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ADH Sediment Module Testing

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PURPOSE: The Kate Aubrey reach of the Mississippi River, located north of Memphis, TN, was used as a test domain for the ADaptive Hydraulics (ADH) sediment transport routines. This 27.4 km (17-mile) stretch of river experiences times of wetting and drying and contains several nonerodable dike structures and revetments. This reach is a good test condition for a model since there are two dike configurations in its history, one that did not maintain a navigation channel and a second that, for the most part, did maintain a navigable channel. This results in a clear way to test the suitability of a model. Tests included single and multiple grain sizes for steady-state and 3-month hydrograph runs. ADH results correctly identified navigation shoaling problems in the first dike configuration and an essentially good navigation condition in the second.

A description of the sediment equation implementation in the two-dimensional (2-D) shallow-water module of ADH is given in this System-Wide Water Resources Program (SWWRP) Technical Note as well as the results and qualitative conclusions for the various Kate Aubrey river morphology simulations that were conducted.

BACKGROUND: ADH is an unstructured finite element package capable of modeling 2-D and 3-D shallow-water equations, 3-D Navier-Stokes equations, groundwater equations, and groundwater-surface water interaction. ADH solves the hydraulic and transport equations while adapting the mesh so that a coarse mesh can give results as accurate as a mesh with finer resolution. The advantage of ADH is its ability to dynamically refine the mesh in areas where it is not sufficient to accurately resolve the hydrodynamics/transport of the model. ADH refines the mesh based on transport and hydrodynamic equations. Therefore the mesh does not have to be any more detailed than the bathymetry. Another benefit is that one tool and file structure is used for several different applications. ADH has been used for 2-D shallow-water equations, 3-D Navier-Stokes equations, and groundwater problems. Two-dimensional noncohesive sediment transport is one focus of current additions to the ADH package and discussed in this technical note.

Sediment Equations and Implementation. Noncohesive sediment transport equations have been incorporated into the 2-D shallow-water equations of ADH. These equations are taken from accepted results and analyses by Van Rijn (1984), Garcia and Parker (1991), Cheng (1997), Christensen (1970), and others. The noncohesive sediment module is implemented according to Figure 1. Given the flow field, the suspended sediment concentrations, bed displacement, and grain-size distributions are calculated over time throughout the model domain.

This process can be used when simulating single and multiple grain sizes, as well as nonerodable surfaces.

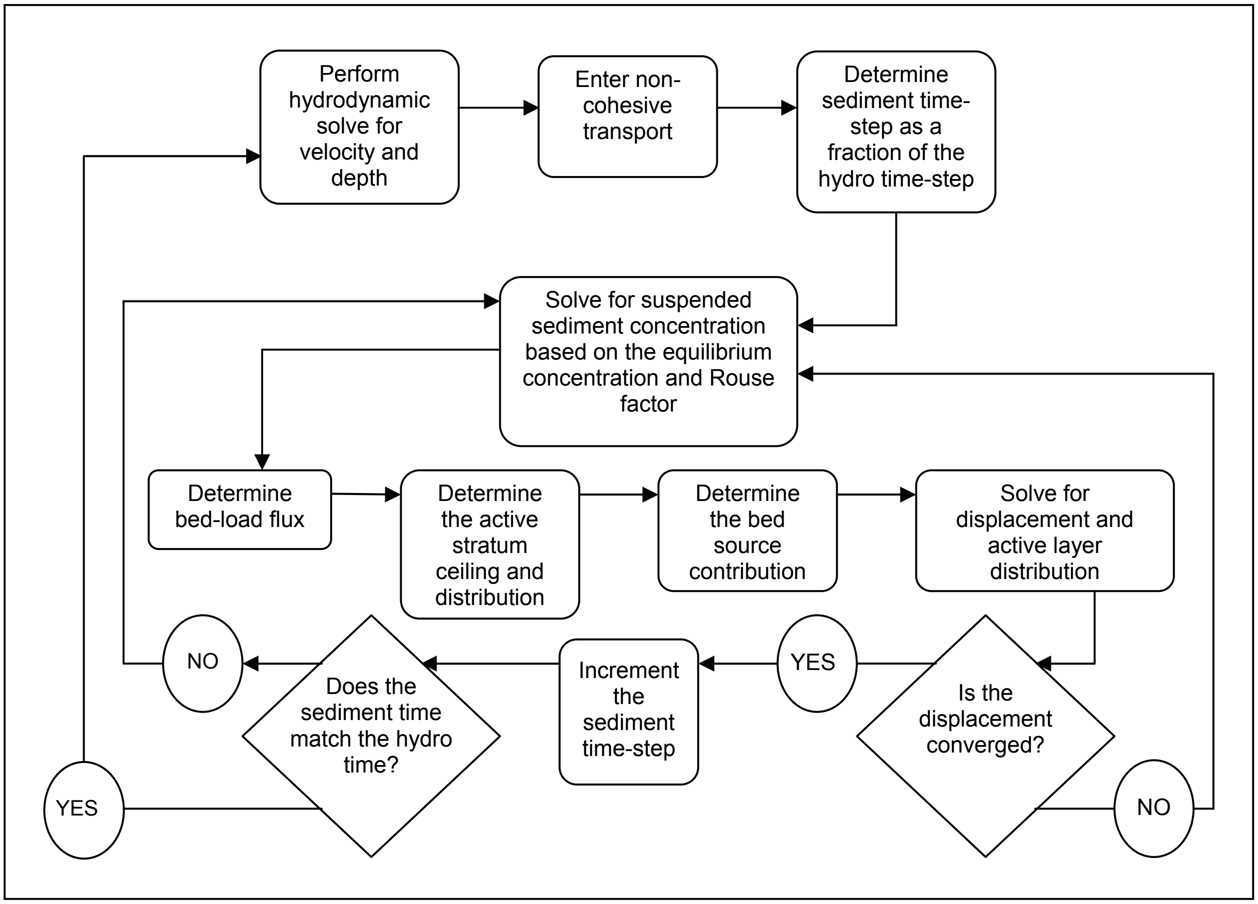

Figure 1. ADH sediment module flowchart

The hydrodynamics are solved first at the user-specified time increment. The sediment module is then entered and the sediment time-step is determined based on the specified number of sediment time-steps per hydrodynamic time-step given in the boundary conditions file. The hydrodynamic equations are not solved again until the sediment time matches the hydrodynamic time. Experience thus far indicates that a smaller time-step should be used for the sediment than for the hydrodynamics. The bed change and suspended sediment concentration field are iteratively solved until they converge. The sediment source from the bed is based on the equilibrium concentration (Garcia and Parker 1991) and the correction for 2-D model concentration is based on the Rouse (1938) term. These values are determined in relation to the shear stress felt by the bed, which is calculated using a modified Manning's formulation by Christensen (1970). The settling velocity for each grain size (Cheng 1997) along with its critical shear velocity for erosion according to Shields (Van Rijn 1984) is determined at the start of the simulation. The suspended concentration for each of the grain classes is determined globally using a finite-element scheme. These concentrations are then used to aid the calculations of the bed changes. The bed-load flux vector is calculated based on Van Rijn (1984) and limited to the bed material available. This term is corrected for the longitudinal and transverse bed slopes as well as the hiding factor (Karim et al. 1987) and the transport mode allocation parameter, also based on Van Rijn (1984). The Exner equation for mass conservation and displacement is then solved. The displacement (calculated as a change from the original bed elevation) and grain distributions are solved at each node, simultaneously for all grain classes. The bed is considered to be converged when the change in the displacement between iterations is less than the smallest grain diameter. The sediment routines, both suspended and bed, are repeated until the bed is converged. When the bed is converged, the water depth is adjusted according to the displacement so that a constant water-surface elevation is maintained. The velocities are also adjusted so that the flow rate is kept constant after the change in the bed. The bed layers and distributions are adjusted at the completion of a sediment time-step to reflect the changes due to the computed displacement and grain distributions. The sediment time-step is then incremented and the sediment process is repeated. When the sediment and hydrodynamic time-steps reach the same time, the hydrodynamic equations are solved at the new time and the cycle continues.

