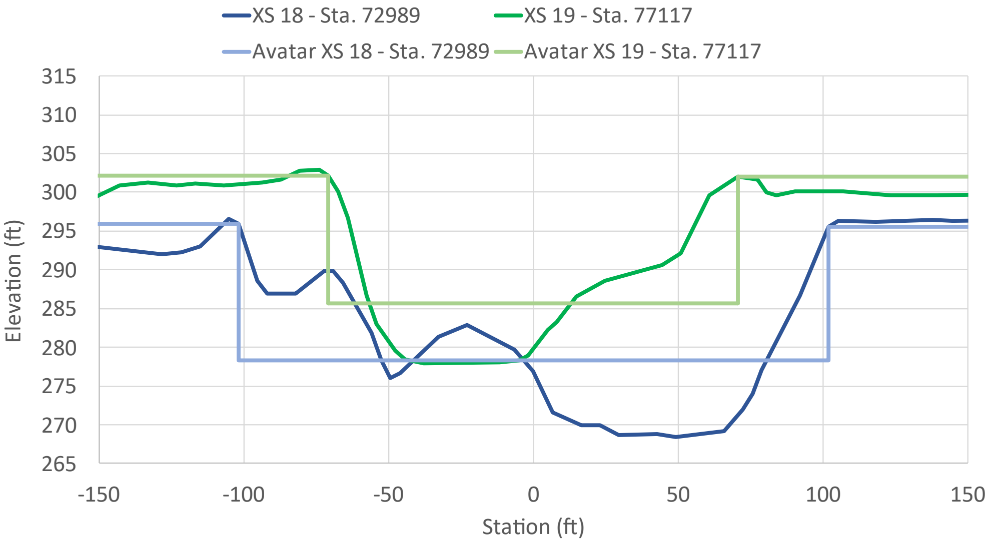

Figure 4. Example of Sabougla Creek channel cross sections and associated avatars

Each avatar cross section was assigned Manning's roughness coefficients of 0.06, 0.035, and 0.06 for the left overbank, channel, and right overbank, respectively. Further, each cross section was assigned a value of 0.1 and 0.3 for the contraction and expansion coefficients, respectively.

Flow-Duration Input Data

The FRAME tool requires a flow-duration curve to be defined at the upstream-most cross section and flow change points can be specified along the reach for tributaries or diversions. As shown in Table 1, the drainage area for the downstream-most and upstream-most cross sections are 126 and 1.99 mi^2, respectively. Due to the significant change in drainage area across the study reach, flow change locations were specified at each of the large tributaries. FRAME also has the option to linearly interpolate flow-duration curves for each avatar cross section based on the distance between flow change locations. This interpolation option was employed for the Sabougla Creek model due to the presence of significant changes in drainage areas between the flow change locations. For example, the upstream end of the Bellefontaine reach has a drainage area of 1.99 mi^{2,} and the drainage area immediately upstream of its confluence with Sabougla Creek is 9.76 mi^2.

Flow-duration curves for the upstream-most cross section and flow change locations were derived from scaling mean daily discharge data from the USGS 07282000 gage located on the Yalobusha River (295 mi^2 drainage area). Sabougla Creek is a tributary of the Yalobusha River and has similar watershed characteristics. Continuous daily discharge data from 1951 to 2005 were used to construct annual flow-duration curves which were then discretized to produce flow frequency histograms. From these data, a time-averaged annual flow-duration curve composed of six discharge classes was developed for the Yalobusha site. Drainage-area scaling relative to the Yalobusha gage was then used to generate flow-duration curves for the upstream-most cross section and tributary change locations in the Sabougla Creek site. Table 1 lists the drainage areas for these locations. Time-averaged flow-duration curves were used for the baseline and erosion control scenarios. For the climate change scenario, the flow-duration curves were increased linearly from a scaling factor of 1.0 to 1.5 over the 100-year period.

Erosion and Sedimentation Analyses

The Yang (1973) method for sand material with a bed material load calibration factor of 1.0 was used to compute sediment transport capacities. The sediment supply adjustment factor was set to 1.0 for River Miles (RM) 1 to 12.5 and 15.4 to 20.0 for all scenarios. For RM 12.4 to 15.4 in the baseline and climate change scenarios, the adjustment factor was set to 1.1 to simulate additional sediment supply from bank erosion; for the erosion control scenario, the factor was reduced to 1.0 to account for hypothetical bank stabilization measures.

