Predicted Sediment Transport for Pool Lowering at Nolichucky Dam

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ABSTRACT:

Nolichucky Dam is owned by the Tennessee Valley Authority (TVA) but predates that agency as the dam was completed in 1913 and acquired during the Second World War. In the 1970s TVA halted power generation and let the reservoir fill with sediment. In order to perform an environmental (NEPA) review and coordinate with the state environmental agency, TVA needed to activate the controlled spillway gates to lower the pool below the uncontrolled spillway level to perform inspections. TVA needed to know if the stored sediment would be expected to move during the spill, and if so, what would be the volume mobilized and resulting concentrations. TVA tasked WEST Consultants (WEST) to evaluate sediment transport through Davy Crockett Reservoir and over Nolichucky Dam during the planned spillway operations. WEST developed a numerical model using the two-dimensional (2D) hydrodynamic and sediment transport model SRH-2D. Several modeling challenges were encountered as described in the paper. Model results indicated that the existing velocities and shear stresses in the reservoir are very low and are not strong enough to move significant amounts of sediment for flow rates expected during lowering both for existing conditions with the gate closed and after the gate is opened, although there is a small increase in concentration immediately after gate opening. The predicted volume of sediment scoured during lowering was approximately two orders of magnitude less than the amount expected to be moved with the gate closed during an approximately yearly flow event.

1 INTRODUCTION

1.1 *Purpose*

WEST Consultants, Inc. (WEST) was tasked by the Tennessee Valley Authority (TVA) to evaluate sediment transport through Nolichucky Reservoir on the Nolichucky River in eastern Tennessee, USA, upstream of Nolichucky Dam. The purpose of the study was to provide scour and sediment loading predictions resulting from planned spillway operations, in support of spillway inspections.

1.2 *Study Location*

Nolichucky Dam is a concrete dam on the Nolichucky River near Greeneville, Greene County, TN, USA. The dam is located about 46 miles (74 km) upstream from the Nolichucky River mouth and impounds Nolichucky Reservoir (Davey Crockett Reservoir) which extends about 6 miles (9.65 km) upstream of the dam. Nolichucky Dam is a concrete gravity overflow type dam that is 94 feet (28.6 m) high and 482 feet (147 m) long. The dam has an ogee-type spillway with a vertical lift gate that is 25 feet (7.6 m) wide and 10 feet (3 m) high. The elevations of the dam crest and the gated spillway crest are 1,240.9 feet (378 m) and 1,230.9 feet (375 m), respectively.

1.3 *Approach*

In order to evaluate sediment transport through Nolichucky Reservoir during the planned spillway operations, WEST developed a numerical model using the two-dimensional (2D) hydrodynamic and sediment transport model SRH-2D (USBR, 2017), and the Surface-water Modeling System SMS (Aquaveo, 2014). SRH-2D solves the 2D dynamic depth-averaged St. Venant equations, and allows for simulation of non-equilibrium sediment transport. SRH-2D is a coupled model, that is, at every time step the hydrodynamics is computed first, then sediment transport is computed based on the local and instantaneous values of shear stress, and finally the bed is adjusted to take into account computed erosion or deposition. This cycle is repeated for the following time steps.

Non-equilibrium sediment transport is expected to occur during hydraulic transients, such as during the opening of a gate, when unsteady flow conditions are dominant. The numerical model was developed in order to include the area of Nolichucky Reservoir that may be subjected to erosion from the planned spillway operations. The Nolichucky Dam spillway was set as the downstream model boundary and the upstream model boundary was set approximately 1 mile (1.6 km) upstream from the dam. The model length of 1 mile was based on the fact that sediment accumulation is principally in the downstream section of the reservoir, in proximity to the gate.

Model development involved the following steps:

1. Acquisition and clean-up of bathymetric data for Nolichucky Reservoir.
2. Development of a numerical grid with cell sizes ranging from 3 to 15 feet (1 to 4.6 m).
3. Development of appropriate boundary conditions downstream and upstream to include inflows of 1,900 cubic feet per second (cfs) (53.8 m^3/s) and 13,000 cfs (368 m^3/s).
4. Development of a conceptual *surface model* to characterize the hydraulic roughness of surface materials of the lake bed and bank.
5. Development of a conceptual *subsurface model* to characterize the different sediment types in the lake bed and banks, such as non-cohesive sand and cohesive silt and clay.

