ISSUES IN DEVELOPMENT OF A 1000-MILE-LONG NUMERICAL SEDIMENTATION MODEL OF THE MISSISSIPPI RIVER

Ronald Copeland, Hydraulic Engineer, USACE Vicksburg District, Vicksburg, MS, Ronald.R.Copeland@usace.army.mil; Basil K. Arthur, Hydraulic Engineer, USACE Vicksburg District, Vicksburg, MS, Basil.K.Arthur@usace.army.mil; Roger Gaines, Hydraulic Engineer, USACE, Memphis District, Memphis, TN, Roger.A.Gaines@usace.army.mil; Leslie Lombard, Hydraulic Engineer, USACE New Orleans District, New Orleans, LA, Leslie.Lombard@usace.army.mil; Dennis Stephens, Hydraulic Engineer, USACE St Louis District, St Louis, MO, Dennis.L.Stephens@usace.amy.mil; Clarence E. Thomas, Hydraulic Engineer, USACE Mississippi Valley Division, Vicksburg. MS, Clarence.E.Thomas@usace.army.mil

Abstract Unique challenges were encountered in developing a one-dimensional numerical sedimentation model of the Mississippi River from Chester on the Upper Mississippi River and Lock and Dam 53 on the Ohio River to Pilots Station at the end of Southwest Pass – over 1000 miles. The purpose of the study was to develop a numerical sedimentation model that could identify and predict the effects of planned Mississippi River and Tributaries Project features and dredging strategies on long-term sedimentation trends. The study was conducted by engineers from four U.S. Army Corps of Engineer Districts. The study approach was to develop a numerical model using the one-dimensional HEC-6T model. This model has been applied successfully to evaluate long-term sedimentation responses to various engineering projects along the Lower Mississippi River. These applications have included river response to dredging, flow diversions through distributaries, construction of a low-flow sediment sill and contraction works. It is recognized that river response to dikes, especially overtopping dikes, is not strictly a one-dimensional, steady-flow, problem; however, it is hypothesized that one-dimensional effects are dominant and that careful application of the numerical model will be useful in determining appropriate lengths, heights, and longitudinal extent for dike field construction and long-term sedimentation trends in the river. The model does not try to study a specific area in detail. The model is constructed so that more refinement can be added to study specific problem areas.

This paper discusses some of the issues encountered in development of this model. These issues include: careful examination of measured data to determine if reported information is reasonable, identification and evaluation of appropriate calibration data, adequate transport of sediment by size class, and the importance of knowledge of both recent and historical geomorphologic changes in the river system. The length of the model requires calibration at several intermediate points between the model boundaries.

INTRODUCTION

Purpose The purpose of this study was to develop a numerical sedimentation model that could identify and predict the effects of planned Mississippi River and Tributaries Project features and

dredging strategies on long-term sediment trends between Cairo, Illinois (RM 980.9)[1] and Pilots Station, Louisiana (RM -18.0).

Study Approach The study approach was to develop a numerical model using the one-dimensional HEC-6T model (Mobile Boundary Hydraulics, 2008). This model has been applied successfully to evaluate long-term sedimentation responses to various engineering projects along the Lower Mississippi River. These applications have included river response to dredging, flow diversions through distributaries, construction of a low-flow sediment sill and contraction works. It is recognized that river response to dikes, especially overtopping dikes, is not strictly a one-dimensional, steady-flow, problem; however, it is hypothesized that one-dimensional effects are dominant and that careful application of the numerical model will be useful in determining appropriate lengths, heights, and longitudinal extent for dike field construction and long-term sedimentation trends in the river.

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NUMERICAL MODEL DESCRIPTION

Description The HEC-6T program produces a one-dimensional model that simulates the response of the riverbed profile to sediment inflow, bed-material gradation, and hydraulic parameters. The model simulates a series of steady-state discharge events, their effects on the sediment transport capacity at cross sections and the resulting degradation or aggradation. The program calculates hydraulic parameters using a standard-step backwater method.