The bed material load calibration factor was set equal to 1.0 and the upstream boundary sediment supply factor was set equal to 1.0 for all scenarios. The tributary sediment inflow concentrations for all time steps were set equal to the initial local main channel concentration with a unique calibration multiplier for each tributary (see Table 3). For the baseline, bank stabilization, and climate change scenarios, the tributary sediment multipliers were set to 1.0, 1.0, 0.75, and 1.0 for the Sabougla Creek, Little Creek, Lindsay Creek, and Little Horse Pen Creek, tributaries, respectively. For the tributary erosion control scenario, the tributary sediment concentration multiplier was set to 0.75 for the Sabougla Creek tributary with all other factors staying the same as the baseline condition.

For the cohesive scour input parameters, the calibration erosion rate, E_h, was set to 0.8 ft/day with an associated reference high-intensity specific stream power, ω_h, of 20.6 ft-lb/sec.ft^2 (300 W/m^2) which corresponds to a threshold for large-scale geomorphic change recommended by Magilligan (1992). The P_{SP0} index for calibration was set to 0.05; and the local erodibility calibration factor, $C_{E,i}$, was set to 1.0 for Reach 1 to Reach 6 and 2.2 for Reach 7 and Reach 8. The initial depth of granular material above the cohesive layer was set to three ft for Reach 1 to Reach 6 and set to zero for Reach 7 and Reach 8.

Additional Model Setup Details

Each scenario was modeled for a 100-year period. The FRAME tool has separate time steps for hydraulic calculations and sediment mixing. The hydraulic time steps are adaptive based on a maximum allowable bed elevation change of 0.04 ft for any cross section. Hydraulic times steps ranged from approximately 0.5 to 20 days with shorter time steps at the beginning of the simulation and longer time steps near the end of the simulations as the channel approaches an equilibrium condition. The sediment mixing timestep was set to 15 minutes with a maximum allowable bed elevation change of 0.04 for a given time step.

A normal depth downstream hydraulic control was used for each of the unique water surface profiles developed for the discharge values in the flow-duration curve. The bedslope used in the normal depth calculations was computed using the avatar bed elevations of the eight downstream-most cross sections. The normal depth downstream control was recomputed throughout the simulation as the cross-section elevations adjusted.

The sediment supply to the upstream most-cross section was set equal to the computed transport capacity for the upstream-most cross section. Sediment inputs for tributary locations were computed based on the sediment concentration of the main channel at the initial time step, the tributary inflow rate, and an assigned tributary sediment concentration multiplier. For model stability, the upstream-most and downstream-most avatar channel bed elevations were fixed and not allowed to change over time.

Results and Discussion

Baseline Condition

The initial and final bed elevation profiles for the 100-yr baseline scenario (BC) are shown in Figure 5. For the final profile, degradation was observed upstream of the confluence of Sabougla Creek and Bellefontaine Creek (Reaches 7 and 8); and aggradation was observed in all sections downstream of the confluence (Reaches 6 to 1). Figure 6 shows the computed bed elevation changes over time for all reaches. Reach 1 attains a quasi-equilibrium state at approximately year 40. Reaches 4 and 5 initially have degradational trends that transitioned to aggradation at approximately year 10. Throughout the simulation period, Reaches 2, 3, and 6 have continuous aggradation trends and Reaches 7 and 8 have continuous degradation trends.

Figure 7 illustrates the computed median bed material grain size (D_{50}) over time for each of the eight reaches. The initial D_{50} values for each reach varied from 0.16 to 0.43 mm. The grain size distribution for the upstream-most cross section is held constant representing the sediment supply composition at the model boundary. Accordingly, minimal changes were observed in the D_{50} value for Reach 8. The D_{50} value for Reach 1 increased from approximately 0.16 to 0.31 mm indicating that coarser material from the upstream reaches is depositing and mixing with the finer bed material. A constant decrease in the Reach 7 D_{50} value was observed and will need to be investigated further to reveal what factors are driving this trend.

