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NUMERICAL SIMULATIONS OF CHANNEL RESPONSE TO RIVERINE STRUCTURES IN ARKANSAS RIVER

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ABSTRACT

Numerical simulation of flows, sediment transport and river channel change in complex geometries of natural environment is a challenge to computational fluid dynamics (CFD). The difficulties include not only the discretization of the physical domain with a computational mesh, but also the capabilities of simulating the short and long term channel morphologic change in response to adjustment of hydraulic structures. Therefore, a robust numerical modeling system consisting of an efficient mesh generator and fluvial process simulator is needed.

In this study, the response of the Arkansas River navigation channel to riverine structure modifications was simulated by using a hydrodynamic and sediment transport computational model, CCHE2D. The feasibility of deepening the channel using modified dike fields with more, higher and longer dikes was confirmed with this model. In addition, the new design of the dike fields was further improved by multiple simulations of the computational model.

1. INTRODUCTION

Arkansas River stretches 1,450 miles from its head in Colorado, through Kansas, Oklahoma and Arkansas, it then empties into the Mississippi River. The Arkansas River is not only a scenic natural beauty, a water resource for irrigating farming fields, but also the most important waterway to the regional economy. In June 1971, a cascade lock and dam system along the River (13 in Arkansas and 5 in Oklahoma) was established, the channel navigation and commercial transportation are much more efficient and economical since. In 2004 total tonnage shipped on the system was almost13 million.

The increasing needs for low cost commercial transportation demands larger and heavier boats which require a deeper channel of the waterway. The US Army Corps of Engineers has designed new and improved riverine structures to be built in the waterway which will help to create a deeper

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and more efficient channel. The National Center for Computational Hydroscience and Engineering at the University of Mississippi was asked to evaluate the effectiveness of these structure designs in part of the channel using the state of the art computational models developed at the Center.

This paper reports the numerical study of channel change in response to river training structures and their adjustment in order to improve the channel's navigability in the Arkansas River (Pool 7). The study reach is a geometrically complex navigation system, in which many spur dikes and revetments were constructed to protect the bank and confine the flow. To have a reasonable and efficient evaluation of the effectiveness of planned structure adjustment on the channel change, computational simulations were applied. The numerical model is required to be capable of simulating unsteady flows, non-uniform sediment transport, helical secondary flow effect, bed topographic change and wet/dry conditions. To make the evaluation more reliable, a 50+ year return flood event was also included in the simulation.

The hydrodynamic and sediment transport model, CCHE2D, was applied. The numerical simulation study was accomplished by using the CCHE2D Mesh Generator and the CCHE2D-GUI. The computed flow fields were validated by measured velocity profiles across many sections with numerous spur dikes of different height, length and shape in this reach with excellent agreements. Long term hydrodynamic processes and associated channel geomorphic response were then computed. The optimal modification was identified from many alternative designs by using simulations. It is shown that the numerical modeling system is an efficient and powerful tool for river training structure design.

2. NUMERICAL MODEL

CCHE2D is a depth-integrated two-dimensional model for simulating environmental hydrodynamics. The model is capable of simulating turbulence flows with complex channel and multi-hydraulic structures. It is also capable of simulating non-uniform suspended and bed load sediment transport with bed changes. The governing equations of the model are solved using a mixed finite element and finite volume (efficient element) method. The momentum equations for depth-integrated two-dimensional turbulent flows solved in a Cartesian coordinate system are:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-g\frac{\partial \eta}{\partial x}+\frac{1}{h}\left(\frac{\partial h\tau_{xx}}{\partial x}+\frac{\partial h\tau_{xy}}{\partial y}\right)-\frac{\tau_{bx}}{\rho h}+f_{Cor}v \tag{1a}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-g\frac{\partial \eta}{\partial y}+\frac{1}{h}\left(\frac{\partial h\tau_{yx}}{\partial x}+\frac{\partial h\tau_{yy}}{\partial y}\right)-\frac{\tau_{by}}{\rho h}-f_{Cor}u \tag{1b}$$

where u and v are depth-integrated velocity components in x and y directions, respectively; t is the time; g is the gravitational acceleration; η is the water surface elevation; ρ is the density of water; h is the local water depth; f_{Cor} is the Coriolis parameter; τ_{xx}, τ_{xy}, τ_{yx}, and τ_{yy} are depth integrated Reynolds stresses; and τ_{bx} and τ_{by} are shear stresses on the bed and flow interface. The shear stress terms at the water surface are dropped since wind shear driven effect is not considered in this version of the model. Free surface elevation for the flow is calculated by the depth-integrated continuity equation:

$$\frac{\partial \eta}{\partial t}+\frac{\partial uh}{\partial x}+\frac{\partial vh}{\partial y}=0 \tag{2}$$