Channel Geometry The initial channel geometry for the HEC-6T model was developed from hydrographic survey data from the four USACE districts. Cross sections from the two most recent hydrographic surveys were used. The older of the two surveys was used in the model to represent initial conditions. The most recent survey was used for calibration and verification of the model. New Orleans channel and overbank cross sections came from the 1991-1992 hydrographic survey. Vicksburg channel and overbank cross sections came from a HEC-2 model based on 1988-89 hydrographic survey. Memphis channel cross sections came from the 1988-89 hydrographic survey. St Louis channel and overbank cross sections came from the 1988 hydrographic survey. USGS quads or LiDAR data were used to define overbank geometry. In the dike fields, hydrographic survey data were modified so that the projection of dike crest elevations obstructed conveyance in the channel. Newly constructed dikes were added to the model at appropriate times during the historical simulation.

The cross sections are coded from left to right looking downstream and generally have reach lengths of 2 to 4 miles. Some cross section distances are less than a half-mile in more complex areas of the river such as, bends, dike fields, and crossings. Some cross section reach lengths are greater than 4 miles in reaches where it was difficult to find a representative cross section for one-dimensional flow.

[1] RM on the Mississippi River between the outlet at Southwest Pass (RM -18.0) and Cairo, Illinois (RM 980.9) refer to river miles upstream or downstream from Head of Passes (RM 0.0).

Sediment Inflow A combination of measured and calculated data were used to establish sediment inflow boundary conditions. In order to model sedimentation trends in the Mississippi River it is necessary to account for movement and storage of each sediment size class. HEC-6T allows for this accounting, however, the required input data are generally lacking. Long-term size class sediment data are available in the study reach, at the upstream boundary on the Upper Mississippi River at Thebes, located 44 miles upstream from the Ohio River, and Chester, located 110 miles upstream from the Ohio River. Long-term size class data are also available at Union Point and Tarbert Landing, which are located upstream and downstream from the Old River Structure. A shorter record is available at Belle Chasse, located 76 miles above Head of Passes. Data for the major tributaries, including the Ohio River, are generally limited to the sediment concentrations greater and less than 0.062 mm. The lack of boundary condition data required that size class percentages be estimated by calculation. The Thebes and Chester data were used as a boundary condition and the Union Point, Tarbert Landing, and Belle Chasse data were used to verify the model's performance.

Sediment Concentration at Diversions The ratio of sediment concentration in diversions to upstream concentrations in the river must be provided as a model input for each size class. Unfortunately, data are sparse. Diversion ratios at the Old River Structures were determined from measured data, but for most diversions the diversion ratios were calculated assuming a laterally averaged logarithmic velocity profile and a Rouse distribution. This calculation accounts for reduced concentrations of coarser size fractions, when the bed elevation in the diversion is significantly higher than the bed of the river. However, it does not account for the lateral variation of sediment concentration at bends.

Bed Material Gradations Bed material sampling programs of the Mississippi River have indicated significant longitudinal variability in the bed material gradation. This variability is primarily due to the variability in bed shear stresses associated with the natural bends and crossings. This variability makes it difficult to determine if there has been any long-term change in the bed material gradation. Nordin and Queen (1991) compared thalweg bed-material samples that they collected in 1989 to thalweg bed-material samples collected in 1932 (WES 1935) and concluded that the bed sediments were generally smaller between Cairo and Old River, but downstream from Old River there was no long-term change in median grain size. The changes in size class distributions were rather subtle. Both the 1932 and 1989 sampling programs showed a general decline in mean gain size in a downstream direction, but also showed considerable deviations from the general downstream fining trend from cross section to cross section.

Initial bed-material gradations in the numerical model were adjusted to allow for variability associated with cross section shape and velocity. Starting with data from Nordin and Queen (1991) bed gradations were calculated using a 2-yr discharge for 30 days at the upstream boundary. These new calculated bed-gradations were then set as initial conditions in the numerical model.

Model Calibration The numerical model was calibrated to measured water surface elevations, sediment transport at intermediate gages, and to dredging records in Southwest Pass. Water surface elevation calibration was accomplished by varying Manning's roughness coefficients

with discharge. This was done for the initial hydrographic survey geometry. The model was then run for a 12-year calibration period and calculated water-surface elevations at the end of the calibration period were again compared to measured stages to evaluate the model's ability to predict specific gage changes. Intermediate gages at Union Point, Tarbert Landing, and Belle Chasse were used to evaluate the ability of the model to transport the appropriate volume of each size class through the study reach. Dredging records in Southwest Pass and above head of Passes were used to evaluate the ability of the model to correctly account for sediment deposition in the lower reaches of the river where significant distributary flow reduces the sediment transport capacity.