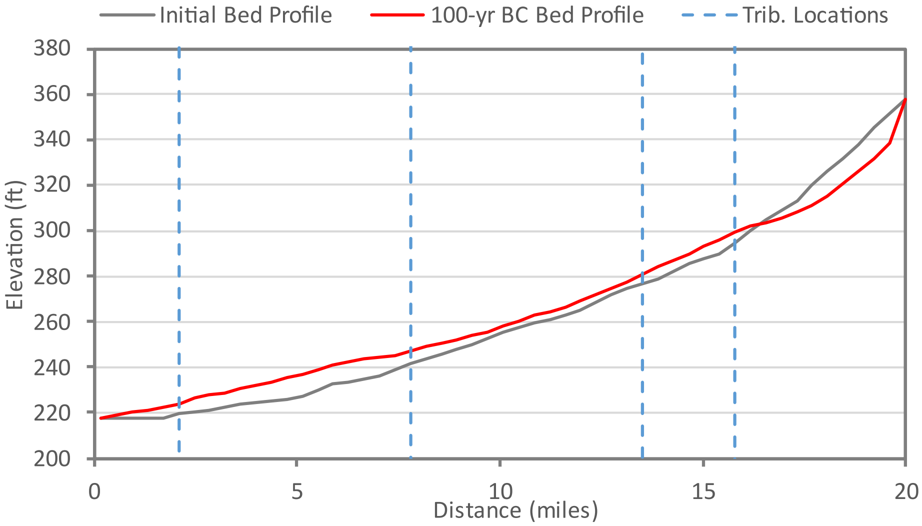

Figure 5. Initial and 100-yr bed elevation profiles for the Baseline Condition (BC) scenario.

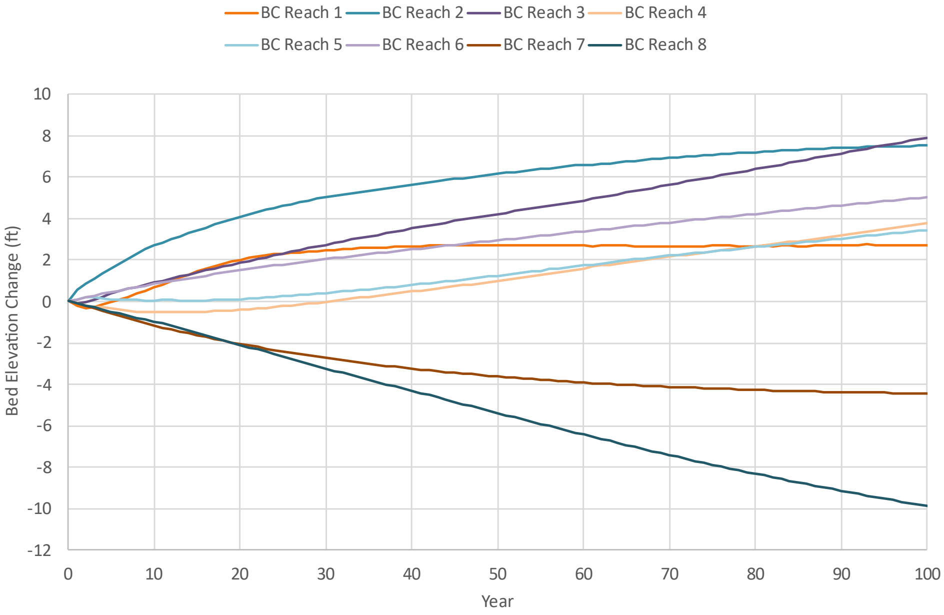

Figure 6. Bed elevation changes by reach for the Baseline Condition (BC) scenario.