Suspended sediment transport is computed with the unsteady convection diffusion equation with sediments exchange near the bed surface as forcing terms:

$$\frac{\partial(hC_k)}{\partial t}+\frac{\partial(UhC_k)}{\partial x}+\frac{\partial(VhC_k)}{\partial y}=\frac{\partial}{\partial x}\left(\varepsilon_s h\frac{\partial C_k}{\partial x}\right)+\frac{\partial}{\partial y}\left(\varepsilon_s h\frac{\partial C_k}{\partial y}\right)+E_{bk}-D_{bk} \tag{3}$$

Eq. 3 and bed load transport continuity equation

$$(1-p')\frac{\partial z_{bk}}{\partial t}+\frac{\partial(\delta\bar{c}_{bk})}{\partial t}+\frac{\partial q_{bkx}}{\partial x}+\frac{\partial q_{bky}}{\partial y}=-E_{bk}+D_{bk} \tag{4}$$

the non-equilibrium transport equation

$$(1-p')\frac{\partial z_{bk}}{\partial t}=\frac{1}{L_b}\left(q_{bk}-q_{b*k}\right) \tag{5}$$

enable one to solve suspended sediment, bed load and bed change. Where the subscript *k* indicates sediment grain size class. The formula for determining the fractional bed load transport capacity and fractional suspended load transport proposed by Wu, Wang and Jia (2000) were applied for this investigation

3. STUDY REACH AND FLOW CONDITIONS

The navigation channel studied is a reach of 5.5km (3.3 mile) in Pool 7, about 15 miles upstream of Murray Lock & Dam. The reach consists of two bends, minor side tributaries and the Beaver Dam Island. There are many dikes installed in along the banks which confine the flow toward the center of the channel. Under the current conditions, dredging is needed to maintain the flow depth for navigation. The dike fields are redesigned for eliminating dredging and a deeper channel. Some of the dikes are planned to be raised in elevation or extended further toward channel center or both. Some additional dikes are also designed to confine the cross-over segment (Figure 1).

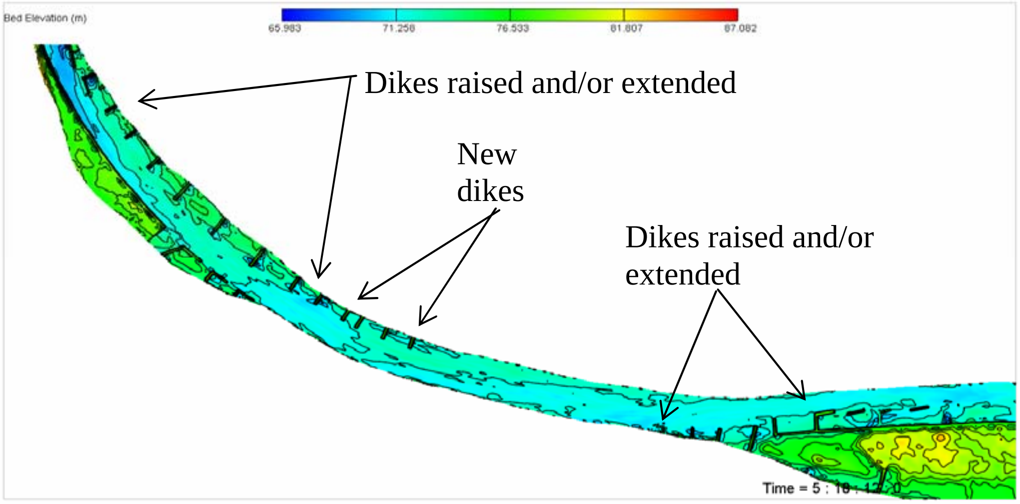


Figure 1. Bed topography and dike field in the concerned (partial) reach of Pool 7

The lock&dam system in Arkansas River has limited control to the natural process of channel flow, particularly high discharges. Figure 2 shows a 20 years (1985-2002) flow hydrograph with those lower than critical for moving sediment (<50,000cfs or 1400m^3/s) being removed. The peak flow is estimated to be a 50+ year event.