Limitations of the present analysis include:

1. Because of safety issues, the bathymetry within 80 feet (24.4 m) of the gate could not be collected. This uncertainty is expected to affect sediment transport near the dam. Sediment transport uncertainty was assessed by assuming a constant elevation bathymetry upstream of the gate.
2. 2D modeling focused on the first mile of Nolichucky Reservoir upstream of the dam. The rest of the lake was modeled based on the available Elevation-Storage curve from 1970. This limitation is expected to affect the duration of the transient after the gate is fully open. With the existing Elevation-Storage curve, the transient after the gate is fully open lasts about 24 hours.

2 DATA AVAILABILITY AND MODEL DEVELOPMENT

2.1 *Nolichucky Reservoir Numerical Grid*

A sonar bathymetric survey covering the Nolichucky Reservoir bed from just upstream of the dam to about one mile (1.6 km) upstream was conducted by TVA on March 16 (Figure 1). Due to the shallow depths of the lake, the sonar head was maintained near the water surface and this caused air bubbles that led to some noise in the data (TVA, 2018a). In order to obtain a smooth bottom, WEST removed the spikes by averaging the data based on nearby points. The sonar survey revealed that sediment accumulation at an elevation of 1,228 feet (374 m) exists around 100 feet (30.5 m) upstream of the dam.

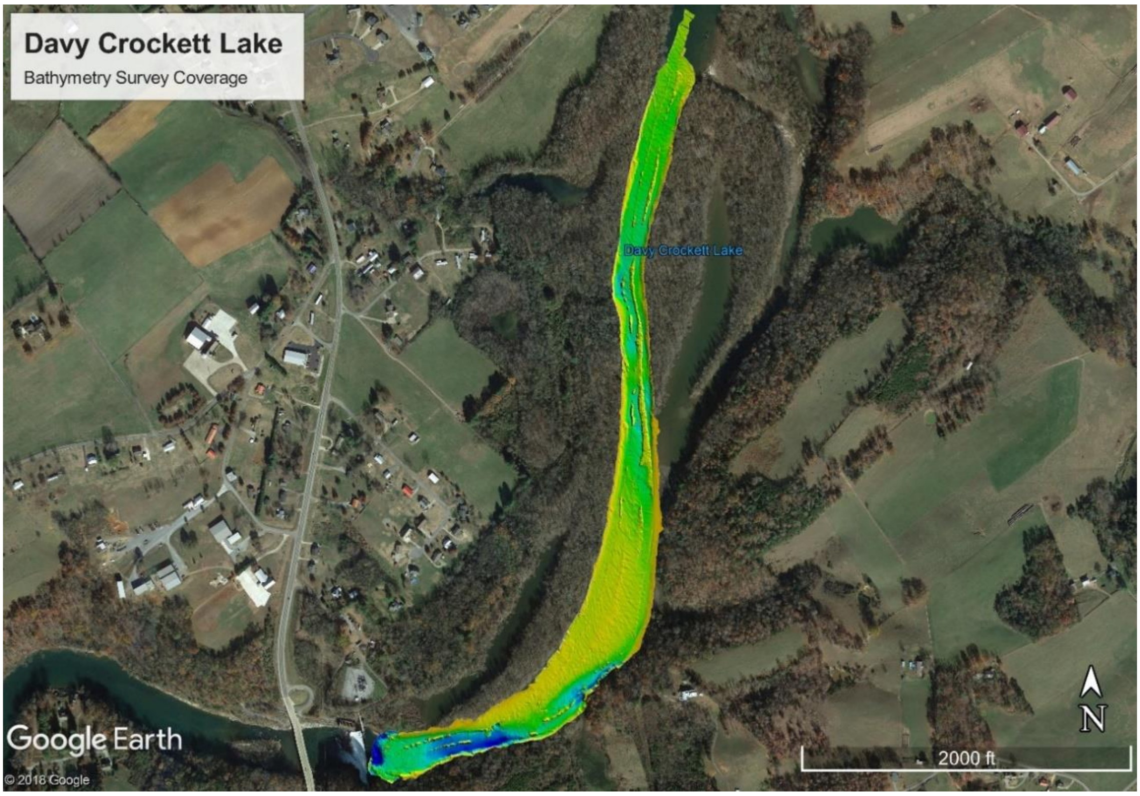

Figure 1. Coverage of bathymetric survey of Nolichucky Reservoir provided by TVA (darker colors represent lower elevations as shown in subsequent figures.