Kate Aubrey Test Case. The Kate Aubrey reach of the Mississippi River was selected as a test area for the ADH sediment equations. This test section was chosen since there are survey data for two channel training structure configurations. In nature, the 1975 configuration would not maintain an adequate navigation channel. In the 1999 configuration, the navigation channel was improved although some dredging is still required. These structure configurations had been designed by the U.S. Army Engineer District, Memphis. This 27.4 km (17-mile) section of the Mississippi River is located upstream from Memphis. The reach begins at river mile (RM) 802 and extends downstream to river mile 785, including several dike fields and areas of wetting and drying. Initial tests were made on the 1975 bathymetry and dike configuration during a constant high flow of 28,317 cu m/sec (1 million cu ft/sec). The bathymetry and dike configuration for 1999 was then developed and also modeled for the 28,317 cu m/sec (1 million cu ft/sec) flow rate. These tests were made using a single grain-size bed and a multiple grain-size bed. To further test the equation set, the 1999 bathymetry was used to simulate a hydrograph with a single grain size bed. The nonerodible structures are represented with a large, 2-m, grain-size. The single grain-size tests include one representative grain size, but also this large nonerodible grain.

By testing the two configurations it can be determined if the model would provide useful guidance for training structure designers. That is, will the model show that the 1999 configuration is an open navigation channel while the 1975 configuration is not. ADH would be deemed successful if it showed behavior sufficiently close to that which was observed such that a designer would make correct sediment transport based decisions.

Single grain runs. The representative grain size chosen for the single event was obtained from field data as the 50 percent finer diameter equal to 0.55 mm (see Figure 2). The maximum bed thickness available for erosion was 25 m, except on the nonerodable structures. The inflow conditions for flow were distributed across the upstream boundary, as were the estimated inflow concentrations. Figure 3 shows the bed elevations along the upstream inflow boundary and the corresponding fractions of the total flow as they were distributed across the boundary. As with a natural channel, the higher flows were found in the deepest areas and the lower flows were located along the shallower edges. The applied inflow concentrations were calculated within the model to balance the source/sink terms at the boundary (equilibrium concentrations).

The results of the high flow event for both bathymetry conditions are shown in Figures 4 and 5 for 1975 and 1999 respectively. The figures give the displacement at the end of 58 days of