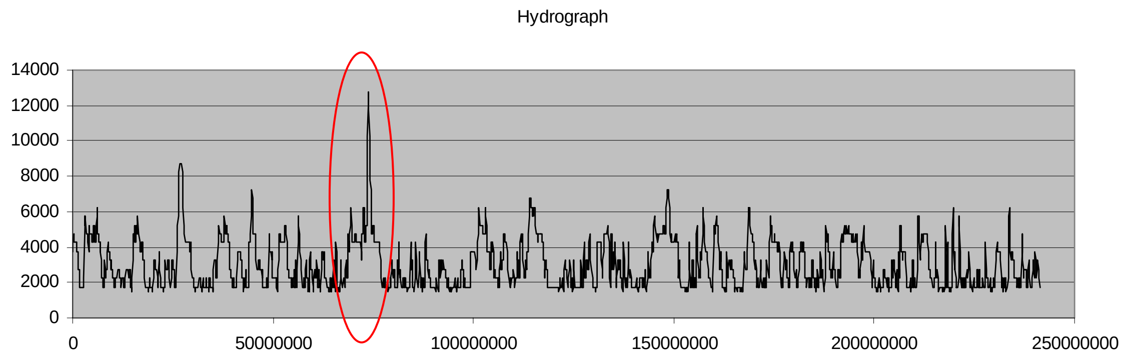


Figure 2. Hydrograph of observed flow from 1985 to 2004 with flows below 1400m^3/s removed.

Sediment in natural rivers are non-uniform, it is normally a mixture of different grain sizes. It is therefore desirable to simulate the fluvial processes with true, multiple sediment sizes. Since non-uniform sediment simulations require more time, uniform sediment simulation is often preferred whenever possible. The data in Figure 3a indicates that the sediment in Pool 7 is quite uniform. Since the study reach is away from the upstream and downstream locks, water surface elevation boundary conditions needed for flow and sediment simulation were obtained from a one dimensional model provided by USACE, Little Rock District.

The boundary conditions for the suspended sediment and bedload sediment conditions at upstream of the study reach are needed. According to the data available (Figure 3b), the relation of suspended sediment via flow discharge is approximately (with R^2~0.44)

$$C = 0.002Q^{0.4421} \tag{1}$$

This relation was used to generate the hydrographs for the suspended sediment and bedload sediment. The actual boundary conditions for the sediment have calibrated once more in the initial process of the simulations.

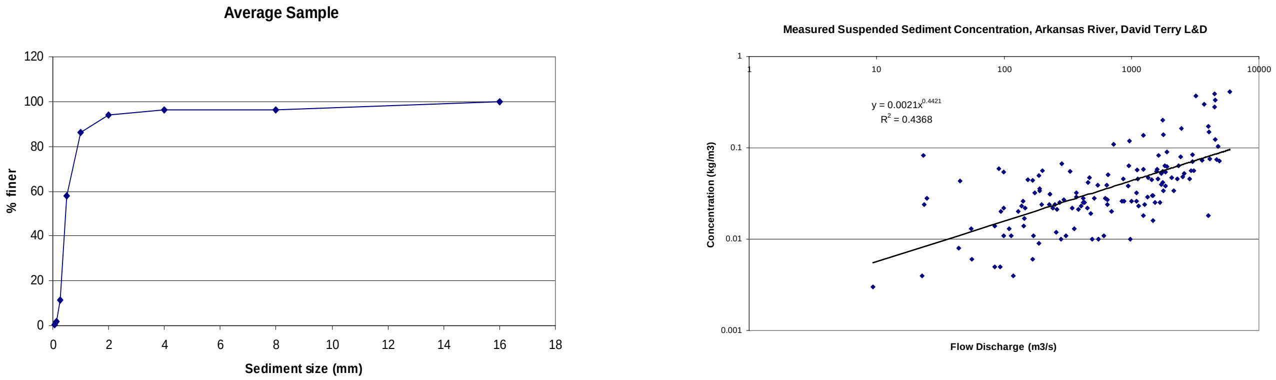


Figure 3a, Averaged bed material size distribution in Pool 7; 3b, The correlation of suspended load (kg/m3) and flow discharge (m3/s).

4. MODEL CALIBRATION AND VALIDATION

Figure 4 shows the calibration results of water surface elevation profile. It was found the Manning's coefficient best fit the 2D model (n=0.027) was slightly less than that for the 1D HEC-RAS model (n=0.03). It is due to that the 2D model resolves the flow distribution in the horizontal plane; the flow turbulence would also cause energy loss and resistance.