Modeling Issues Several issues, encountered during the development of the sedimentation model, required resolution. These included both analysis of available data and modeling technique. Some of these issues are discussed in the following paragraphs: 1) the evaluation of reported stage data, 2) movable bed assignments in dike fields, and 3) inflow hydrograph development for a large model network.

EVALUATION OF REPORTED STAGE DATA

Using reported stage data from stream gages to calibrate a one-dimensional numerical model can be problematic. Difficulties can occur due to several factors, which include wind, tidal effects, datum changes, and subsidence. Specifically, measurable subsidence can be observed below Baton Rouge, Louisiana, but is site specific. Below Venice, Louisiana, subsidence can be as much as one foot over a ten year period. However, above Baton Rouge, the aforementioned factors have little or no impact on the model. Nevertheless, the purpose of the HEC-6T model developed for this study was to evaluate long-term sedimentation effects that could be attributed to proposed geomorphic modifications at various locations along the 1000 mile study reach. Therefore, a relatively simple boundary condition was sought for the downstream water surface elevation.

Initially, the downstream starting water surface elevation was to be determined from reported USACE gage data. However, an analysis of the daily stage data in Southwest Pass showed that stages at East Jetty (RM -20.6) and Mile 9.2 (RM -9.2) were higher than those at Head of Passes (RM 0.0) and Venice (RM 10.7) at low discharges. This inconsistency is demonstrated in Figure 1, which shows plots of reported daily stages versus routed discharges from Tarbert Landing for water years 1991 and 1992. These inconsistencies may be due to tidal influence and/or subsidence. Attempts were made to compensate for these variances by calculating an average daily stage, but this was complicated by missing data at these gages. Incidentally, the Corps had an independent surveyor tie-in selected gages in Southwest Pass and above Head of Passes for the Mississippi River Hydrographic Survey Book. However, the correction factors from these tie-ins are referenced to NAVD88. The Corps stage data are referenced to NGVD29. Correction factors associated with the gages in Southwest Pass are not available.

For this study, downstream water-surface elevations at Pilots Station were set based on average monthly stages using NOAA tide data. The simplifying assumption of an average monthly stage at the downstream boundary of the model is adequate for purposes of the generalized model developed in this study. However, studies of specific morphologic changes in the Mississippi

River below Belle Chasse, especially in response to river diversions, may require more a detailed description of the downstream stages.