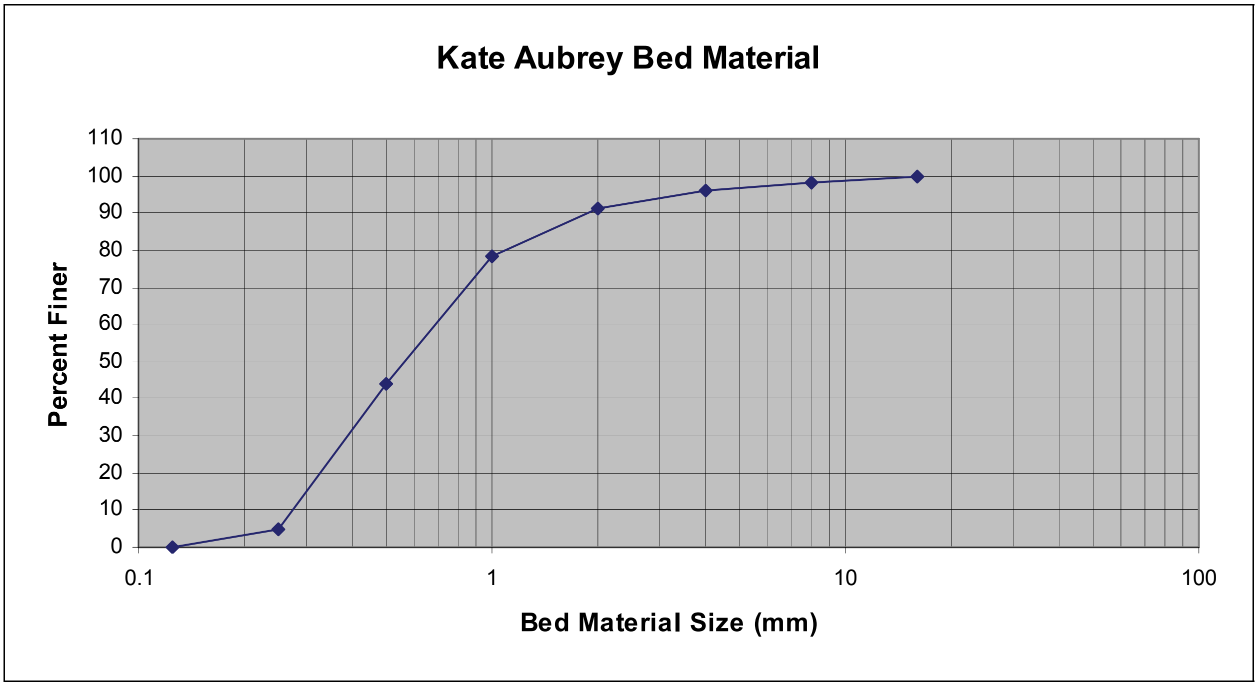

Figure 2. Bed material grain distribution for Kate Aubrey reach

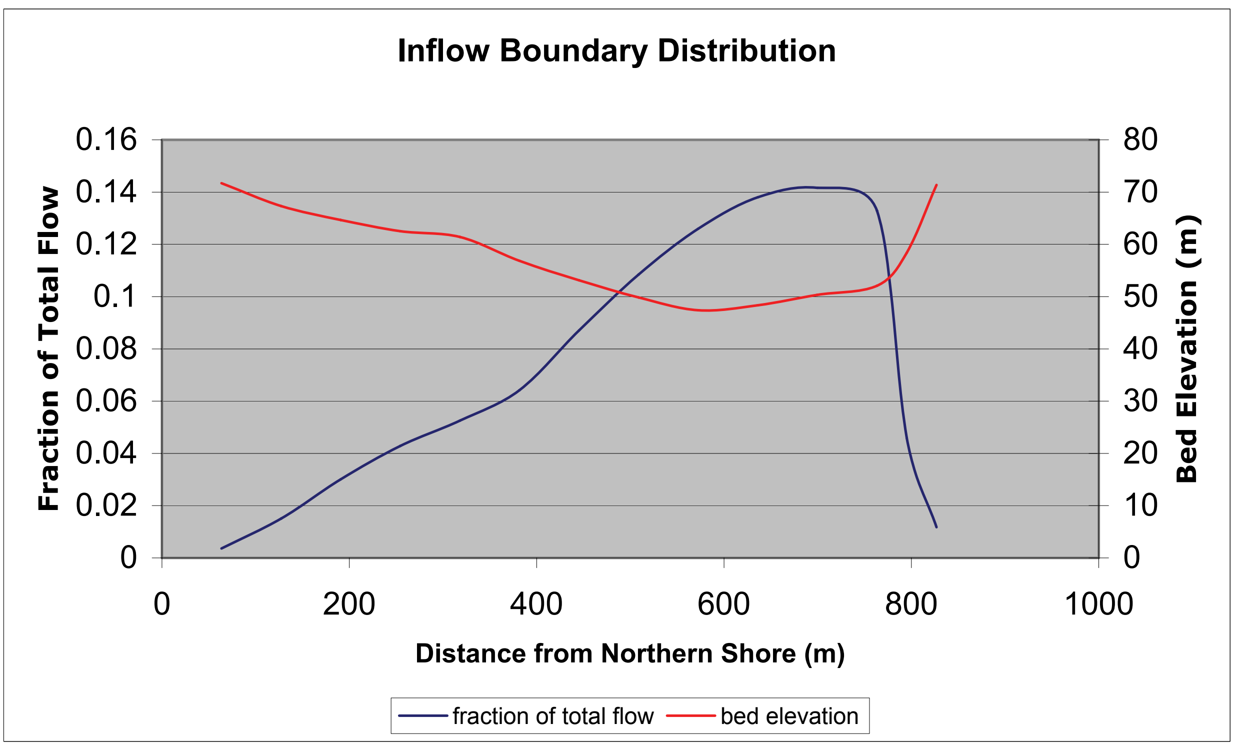

Figure 3. Inflow boundary flow distributions and comparison to bed elevation

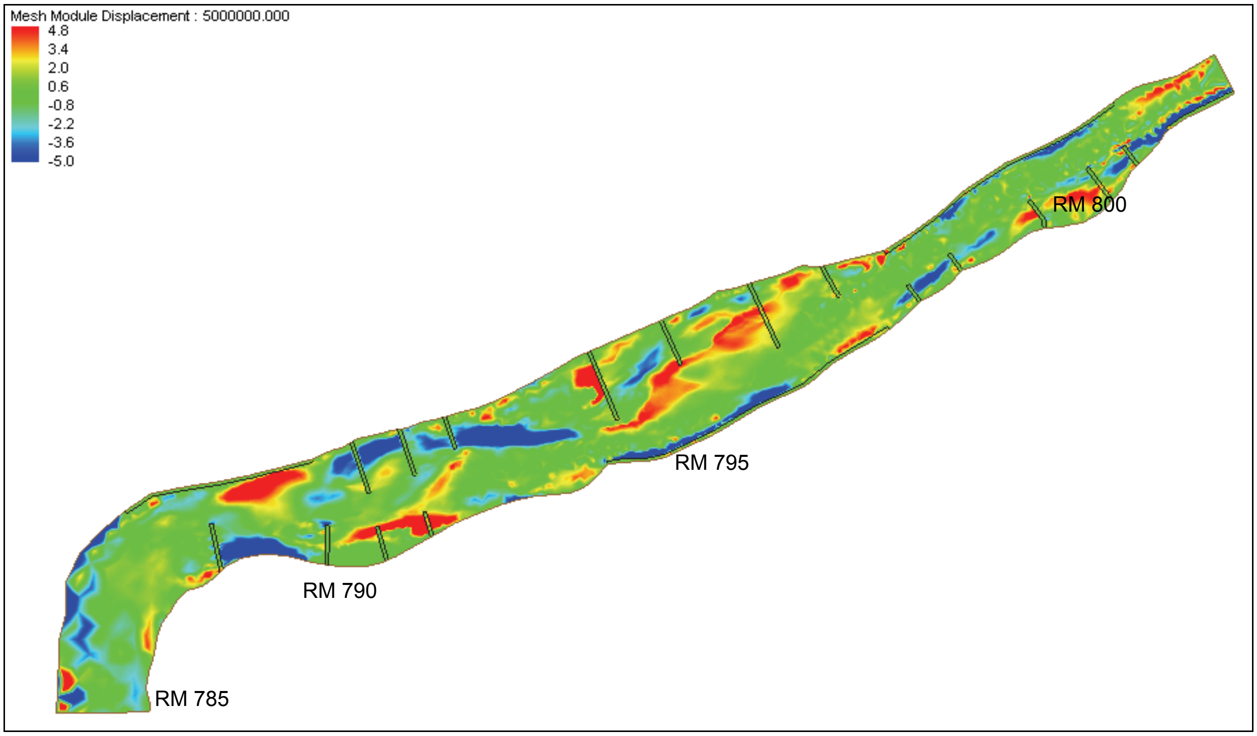

Figure 4. 1975 bathymetry displacement results at 58 days

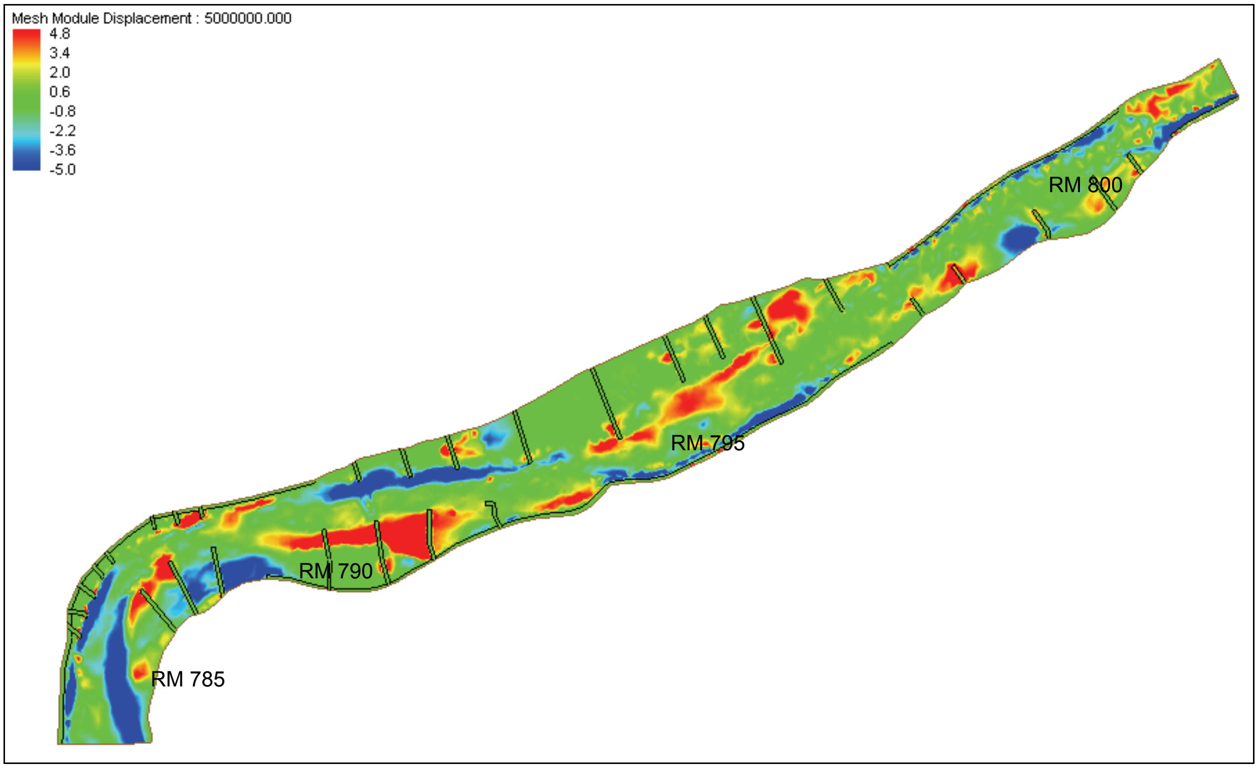

Figure 5. 1999 bathymetry displacement results at 58 days

simulation with the nonerodable dikes outlined in black. Red indicates higher deposition (positive displacement) and blue is indicative of higher erosion (negative displacement). It appears that the downstream section near river mile 790 of Figure 5 is not developing a channel under this high flow event. Given more time at high flow, the channel may eventually form, but the high flow is unlikely to last for such an extended period. The 1999 configuration in the model shows an open channel through all but the last bend. Figures 6 and 7 show the bed elevations at the completion of the 58-day runs. The improved channel formation for the 1999 dike configuration is apparent from the figures. The simulations appear to confirm that ADH would give good guidance for river design.