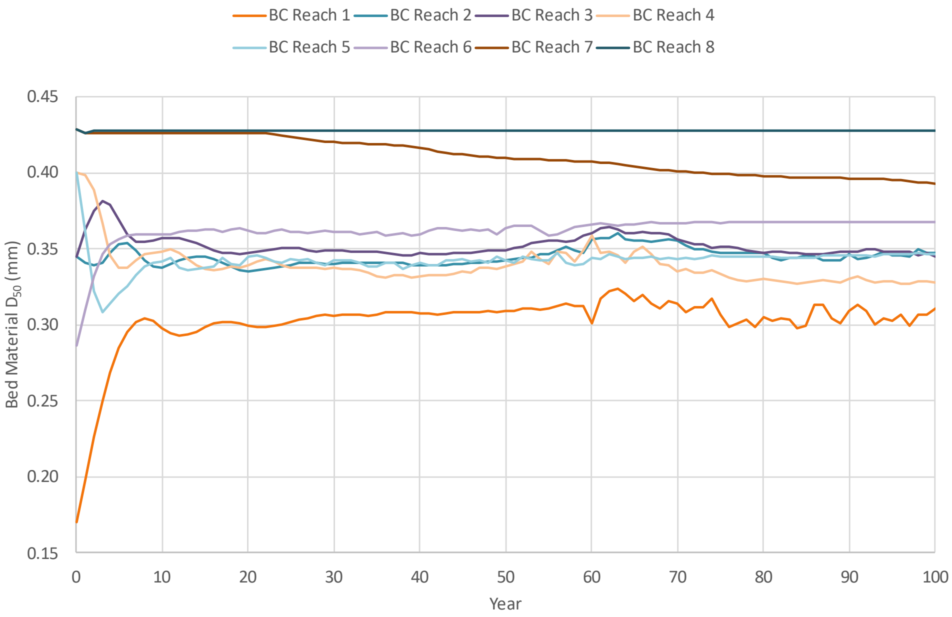

Figure 7. Median bed material grain size changes by reach for the Baseline Condition (BC) scenario.

Bank Stabilization Erosion Control (BSEC) Scenario

The BSEC scenario simulated reduced sediment supply from bank erosion from RM 12.4 to 15.4 (encompassing portions of Reaches 5 and 6). Comparisons of bed elevation changes for the BSEC and BC scenarios are shown in Figure 8 and Figure 9 for Reaches 1 to 4 and Reaches 5 to 8, respectively. The key differences between the BSEC scenario relative to the BC scenario are reduced aggradation in Reaches 2, 3, and 4, and increased degradation in Reaches 5, 6, and 7. Degradation trends observed in Reaches 5 and 6 are directly linked to the reduced bank erosion sediment supply to those reaches, and reduced aggradation in the downstream reaches can be attributed to the overall reduction in sediment supply to the system.

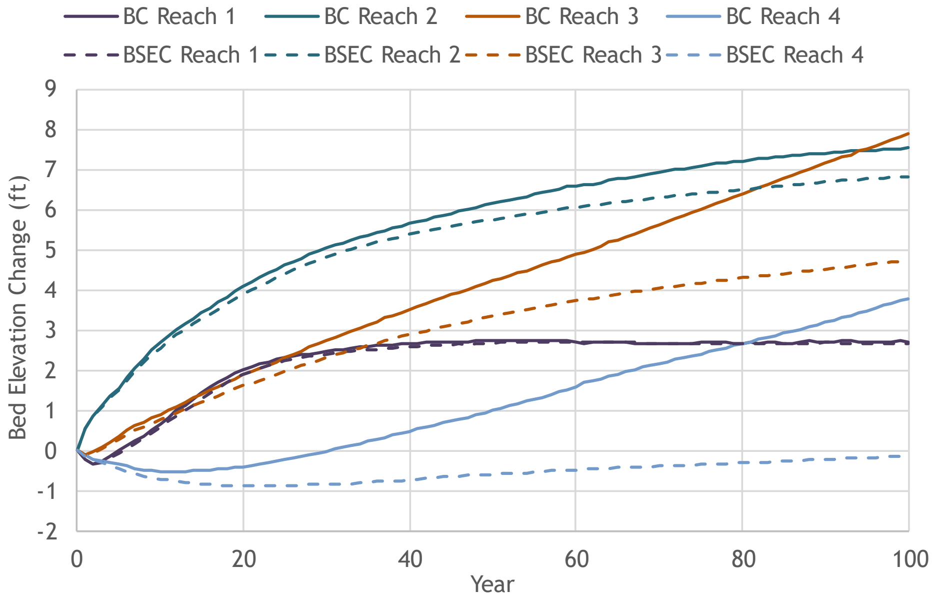

Figure 8. BSEC and BC scenario bed elevation changes for Reaches 1 through 4.