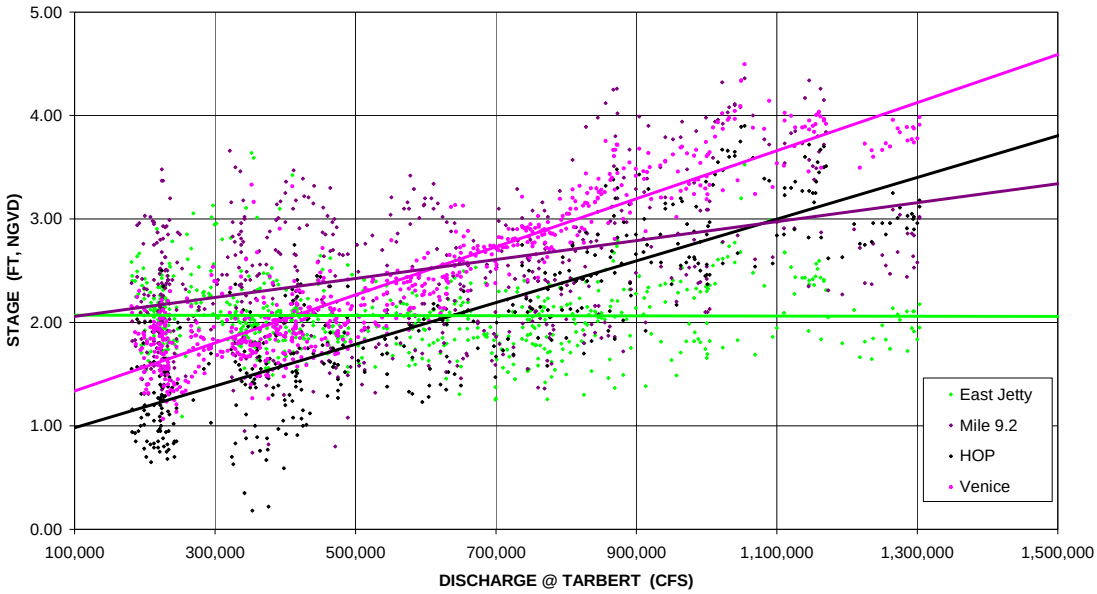

Figure 1 Stage Discharge Rating Curves for 1991-1992 USACE gages in Southwest Pass and Discharge at Tarbert Landing.

MOVABLE BED ASSIGNMENT IN DIKE FIELD

There are two options for modeling a dike field in the one-dimensional HEC-6T model: 1) Allow sediment deposition in dike field, or 2) Restrict the movable bed to the main channel. Constriction works constructed in the Mississippi River at Smithland Crossing (Hog Point), between September 1990 and June 1996, were used to verify the numerical model and evaluate the movable bed assignment in HEC-6T.

The constriction works, which are located between River Miles 297.45 and 300.3, include a trench-fill revetment through the middle of an island that separates two channels, stone dikes on the left bank of the river, and a cutoff structure across the old main channel. Figure 2 is a 1998 navigation map that shows the features at Smithland Crossing. A recent photograph of Smithland Crossing (looking downstream) is shown in Figure 3. In this picture the navigation channel has moved to the left side of the island, the river has eroded to the trench fill revetment, and significant sediment has deposited in the dike field.

The initial geometry for HEC-6T came from the 1991-1992 hydrographic survey. The geometry at Smithland Crossing was modified to account for the closure structure and projection of dikes in the dike field. Bed elevations in the chute were raised to account for the closure structure so that conveyance in the chute was equal to the flow that occurs over the closure weir. The channel banks in the numerical model were set at the top of the trench fill revetment and at the end of the projection of the dikes. This designation is significant because it is the channel hydraulic parameters that are used in the sediment transport equations. Erosion limits in the

model were set at the toe of the dikes and at the toe of the trench fill revetment. To test the effect of movable bed assignments in the dike field, deposition limits were initially set at the right and left bank of the river, which allowed deposition in the dike field, and finally set to match the erosion limits, which allowed deposition only in the main channel.

When deposition was allowed in the dike field, between 12 and 15 ft of deposition above the dike crest elevation was calculated through Smithland Crossing. This is far in excess of that shown in the 2004 hydrographic survey. Erosion cannot be allowed in the dike field because in the HEC-6T model all the bed elevation points within the erosion and deposition limits are moved an equal distance in the solution of the sediment continuity equation during each time step and erosion of the dikes is not appropriate. The one-dimensional model does not allow for lateral variation of erosion rates so it is an all or nothing choice.

When deposition was allowed only in the main channel between the trench-fill revetment and the toe of the dikes, calculated erosion between 1992 and 2004 was within 90 percent of the measured erosion. Calculated results at River Mile 299.5 are shown in Figure 4. The dike field added to the 1991-1992 geometry is indicated by the shaded green area in the figure. Blockage of the cross sectional area in the chute for conveyance calculations is indicated by the shaded blue area in the figure. The 1991-1992 geometry with the shaded dike field removed and blocked conveyance area was used as the initial conditions in the model. The cross section labeled "2004"shown in the figure is from the 2004 hydrographic survey. Aggradation and degradation calculated by HEC-6T between 1991 and 2002 is shown on the figure. Note that