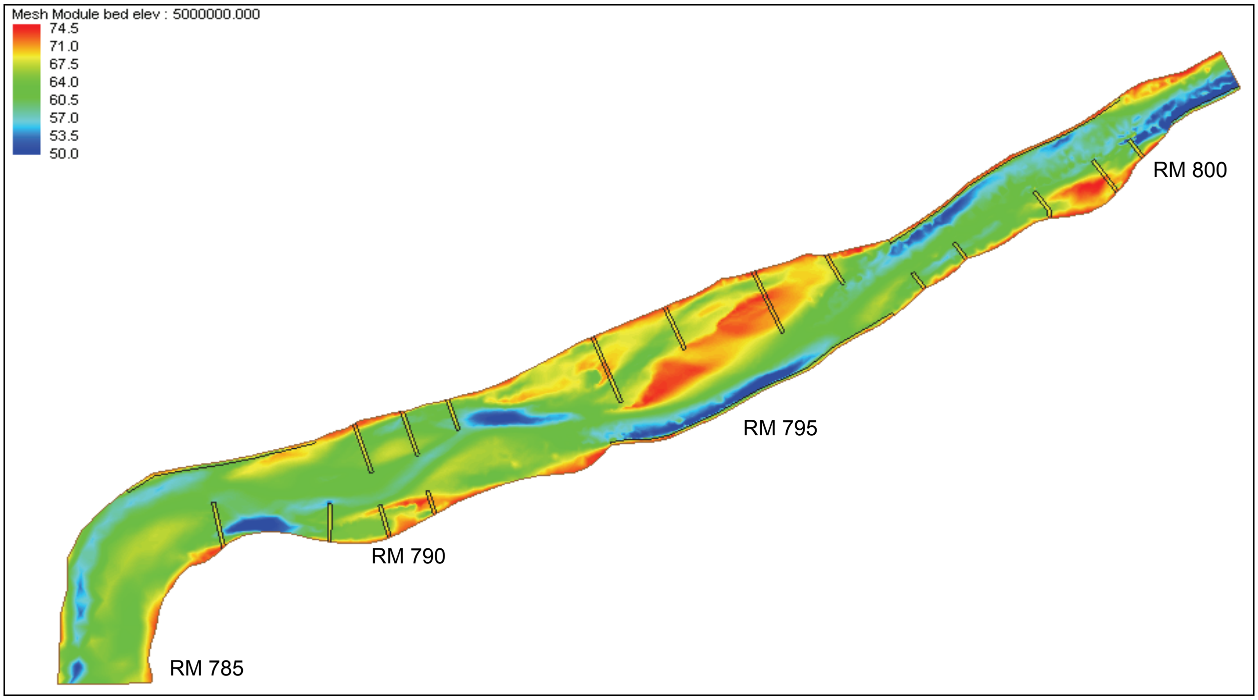

Figure 6. 1975 bathymetry bed elevations at 58 days

Multiple grain runs. The multiple grain-size runs were made to check the ADH model's capability to pick up more detailed distribution of the channel bed. The multiple grain-size simulation was made on the 1975 bathymetry and the 1999 bathymetry. Both runs included four grain sizes representative of the bed-material size distributions (see Figure 2). The sizes were grouped according to the American Geophysical Union's (AGU's) grain-size classifications, and the distribution for each class was based on the field data grain distributions. Table 1 gives the representative grain size (geometric mean) and the bed fractions for each size class applied to the model. The grain distributions were scaled to obtain a 100 percent total fraction due to the exclusion of the finest and coarsest grain sizes. The finest and coarsest 5 percent grain sizes were not included since the finest 10 percent is typically all wash load and the coarsest 5 percent is immobile. If too much erosion occurs, this top 5 percent size class can be included to further armor the bed. The same upstream flow conditions as with the single grain simulations were used. All four grain sizes were applied at the upstream boundary and also calculated within the model as in the single grain simulation. The nonerodable surfaces (the dikes and revetments) were composed only of the 2-m (6.6-ft) grains.

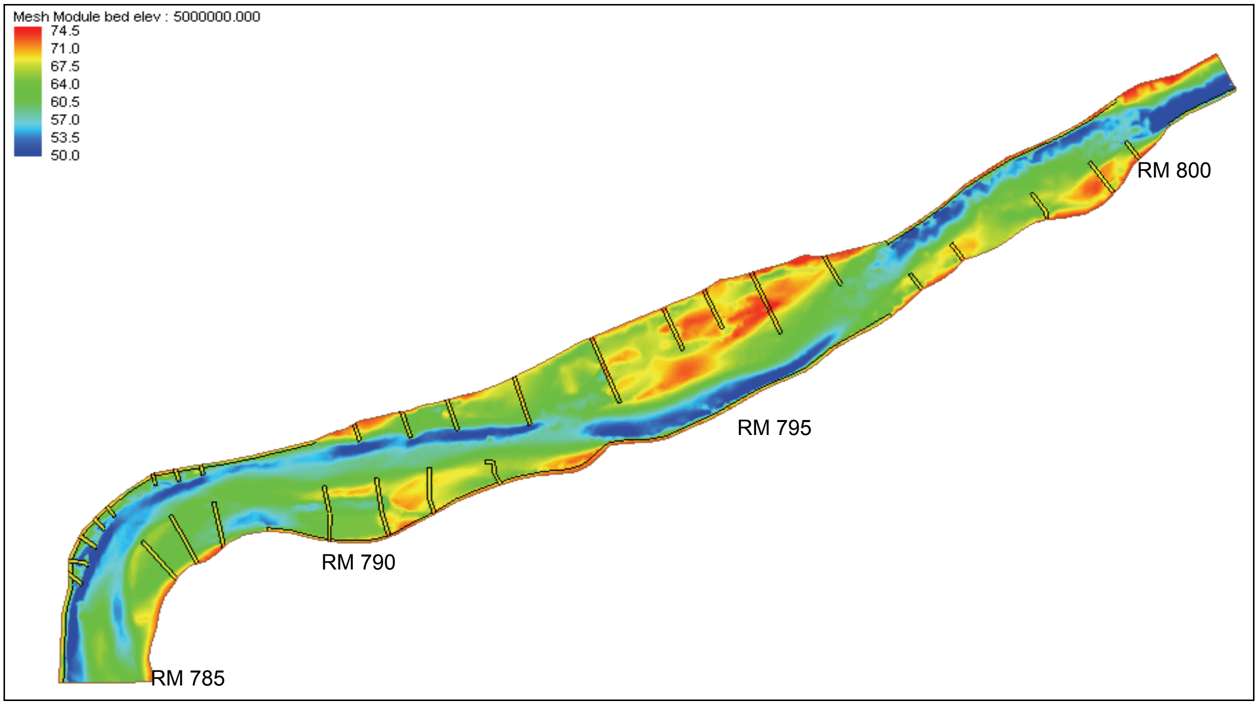

Figure 7. 1999 bathymetry bed elevations at 58 days

Table 1
Bed-Material Distribution Based on AGU Classification

AGU Scale	Size Range, mm		Geometric Mean	Percent Finer		Bed Fraction	Scaled Bed Fraction
Medium Sand	0.25	0.5	0.35	4.6	43.8	39.2	42.9
Coarse Sand	0.5	1	0.71	43.8	78.2	34.4	37.7
Very Coarse Sand	1	2	1.41	78.2	91.4	13.2	14.5
Very Fine Gravel	2	4	2.83	91.4	95.9	4.5	4.9

Figures 8 and 9 show the bed displacements for both channel configurations and Figures 10 and 11 show the bed elevations, all at the completion of 58 days. As seen with the single grain simulation, the 1999 condition develops a much more defined channel when compared to the 1975 condition. The displacement magnitude results from the multiple grain simulation are significantly different from those of the single grain case. For the 1975 condition, the deposition (positive displacement) again shows deposition at the shoal near river mile 792. The 1999 multiple grain-size simulation shows deposition in the channel near river miles 796 and 797, which is different from the single grain size runs. However, it occurs in an area with large depths and perhaps would not develop to the point of interfering with navigation.