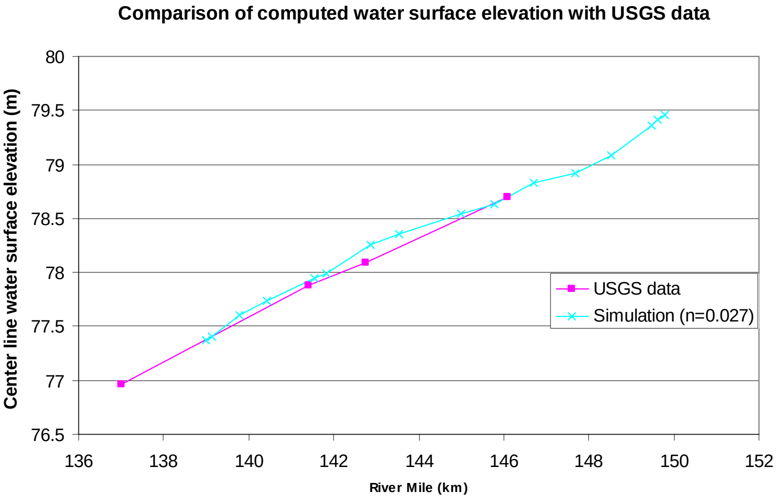


Figure 4. Calibrated water surface elevation profile in the study reach

Two computational meshes were generated for the main channel with dike fields (1204x56) and a mesh includes the flood plains over the banks (1204x94). The former was used for simulations with the channel forming discharge or less; the later was used for high flows including the 50+year flood. Figure 5 shows the simulated flow pattern in the main channel and dike fields. Since the dikes block the flow from being close to the bank, more flow is in the main channel. The dikes have different shape, length, and height, many of them are totally or partially submerged. The flow in the dike field is therefore very complicated. Most of the dikes were made of dump rocks with lumber posts aligned through the top of the rock. Therefore the dikes are permeable if the water level is higher than the rock top. These conditions made it difficult to specify the dikes' physical property with a depth averaged flow and sediment transport model. The computed flows in the field fields are expected to have large errors than those in the main channel.

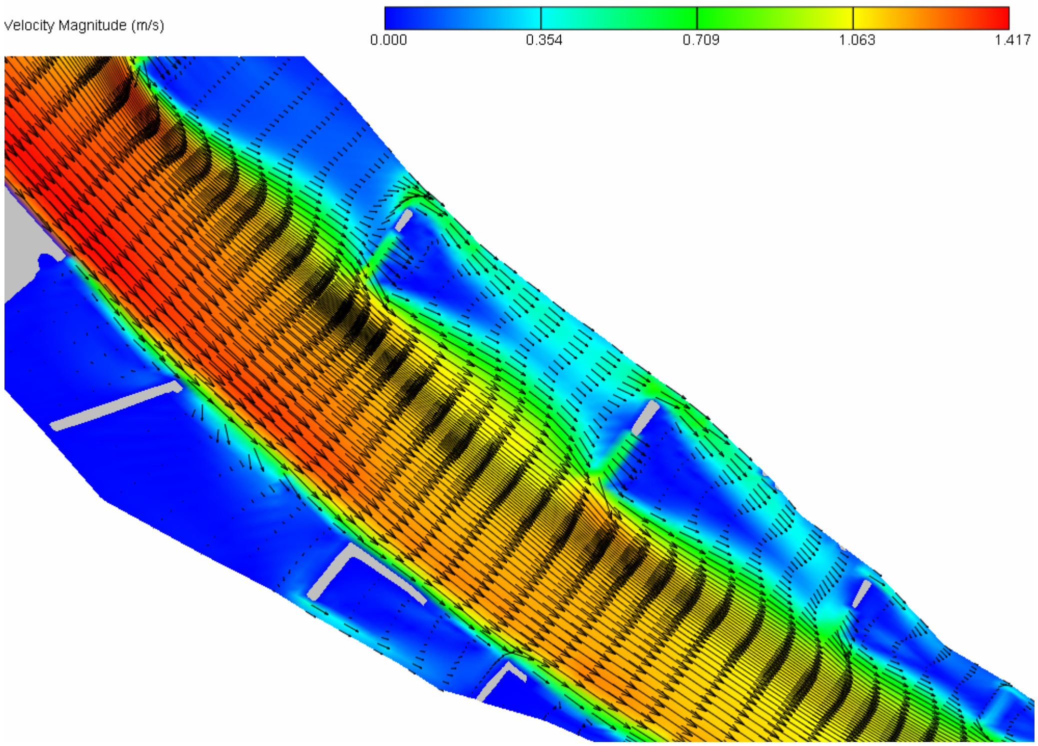


Figure 5, Simulated flow field in the main channel and dike field.