Based on the 2018 and older bathymetry and dam drawings, WEST developed a numerical grid for about 1 mile (1.6 km) of Nolichucky Reservoir. After initial tests, the cell size was set to 15 feet (4.6 m) and an area with refined 3-foot (1 m) cells was created near the spillway to account for the strong curvilinear flow. Two grids were developed to simulate the different gate conditions: Closed Gate and Open Gate (Figure 2). An additional grid with a flat bathymetry of 1,228 (374.3 m) (the elevation of sediment accumulation 100 feet or 30.5 m upstream of the dam) was created in order to assess the uncertainty in bathymetry near the dam.

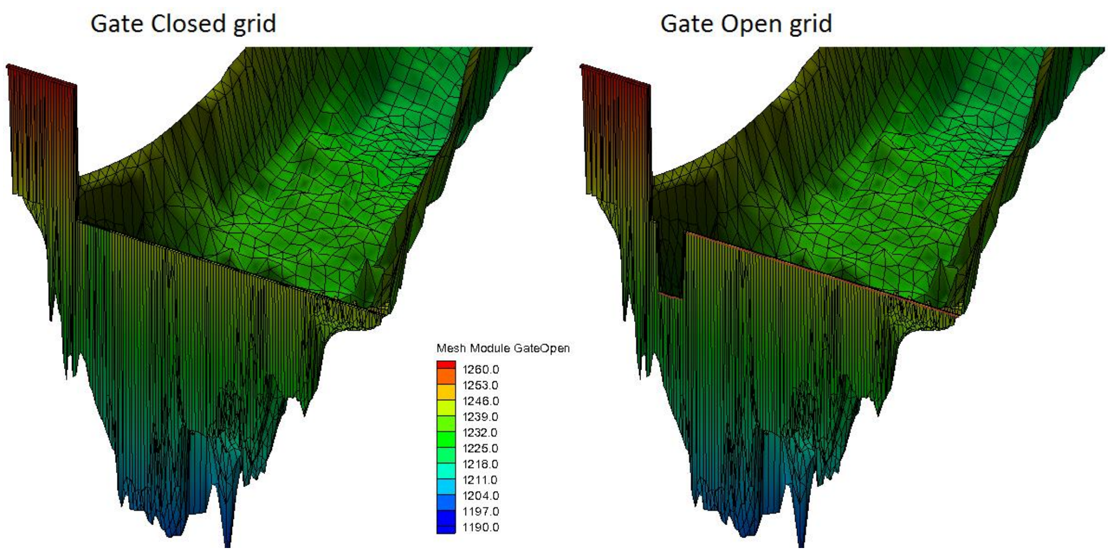

Figure 2. Nolichucky Reservoir numerical grids with gates closed and open

2.2 *Nolichucky Dam Rating Curves*

Rating curves for the Nolichucky Dam spillway and gate were provided by TVA and were used develop boundary conditions for the model (Figure 3). Based on discussions with TVA, the upstream boundary condition was set as a constant inflow of 1,900 cfs (53.8 m^3/s) and two different boundary conditions were set at the dam: the rating curve with the gate closed and the rating curve with the gate open.