The inclusion of multiple grains allows bed armoring to occur by eroding the finer grains and leaving the larger grains on the bed, as is apparent by the limited amount of erosion and deposition in the multiple grain simulation. The areas of deposition are dominated by the smallest two grain sizes, which can be seen in the middle section of the 1975 channel, as shown in Figure 12. The larger grain sizes are dominant in erosional areas of the channel where the

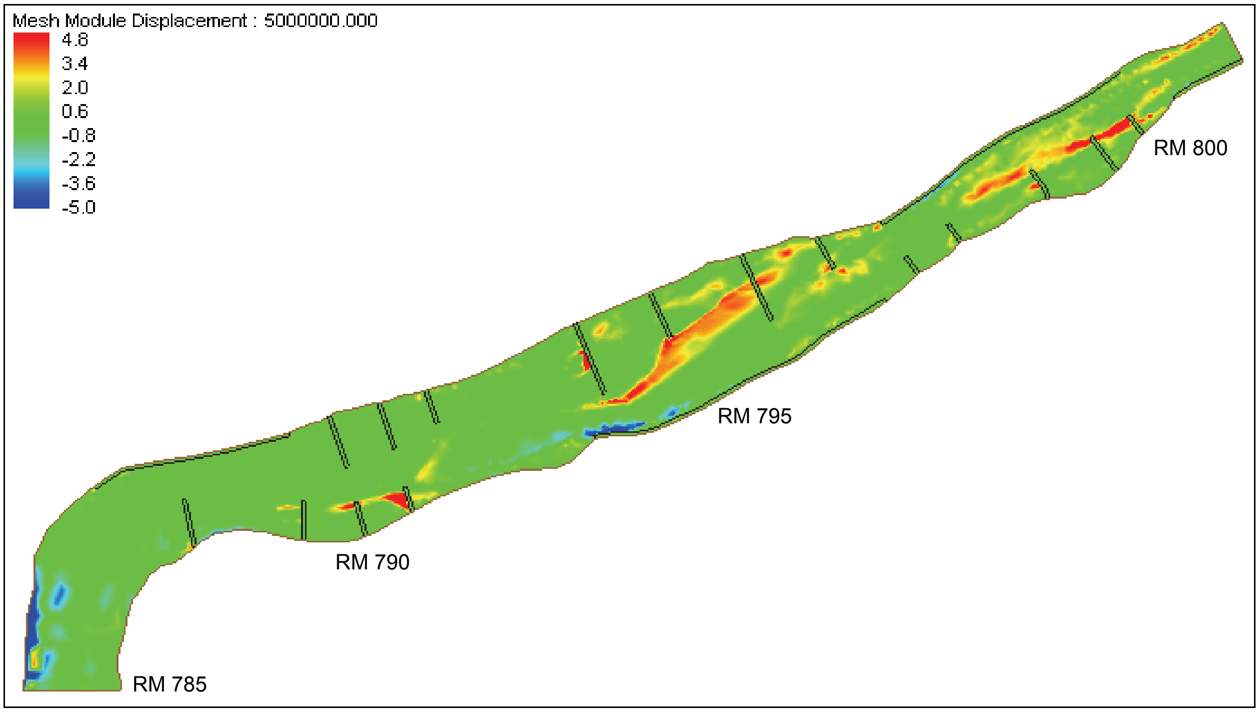

Figure 8. 1975 bathymetry multiple grain displacement results at 58 days

Figure 9. 1999 bathymetry multiple grain displacement results at 58 days

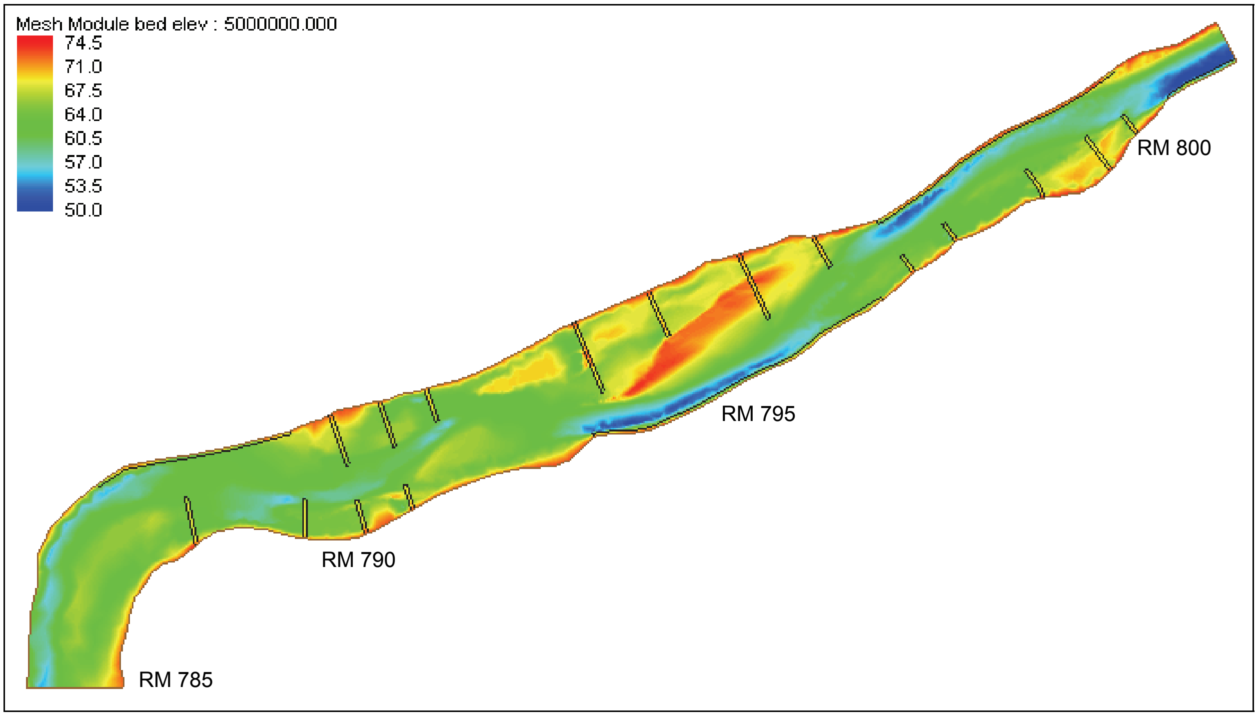

Figure 10. 1975 bathymetry multiple grain bed elevation results at 58 days

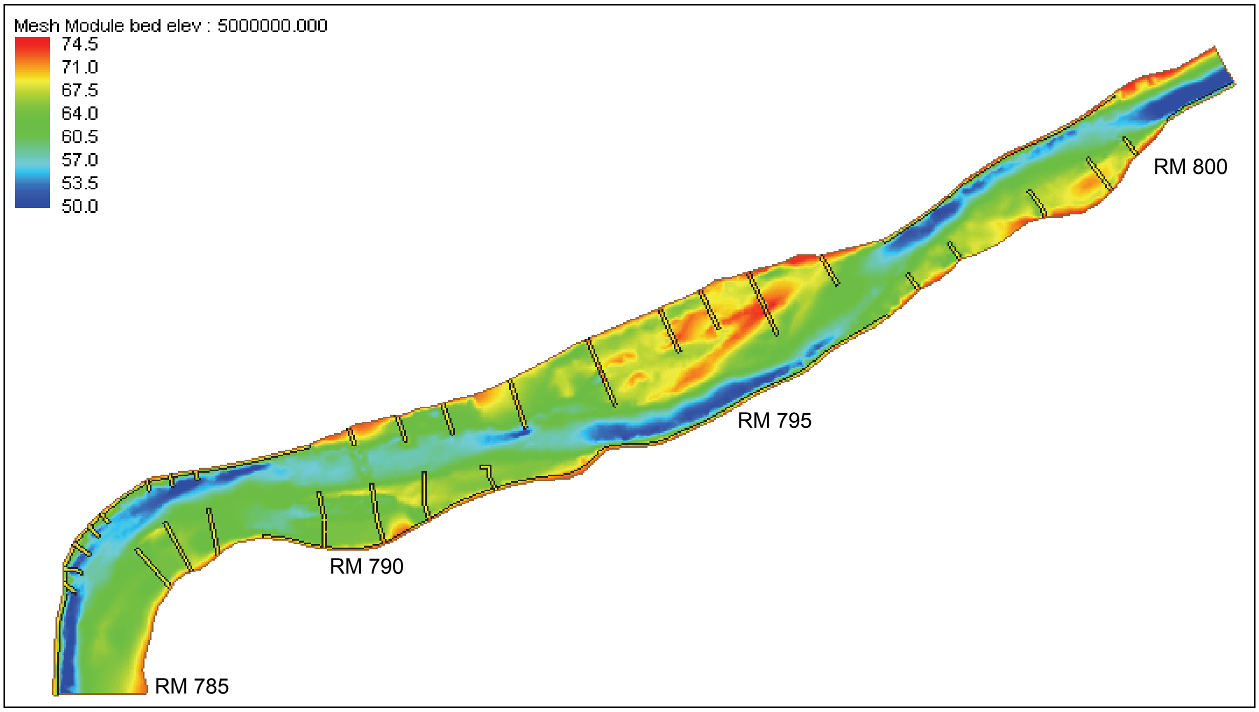

Figure 11. 1999 bathymetry multiple grain bed elevation results at 58 days