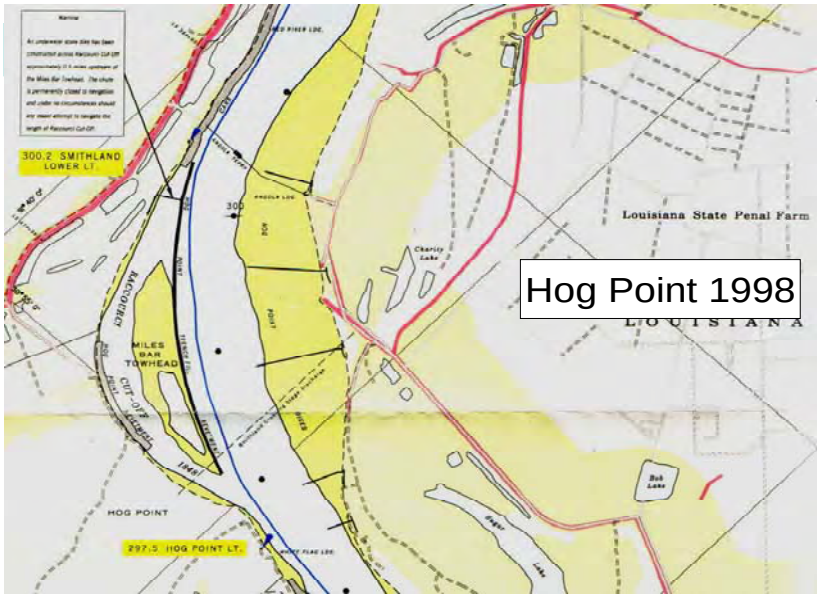

Figure 2 Navigation Map of Smithland Crossing after construction of contraction works.

Figure 3 Looking downstream at Smithland Crossing. The river has eroded back to the trench fill revetment and sediment has deposited in the dike field.

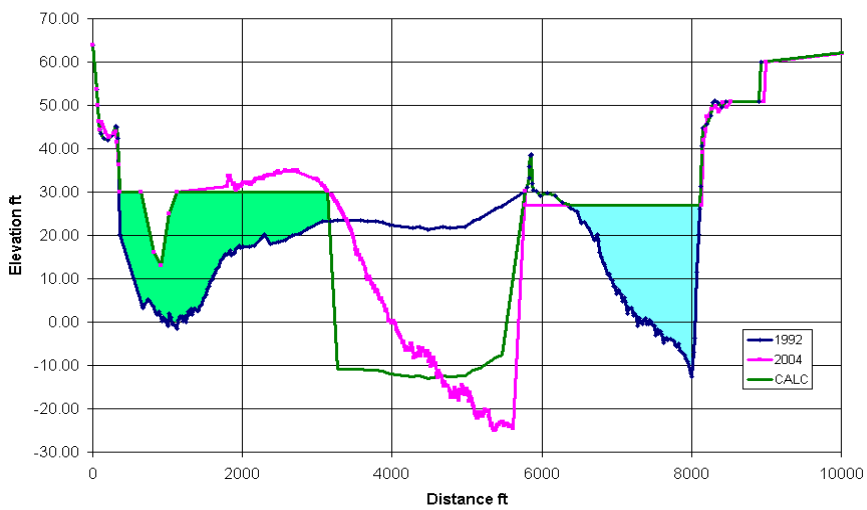

Figure 4 Calculated and measured degradation at Smithland Crossing RM 299.5.

the 2004 hydrographic survey shows that deposition occurred above the top elevation of the dikes. This deposition was not simulated in the numerical model because cross section changes were restricted to the channel.

Calculated bed changes in the HEC-6T model occur equally at each cross section point within the movable bed. Thus, the model is not able to reproduce the change in cross section shape that occurred as a result of the construction of the constriction works. However, the model can be used to estimate the volume of erosion that occurs as a result of channel constriction. The success of the model in producing a reasonable channel shape is especially encouraging

considering the extreme changes in the cross sections that were introduced by the dikes and the closure of the chute.

Just one more thing to consider - Calculated deposition in the dike field is a function of the sediment inflow and sediment transport capacity in the channel. The model deposits excess sediment uniformly across both the dike field and the channel if the movable bed includes the dike field. The flow parameters across the dike field are not considered in the model. Thus, at higher flows when erosion may actually occur across the dike field in the prototype, no erosion occurs in the model.

The model verification results are based on the approach where channel erosion and deposition is limited to the channel. Calculated channel erosion in the Smithland Crossing reach is compared to measured erosion over the 11 year period between hydrographic surveys in Table 1. The tabulation does not include the deposition in the dike field or on the island. The calculated results are based on the assumption that the constriction works were in place at the beginning of the simulation in November 1991. This was true for the dikes, but the chute closure structure was not completed until June 1996. So, modeled erosion is expected to be greater than prototype erosion. The calculated erosion in this reach was within 10 percent of the measured for the 11 year period.