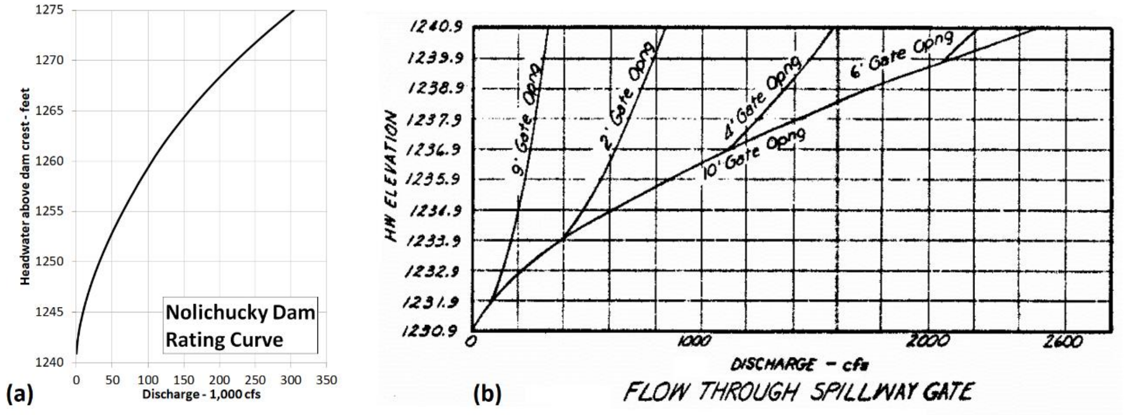

Figure 3. Rating curves for Nolichucky Dam: (a) spillway; (b) gate.

2.3 *Nolichucky Reservoir Bed and Bank Sediment*

The volume of the sediment wedge that accumulated in front of Nolichucky Dam was estimated to be about 2,600,000 ft^3 (73,624 m^3). Sediment data from lake bed and bank samples were provided by TVA (2018b) and included Atterberg limits, soil classifications and particle size analysis of 16 different sampling locations (12 in the river bed and 4 on the right bank). The sediment properties were used to develop different bed zones in SRH-2D and sediment layers up to a depth of 10 feet (3 m). The roughness coefficients were estimated based on Chow (1959) and the sediment grain size distributions. The transport rate of sand and silt was estimated using the total load formula of Engelund-Hansen (1967). The erodibility properties of the fine sediment were based on Briaud et al. (2008) and the soil classifications. The fine graded sediment samples (cohesive sediment) were found to be within the high and low plasticity silt range (MH and ML, respectively) and their erodibility properties are shown in Figure 4.

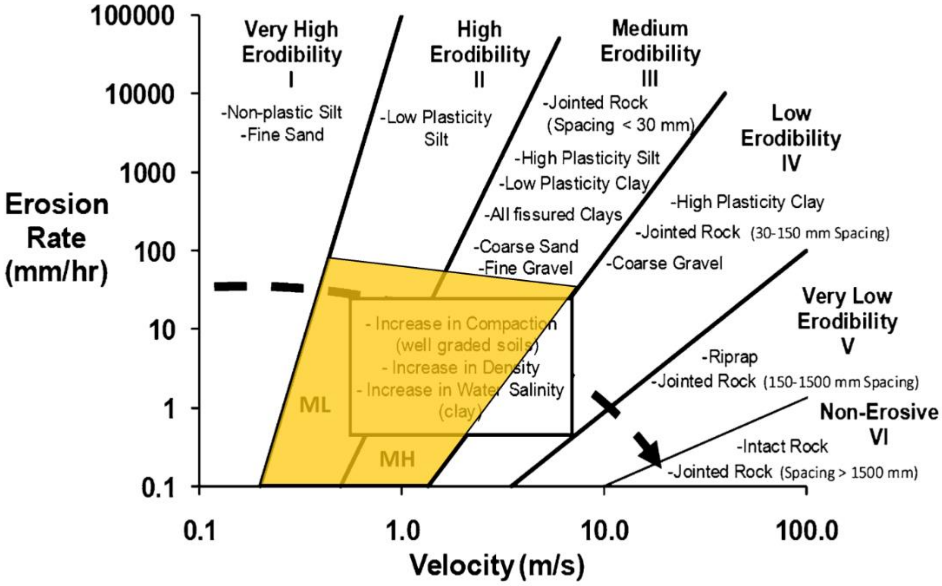

Figure 4. Erodibility categories for Nolichucky Reservoir (yellow). Chart after Govindasamy et al., 2013.