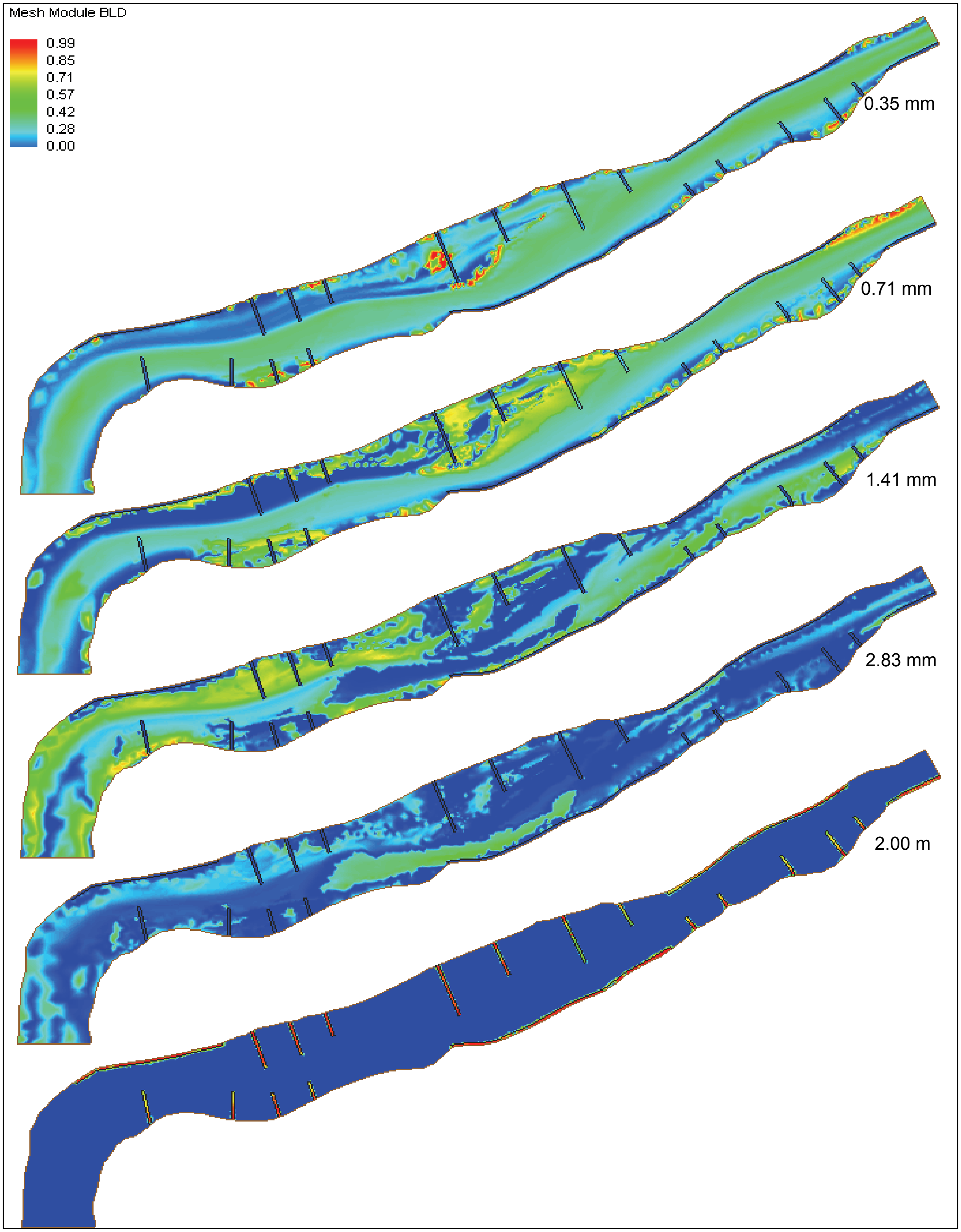

Figure 12. 1975 channel grain size fractions for top bed layer (finest to coarsest, top to bottom)

finer grains are eroded, leaving the larger grains in the bed. The 2.83-mm (0.1 in.) grain size began as 5 percent of the bed material. It has increased greatly in the large area of erosion seen in the channel about midway downstream. Figure 13 shows the bed displacements for the 1975 channel on a smaller contour scale of -0.1 m to 0.1 m (-0.32 ft to 0.32 ft) than Figure 9 so that the areas of erosion and deposition are more visible. Any areas in red will have higher fractions of the smaller grains and areas in blue will be composed of the larger grains. Areas with little bed displacement (those in the green shades) will display bed distributions close to those applied at the beginning of the run (43, 38, 14, and 5 percent for the grain classes, finest to coarsest respectively).