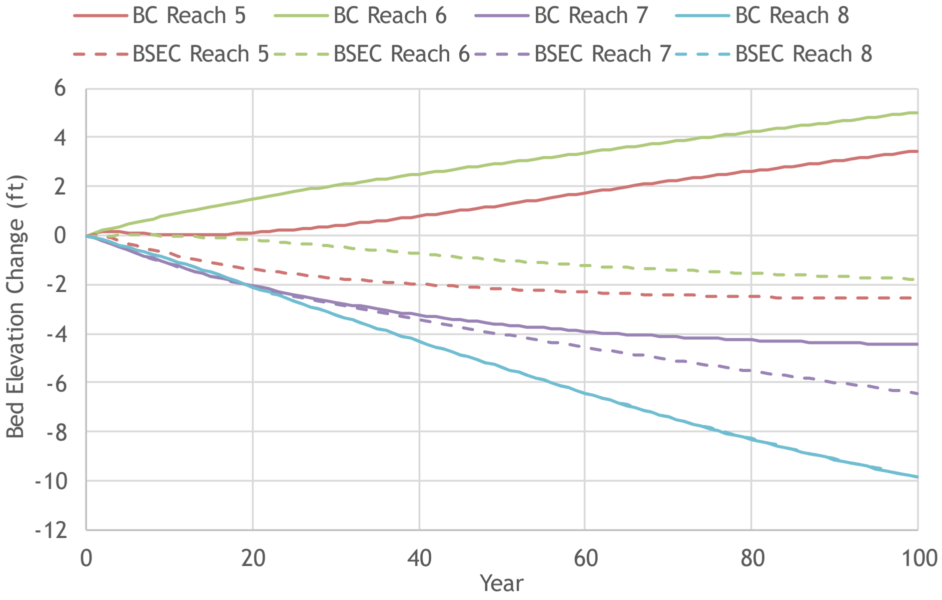

Figure 9. BSEC and BC scenario bed elevation changes for Reaches 5 through 8.

Tributary Erosion Control (TEC) Scenario

The TEC scenario simulated reduced sediment input from the Sabougla Creek Tributary located between Reaches 6 and 7. Comparisons of bed elevation change results for the TEC and BC scenarios are shown in Figure 10 and Figure 11 for Reaches 1 to 4 and Reaches 5 to 8, respectively. The TEC Scenario had negligible differences in bed elevation trends relative to the BC scenario for Reaches 1, 2, and 8, which are near the model boundaries. Reduced aggradation was observed for Reaches 3 and 4, and increased degradation was observed for Reaches 5, 6, and 7. Although, both the increases in aggradation and degradation relative to the BC scenario were significantly smaller than those observed in the SBEC scenario.