3 RESULTS

3.1 *General*

SRH-2D model results were visualized for the lake area in front of Nolichucky Dam. In addition, results were plotted along the thalweg of the lake (shown in Figure 5). Results included several hydraulic and sediment transport parameters which are discussed in the following sections. In the following figures, results from four conditions are compared:

1. *Closed Gate – Q = 1,900 cfs (53.8 m^3/s)*
   This case represents the existing conditions in Nolichucky Reservoir, with a constant upstream flow of 1,900 cfs and the gate closed. This case models low-flow conditions.
2. *Closed Gate – Q = 13,000 cfs (368 m^3/s)*
   This case represents the existing conditions in Nolichucky Reservoir, with a constant upstream flow of 13,000 cfs and the gate closed. This case models high-flow conditions.
3. *Open Gate - Surveyed bathymetry*
   This case represents conditions during spillway operation with the gate fully open and a constant upstream flow of 1,900 cfs (low-flow conditions). The surveyed bathymetry was used for the entire Nolichucky Reservoir bed.
4. *Open Gate - Flat bathymetry*
   This case represents conditions during spillway operation with the gate fully open, a constant upstream flow of 1,900 cfs (low-flow conditions) and an artificially flat bathymetry in front of Nolichucky Dam. The elevation of the flat bathymetry was set equal to the height of the existing sediment accumulation 30.5 m upstream of the dam.

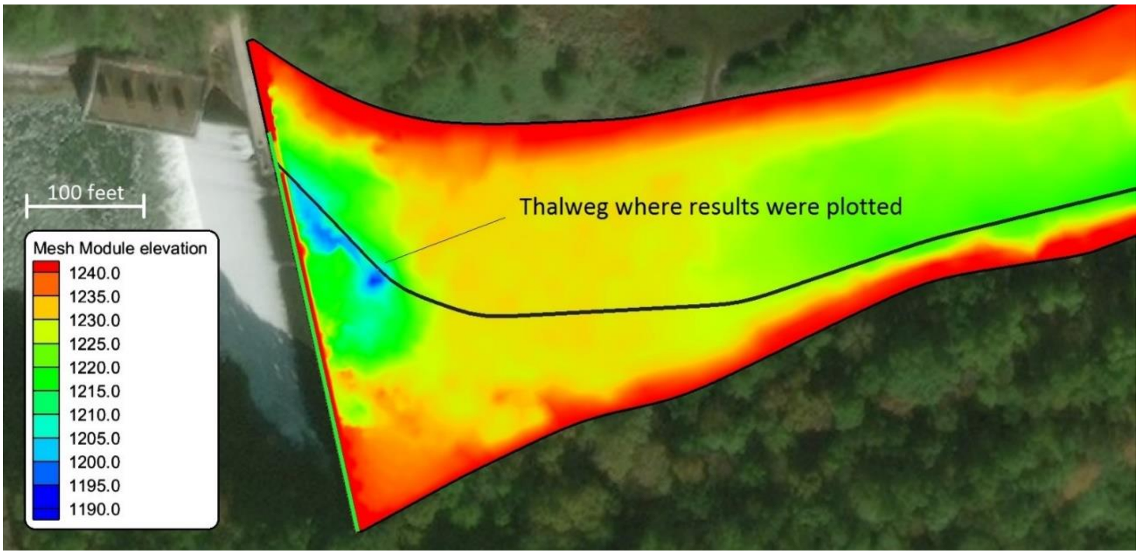

Figure 5. Area in front of Nolichucky Dam and defined thalweg

3.2 *Nolichucky Reservoir Flow Velocities and Shear Stress maps*

Figure 6 shows a map of velocities for the conditions analyzed. The case with the gate closed and a high-flow of 13,000 cfs (368 m^3/s) indicates that the velocities are much higher than the case with the gate open and surveyed bathymetry (at 1,900 cfs or 53.8 m^3/s). Figure 7 shows a map of shear stress for the conditions analyzed. Far away from the dam, the shear stress for the case with a closed gate and a high-flow of 13,000 cfs (368 m^3/s) is much higher than the case with an open gate and surveyed bathymetry (at a flow of 1,900 cfs (53.8 m^3/s)).

Near the gate, both the flow velocity (Figure 6) and the shear stress (Figure 7) are higher when the gate is open than when the gate is closed as a result of the flow discharging through the gate.