The hydrodynamic model was then validated by measured velocity data in 11 cross-sections. The flow discharges for these measurements range from 2,900~3,300m^3/s, with the average 3,100m^3/s used for validation. Figure 6a and 6b indicates comparisons of measured and simulated flow velocities in two of the surveyed cross-sections along the channel. It is noted that the velocity agreed very well in the main channel, but less accurate in the dike zones, due to the fact the flow pattern is more complicated in the dike zone and the exact formation and permeability of these dikes were unknown.

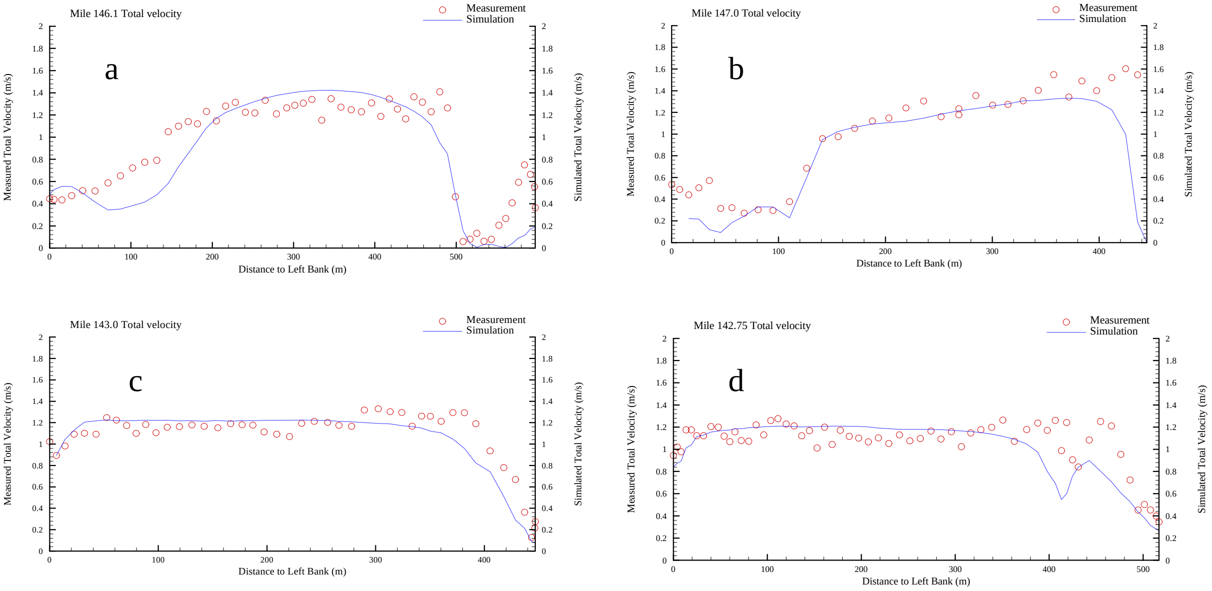


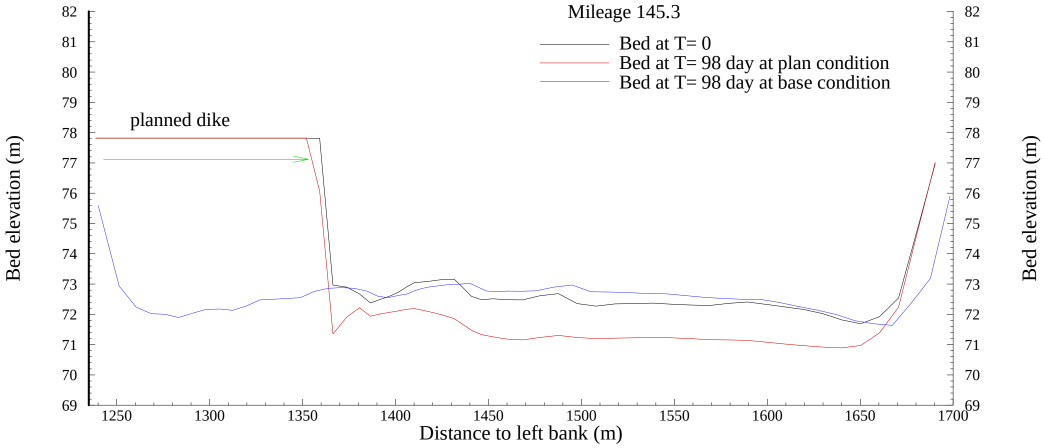
Figure 6. Comparisons of simulated and measured velocity in cross-sections