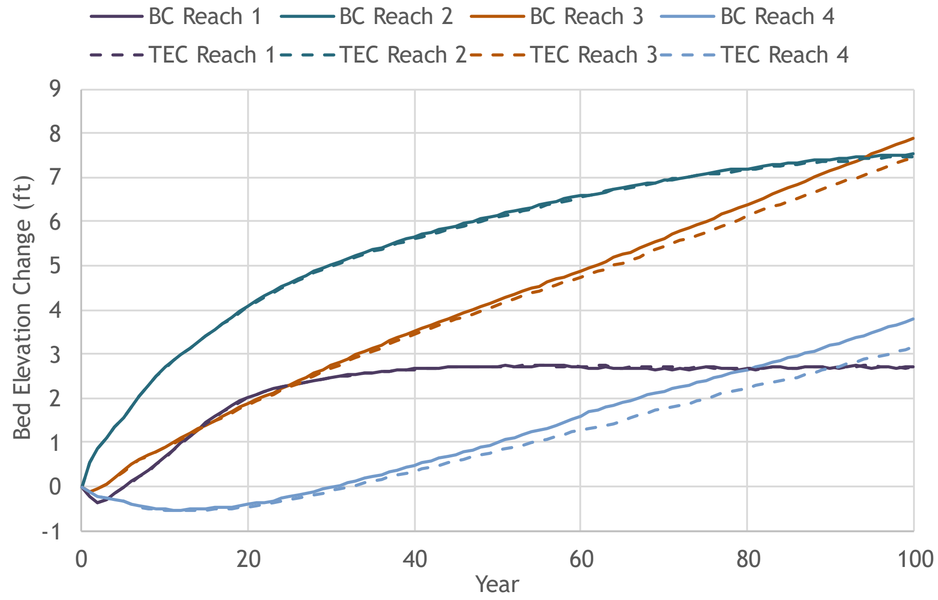

Figure 10. TEC and BC scenario bed elevation changes for Reaches 1 through 4.

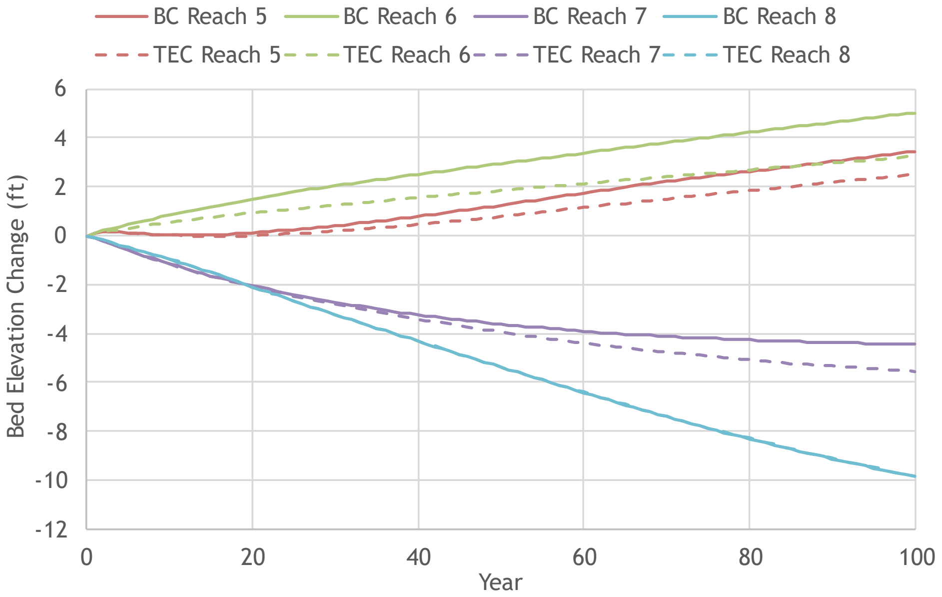

Figure 11. TEC and BC scenario bed elevation changes for Reaches 1 through 4.

Climate Change (CC) Scenario

The CC scenario simulated potential impacts from climate change by increasing the flow-duration curve multiplier linearly from 1 to 1.5 over the 100-year period. Comparisons of bed elevation change results for the CC and BC scenarios are shown in Figure 12 and Figure 13 for Reaches 1 to 4 and Reaches 5 to 8, respectively. Negligible differences in bed elevation trends relative to the BC scenario for Reaches 1 and 2 were observed. Reach 3 had a reduction in aggradation, Reaches 7 and 8 had significantly increased degradation, and Reaches 4, 5, and 6 had consistent degrading trends in contrast to the aggrading trends observed in the BC scenario. The results suggest the increase in flow intensities caused increased sediment transport capacity thereby reducing aggradation and increasing degradation throughout the system.