Hydrograph runs. A 3-month long hydrograph was simulated with the 1999 channel bathymetry and a single grain size. The boundary conditions were determined from the stage data and rating curve for Hickman, KY, and translated to the Kate Aubrey reach. The sediment concentration at the inflow was computed during the run so that the required concentration for no bed change at the boundary was applied. Due to the significant amounts of wetting and drying during the hydrograph, the boundary strings were modified to only include areas that consistently remained wet. That is, the boundary flow entering or leaving the model was restricted to only the part of the section that was flooded throughout the simulation. The rest of the model continued to wet and dry normally. An initial depth and velocity field was determined from a constant water-surface elevation condition by drawing the water down to the tailwater elevation for January 1st of the simulation year. The sediment was then included for the 0.55-mm (0.02-in.) grain size. The large grain was again included to prevent erosion on the nonerodable surfaces and help stabilize the model. Again the total bed thickness was 25 m (82 ft) except on the nonerodable surfaces, which were composed of 5 m (16.4 ft) of the large grains.

Figure 14 shows the upstream hydrograph used to drive the flow into the model domain. The model was run for approximately 3 months, i.e. 1 January 1999 to 5 April 1999. Figure 15 shows the bed displacements and Figure 16 shows the bed elevations at the end of 94.5 days. The hydrograph simulation shows less channel formation at the downstream section of the domain due to the lower and variable flow rate. There is also less deposition occurring in the midsection of the domain, probably because less sediment has been eroded from the channel and is not available to be deposited. As with the constant high flow rate boundary condition, the hydrograph simulation of the 1999 bathymetry and dike configuration yields a better channel formation than the 1975 configuration run at the constant high flow rate. If the channel does not form under the high flow rate or channel forming discharge, it will most likely not form when the model is driven with the hydrograph.

Through these series of tests, the 1975 channel configuration tended to produce a shoal in the area of river mile 792. This shoal is in the channel and would interfere with navigation. The 1999 channel configuration alleviated this problem and produced a more navigable channel in the model tests. The multiple grain size runs showed much less change in the bed elevation. Running a hydrograph during a high flow period showed less bed change than running a constant flow. These results are qualitatively similar to the conditions that have been seen in the field. The ability of ADH to qualitatively reproduce field sediment results for several various run conditions, such as constant and variable flows as well as single and multiple grain beds and inflows, has been demonstrated successfully through this series of tests.

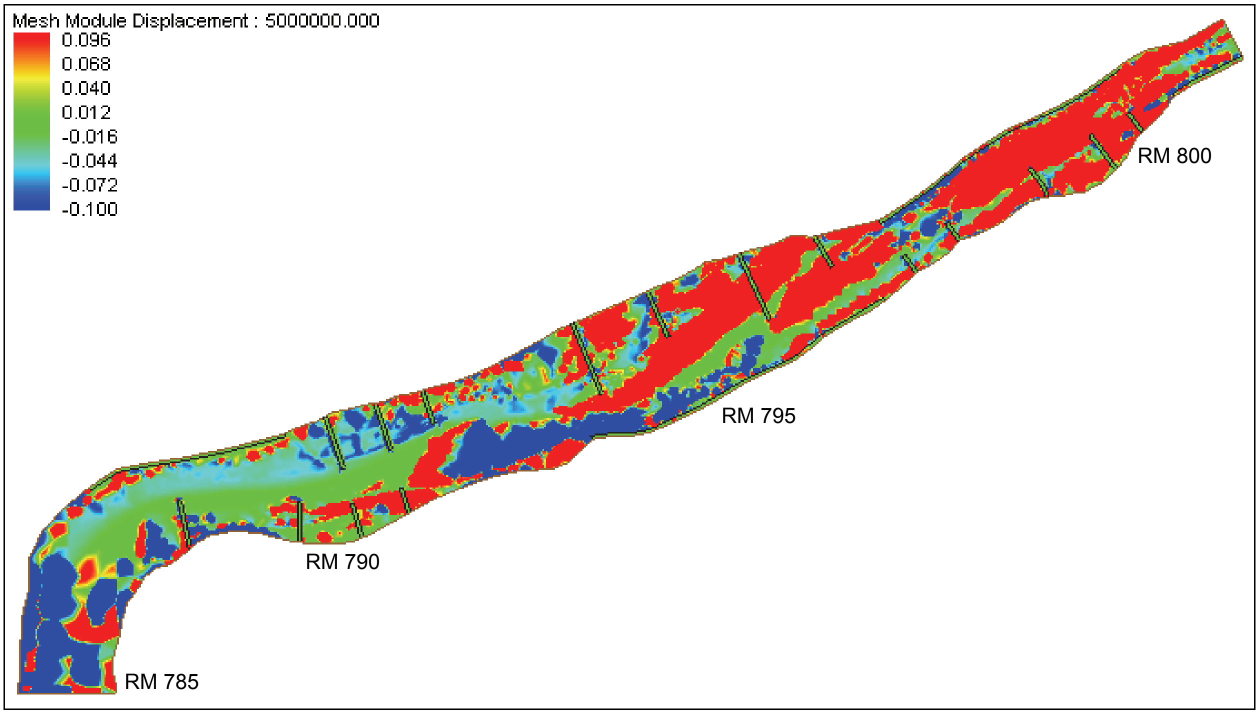

Figure 13. 1975 bathymetry multiple grain bed displacement results at 58 days, contoured -0.1 m to 0.1 m (-0.32 ft to 0.32 ft) for help in viewing Figure 12.