Table 1 Calculated and measured erosion at Smithland Crossing 1991-2002.
Movable bed assigned only to the main channel.

Cross Section	**Calculated with HEC-6T cubic yards**	**Measured cubic yards**
297.45		
	4,370,000	4,176,000
298.1		
	12,778,000	12,692,000
298.9		
	8,695,000	7,300,000
299.5		
	9,309,000	7,854,000
300.3		
Total	**35,152,000**	**32,022,000**

The designation of the movable bed limits will not only affect the shape of the cross sections in the dike field itself, it will also affect the sediment load downstream. A test was made to compare cross section shape and downstream sediment transport load with the 1991-2002 hydrograph for the case where deposition was allowed in the Smithland Crossing dike field and for the case where it was not.

Calculated cross section shape changes at Cross Section 298.1, for the case where deposition was allowed in the dike field and for the case where it was not, are shown in Figure 5. Note that

there is less scour in the main channel for the case where deposition was not allowed in the dike field. Allowing deposition in the dike field resulted in less cross sectional area at all Smithland Crossing cross sections.

Calculated accumulated sediment transport downstream from Smithland Crossing, for the case where deposition was allowed in the dike field and for the case where it was not, are shown in Figure 6. Note that the dike field increased the sediment load downstream for both cases. The net effect of deposition in the dike field and more scour in the channel results in more sediment load downstream. The maximum increase in sediment load due to allowing deposition in the dike field is about 6 percent. The increased sediment load continues for about 100 miles downstream.

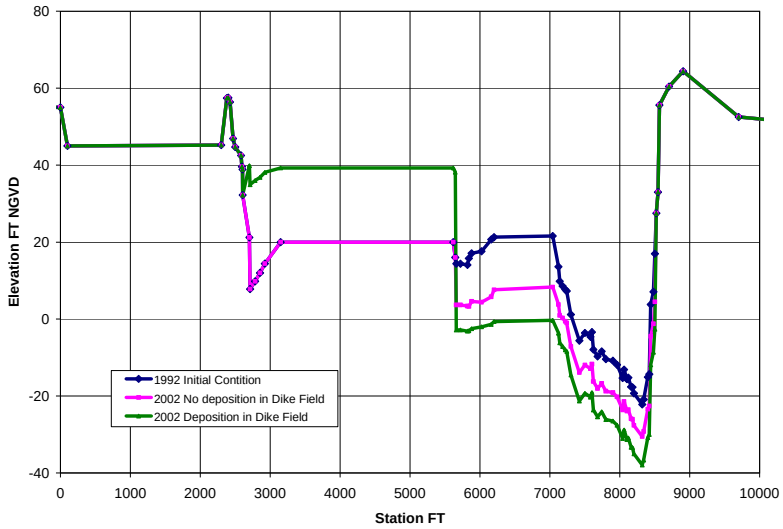

Figure 5 Calculated Bed Changes at Cross Section 298.1 for 1991-2002. Comparing the cases where deposition is allowed in the dike field and where it is not.

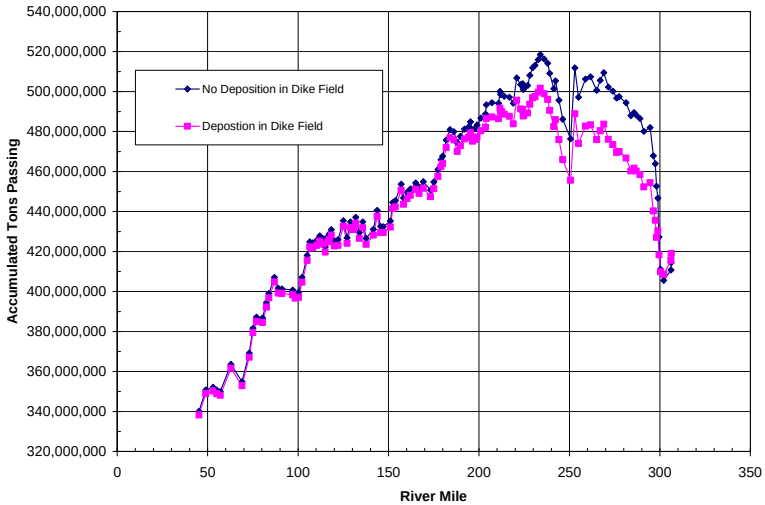

Figure 6 Calculated Accumulated Sediment Load for 1991-2002. Comparing the cases where deposition is allowed in the dike field and where it is not.