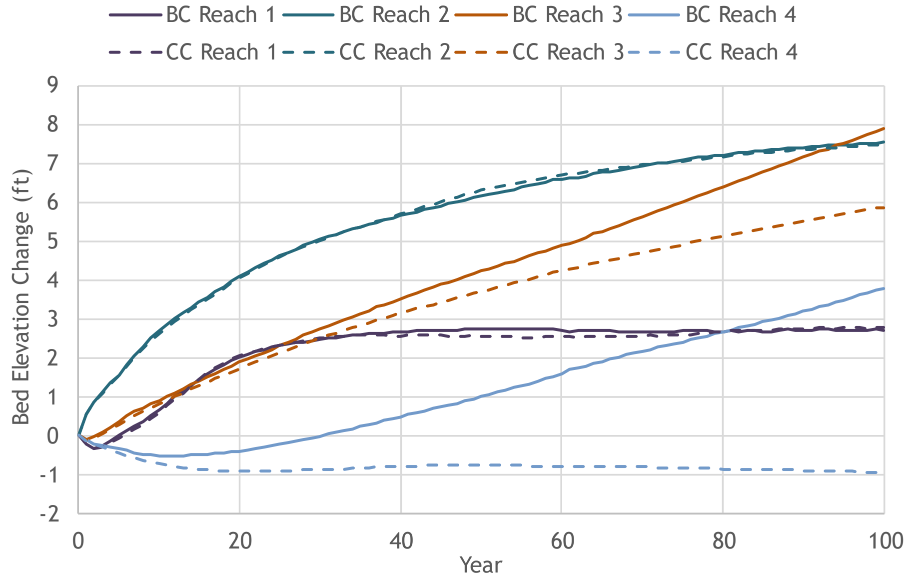

Figure 12. CC and BC scenario bed elevation changes for Reaches 1 through 4.

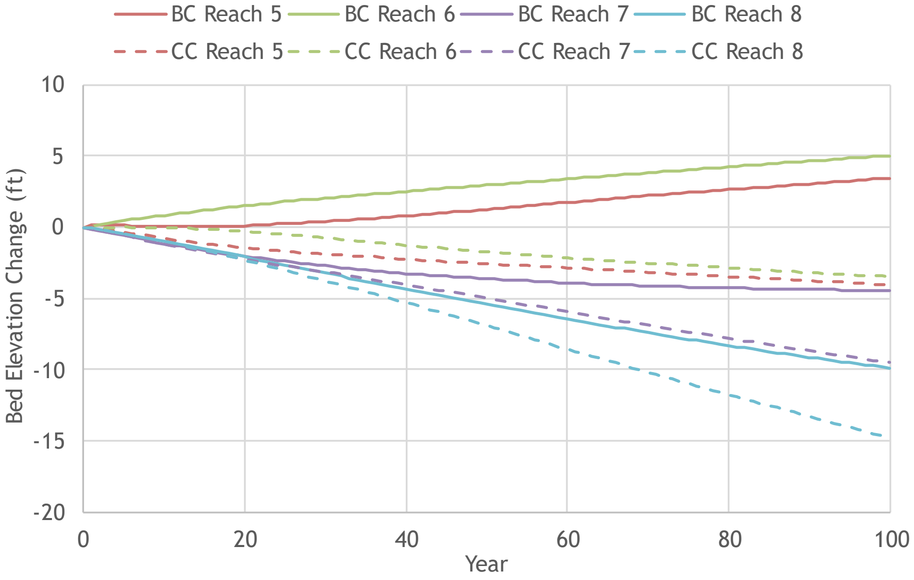

Figure 13. CC and BC scenario bed elevation changes for Reaches 5 through 8.

Summary

Morphological changes over a 100-year period of a 16-mile section of Sabougla Creek and a 4-mile section of Bellefontaine Creek were simulated using the FRAME tool. For this study, several new functional features were developed and implemented in the FRAME tool including multiple tributary inflows, linear interpolation of flow-duration curves between flow change locations, variable bed material gradation inputs, and simulating cohesive scour.

Four scenarios were investigated - a baseline condition (BC) scenario, a bank stabilization erosion control (BSEC) scenario, a tributary erosion control (TEC) scenario, and a climate change (CC) scenario. Generally, the BC scenario forecasted degradation in the upstream portion of the study reach and aggradation in the downstream portion. Relative to the BC scenario, the BSEC scenario predicted: 1) increased degradational trends in Reaches 5 and 6 which can be linked to the reduced bank erosion sediment supply to those reaches, and 2) reduced aggradational trends in the downstream reaches likely caused by the overall reduction in sediment supply to the system. The TEC scenario predicted similar but dampened trends to the BSEC scenario. Finally, the CC scenario forecasted reduced aggradation and increase degradation through the system which is driven by increased flow intensities and associated sediment transport capacities.

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