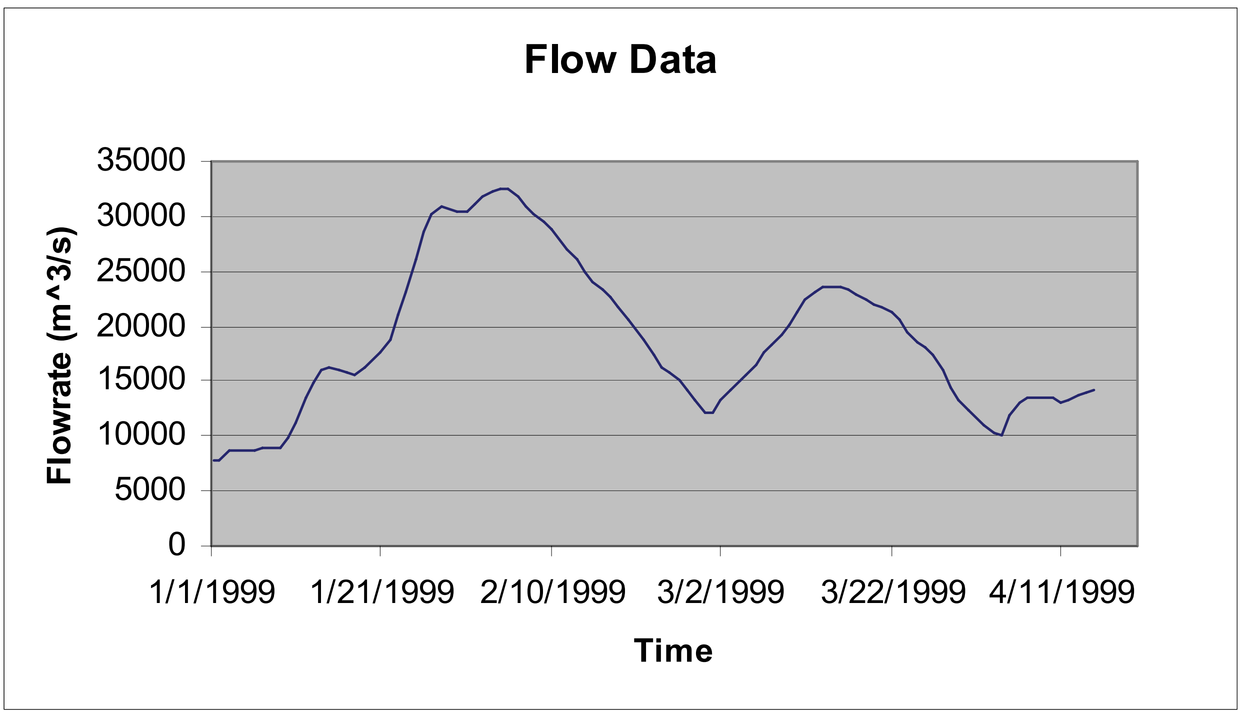

Figure 14. Upstream inflow hydrograph for 1999

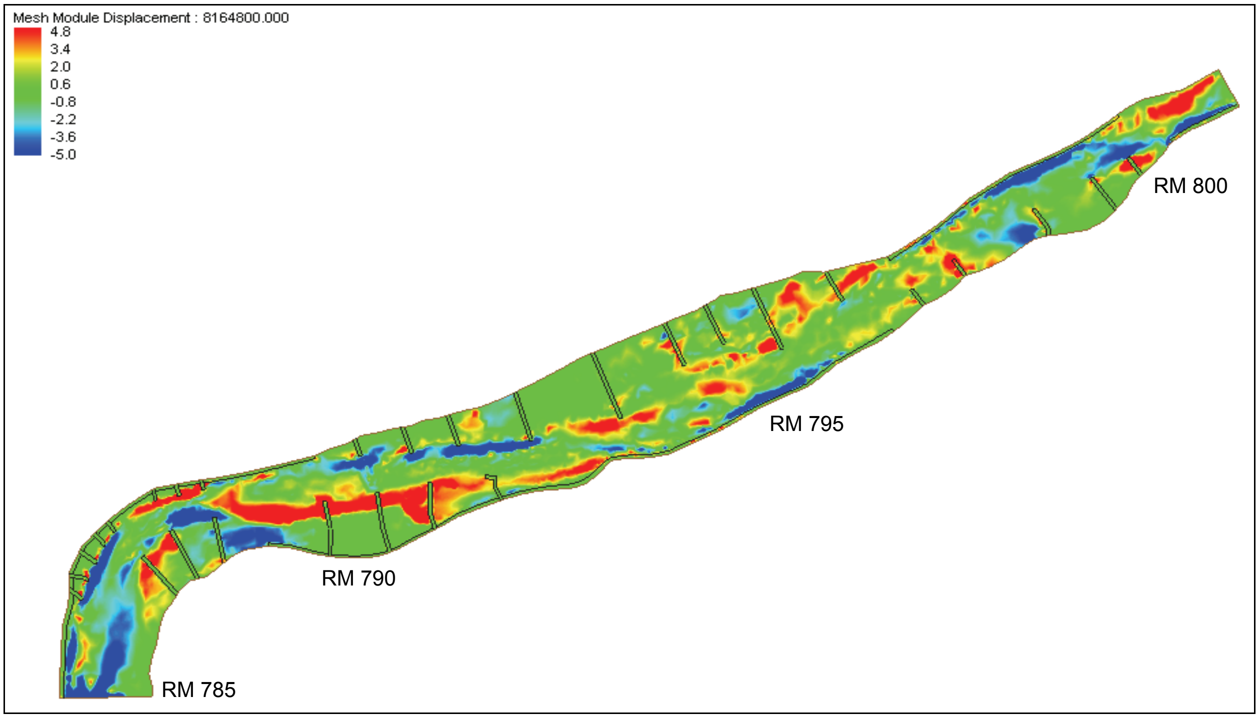

Figure 15. 1999 channel displacement results for single grain hydrograph run at 3 months

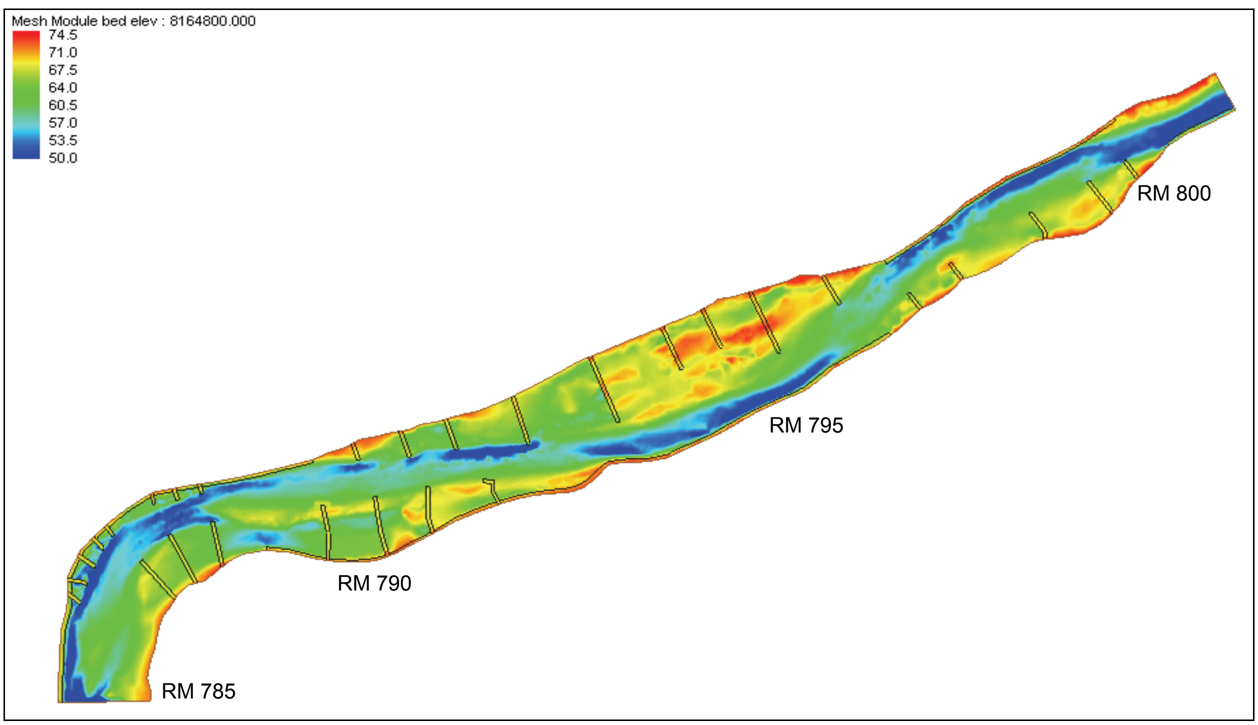

Figure 16. 1999 channel bed elevations for single grain hydrograph run at 3 months

ADDITIONAL INFORMATION: This technical note was prepared by Jennifer N. Tate and Dr. R.C. Berger, Coastal and Hydraulics Laboratory, U.S. Army Engineer Research and Development Center. The study was conducted as an activity of the Regional Sediment Management/River Basin Morphology Modeling and Management-Multidimensional Sediment Model work unit of the System-Wide Water Resources Program (SWWRP). For information on SWWRP, please consult https://swwrp.usace.army.mil or contact the Program Manager, Dr. Steven L. Ashby at Steven.L.Ashby@erdc.usace.army.mil. Questions about this technical note can be addressed to Ms. Tate at Jennifer.N.Tate@erdc.usace.army.mil or Dr. Berger at Charlie.R.Berger@erdc.usace.army.mil. This technical note should be cited as follows:

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