5. SIMULATION OF MORPHOLOGIC CHANGE

Channel morphology response to the adjustment of in-stream dikes are the objective of the numerical study. The validated flow model was then used in conjunction with the aforementioned sediment transport model to simulate the channel scouring. Since there is no data for the bed level change and measured sediment loads close to the study reach, sediment transport computation was calibrated qualitatively using the information of locations of dredging: under the base condition, most deposition should appear where the dredging are located. Although the sediment in the Pool 7 is quite uniform, tests were conducted to confirm the results of fractional sediment simulation and representative size (d_{50}) simulation are essentially the same. The bed change simulations were focused on those with bankfull discharge, one year equivalent flow and 50+year flood event (Fig.2). Both the planned condition with new dike fields and the current base condition were computed for all the needed flow conditions. In addition to calibration, the base condition simulations serve as references to the designed condition simulation.

The effectiveness of in-stream dikes are reflected by simulated channel bed erosion. Without the new dikes, bed responds to the flow just slightly, representing a relatively stable channel; the response is quick however where the new dikes were planned or the original dikes are modified (raised and/or extended). Figure 7 shows two cross-sections in which new dikes are installed. After the big flood, the bed change in these two sections was significant, the new dikes resulted in a lot more channel scouring which is needed for the planned navigation.

It was found in the simulation results that the cross-over segment of the study reach will have some deposition if the dikes in the upstream bend were modified. This is mainly because the width of the segment (~400m) is significantly larger than its dike controlled upstream bend (~250m). Simulation indicates that a new design setting some more dikes in this segment would reduce the amount of deposition. Final design was obtained from the simulation results with many trial locations and lengths of the dikes in this segment, which significantly reduced the problem of deposition in the cross-over.



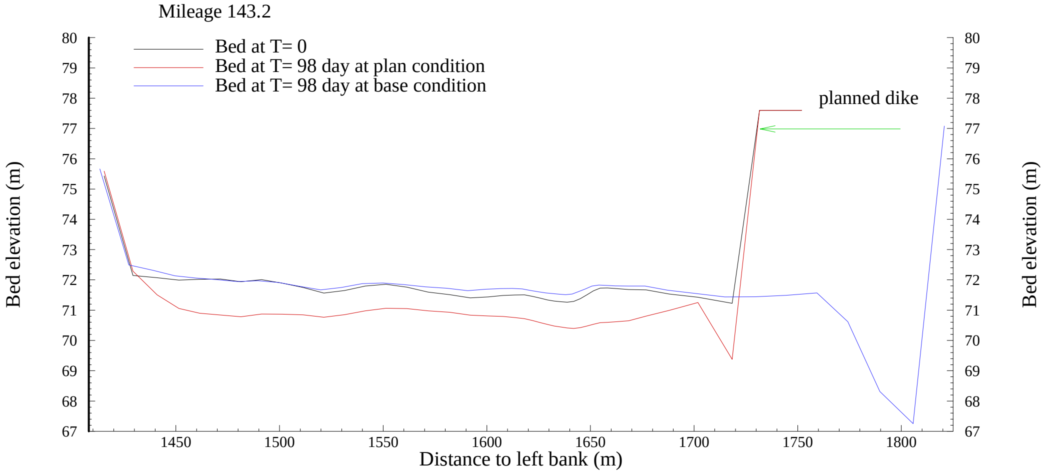


Figure 7. Comparison of simulated bed change in two cross sections.

6. CONCLUSIONS

To deepen the navigation channel so that more commercial cargos could be transported through inland waterways, some existing dikes are planned to be modified and some new dikes to be installed in the Arkansas River. This study investigated the effectiveness of the planned dikes in confining the waterway and causing additional channel erosion using computational modeling approach. CCHE2D model was used to simulate the flow, sediment transport and bed topographic change. The numerical simulations confirmed the original plan for dike field modification and helped to identify a more satisfactory plan for this project.

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