INFLOW HYDROGRAPH DEVELOPMENT FOR LARGE MODEL NETWORK

The availability of measured water discharge for the Mississippi River was limited to a relatively few locations along the main-stem channel. Because tributary backwater effects extended as much as 100 miles from the main-stem, tributary flow could not easily be determined from existing stream gauges. Including long reaches of tributary streams in the current modeling effort was not possible because survey data for tributary streams were limited or non-existent. Further compounding the problem with including tributary streams was the lack of sediment inflow data.

The initial approach adopted for developing model water discharges limited the number of tributary inflow points as necessary to capture expected sources of geomorphic change. Here, sources of geomorphic change meant locations where observed geomorphic features in the main channel resulted from tributary sediment inflows. These features persisted for 10 or more miles in the Mississippi River. The numerical model included inflows for the Ohio, Obion, Hatchie, St. Francis, White, Arkansas, and Yazoo Rivers. The model network utilized a representative reach of the tributary channel as a boundary condition. Initial flow was estimated from historical stream discharge measurement stations located outside zones of backwater influence. Sediment load was estimated using the recirculation option in HEC-6T and sporadic suspended load measurements if available. The resulting inflow hydrograph provided the initial flows for model simulation.

After the model assembly, annual water volumes were compared between model and prototype at measured discharge stations along the main-stem Mississippi River. There was good agreement between model and prototype at the confluence of Ohio and Upper Mississippi Rivers. However, downstream control points did not maintain the close agreement between reported flow and values computed by the model as shown in Figures 7 and 8. These differences may be attributed to unsteady flow effects and/or to assumptions related to tributary inflows.

The quasi-steady flow assumption used in HEC-6T approximates unsteady flow by stepping through a time-sequence of steady discharges. The quasi-steady flow method does not take into consideration flow routing effects. This introduces the potential for timing issues in flow propagation through the model. This is further compounded by the fact that some reaches of the Mississippi River apparently loose flow between upstream and downstream measurement points. For example, the gauge at Memphis, TN shows more discharge than observed at the next downstream gauge at Helena, AR during some historical periods in the data record Figure 9. The reason for the decrease in discharge between these two stations is unknown. Several hypotheses exist including flow lost to the alluvial and deeper aquifers and extensive attenuation due to large backwater areas along the lower St. Francis basin. Nonetheless, the current model effort required an accurate representation of water in terms of flow rate and volume to calculate sediment transport over the simulation period. To achieve discharges and volumes that matched measured data along the Mississippi main-stem, tributary flow was adjusted to account for variances that resulted from using the quasi-steady flow steps estimated using tributary stream gauges. The modified hydrologic data reproduced measured data within 1% at Hickman, KY and within 3% at Helena, AR.

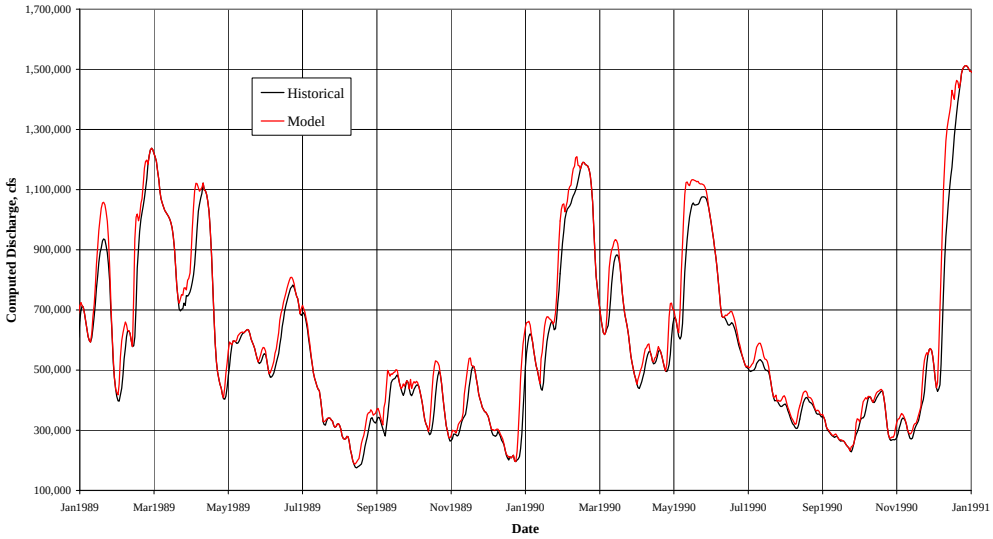

Figure 7 Prototype and Initial Model Discharge at Helena, AR Gauge.

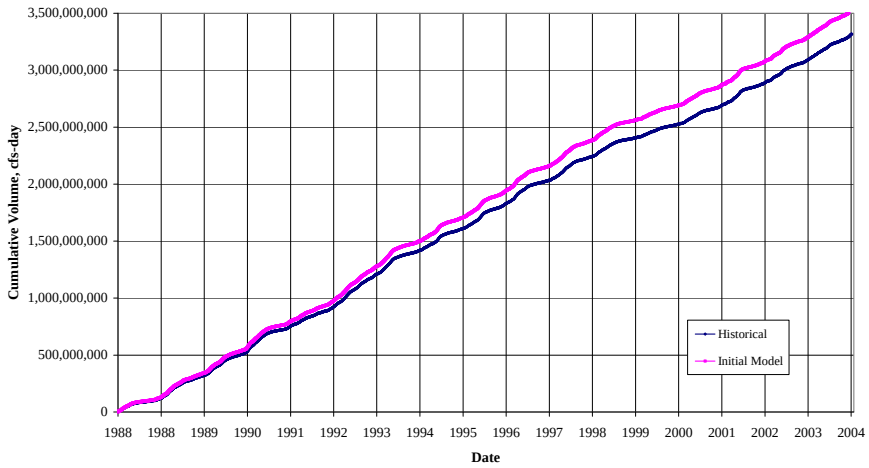

Figure 8 Prototype and Initial Model Cumulative Flow Volume at Helena, AR Gauge.

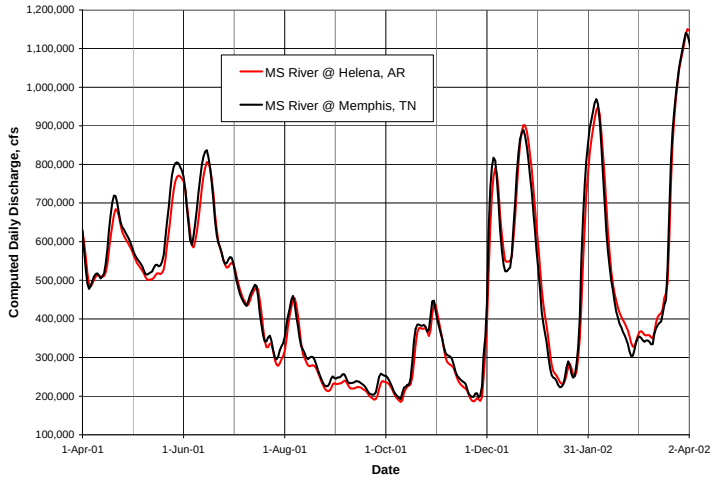

Figure 9 Flow Decrease in Downstream Direction Memphis to Helena Reach.

MODEL PREDICTIONS

The HEC-6T numerical sedimentation model developed for this study can be used to predict long-term effects of future Mississippi River and Tributaries Project construction and natural morphologic changes. These effects include bed changes and subsequent water surface elevation changes during major floods, long-term aggradation trends at crossings that may affect dredging, and long-term degradation trends that may affect bank protection. The model can be used to determine the effect of channel constriction works, channel straightening, and dredging. The model can also be used to evaluate navigation/dredging effects related to flow diversions for purposes of land building and/or freshwater enhancement. The effects of long-term changes in sediment supply can also be evaluated.

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