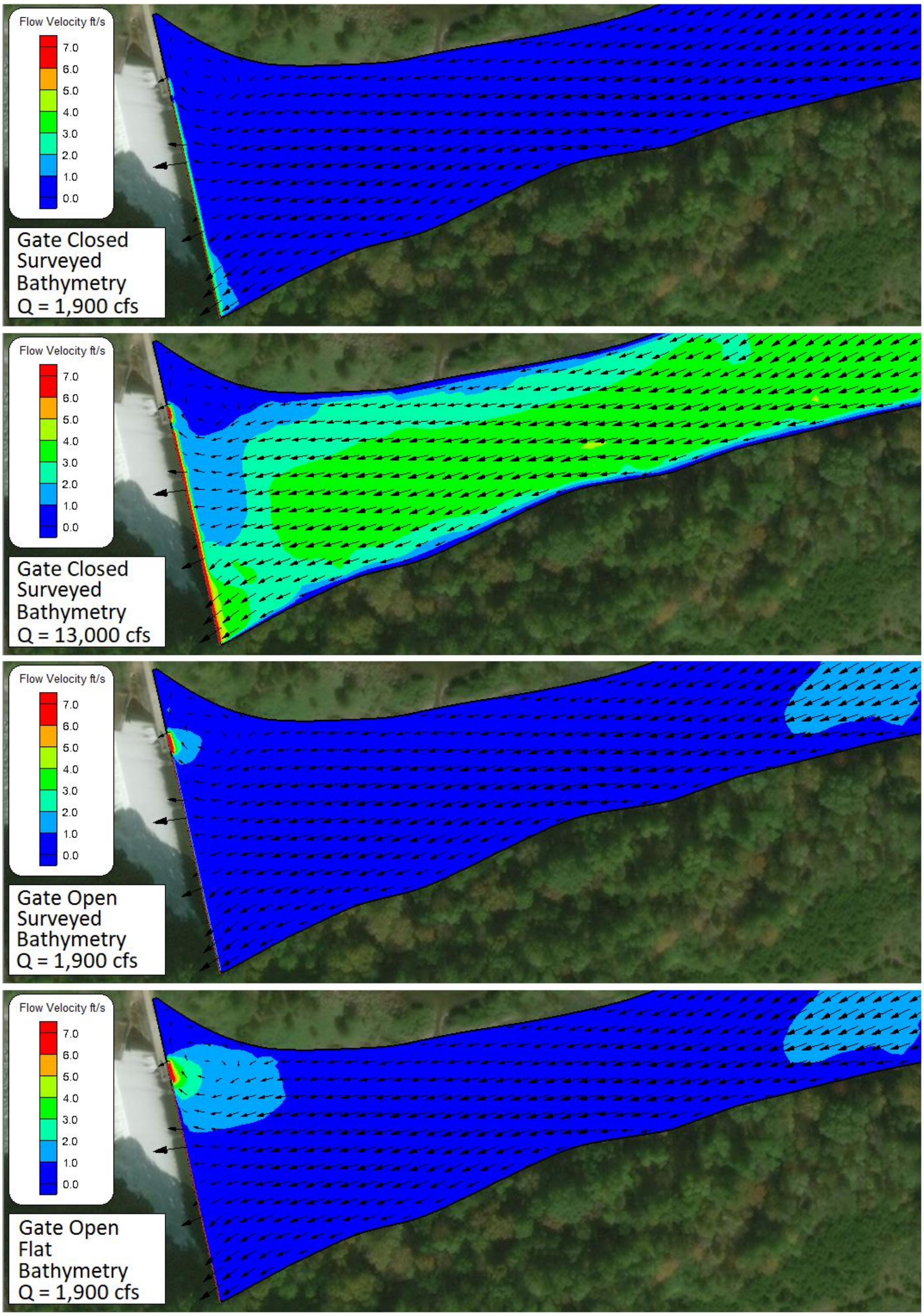

Figure 6. Velocities in Nolichucky Reservoir close to the dam

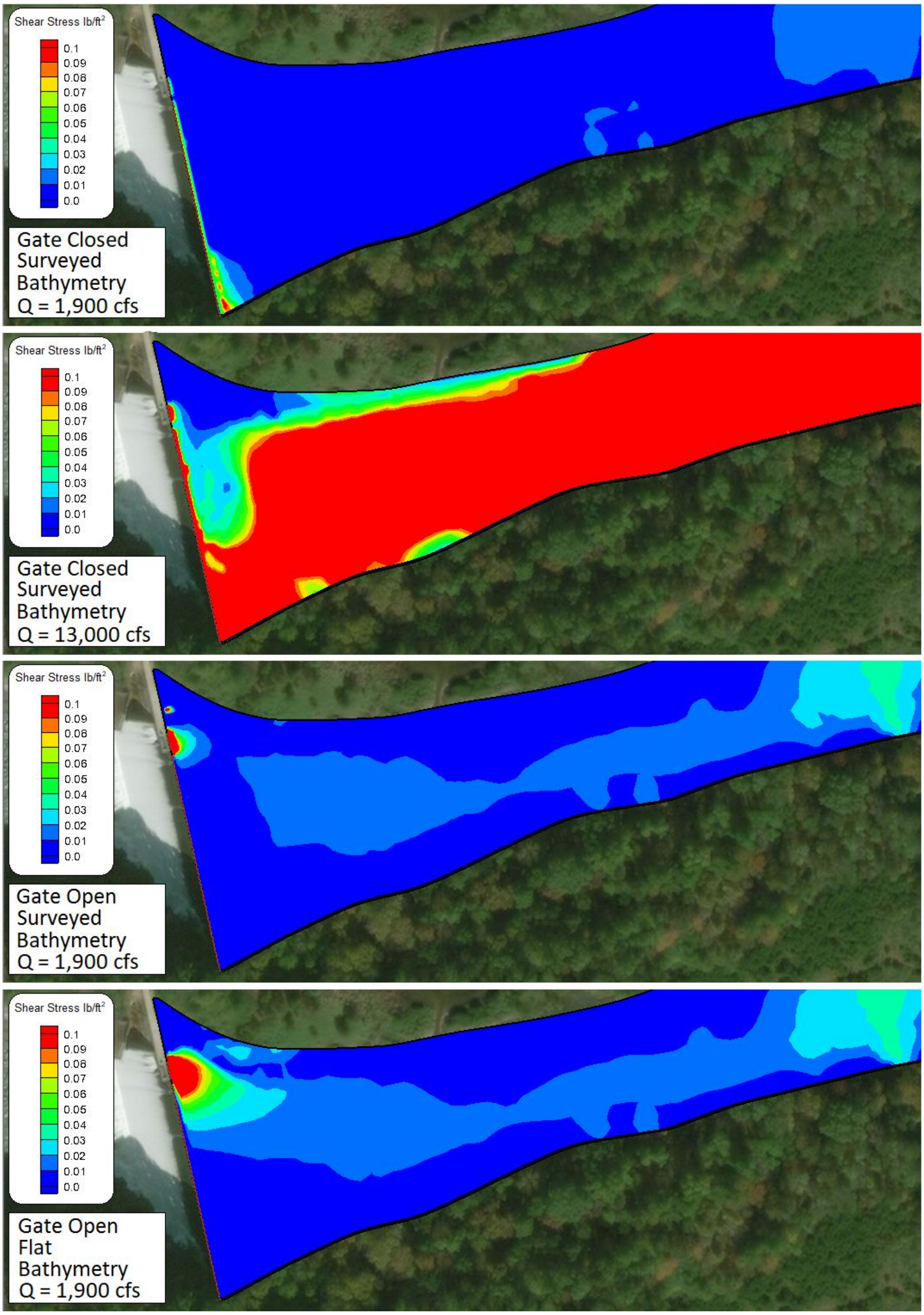

Figure 7. Shear stress in front of the dam for different scenarios

3.3 *Flow Velocity, Shear Stress and Sediment Concentration along the Thalweg*

Figure 8 shows the flow velocity, shear stress and sediment concentration along the Nolichucky Reservoir thalweg. The figure shows that for a low-flow of 1,900 cfs (53.8 m^3/s) the effects of opening the gate are dissipated within 200 feet (61 m) away from the dam: at that distance, both the flow velocity and shear stress are nearly the same as those obtained with the closed gate. This holds true for both the surveyed and flat bathymetries. The sediment concentration during a high-flow of 13,000 cfs (368 m3/s) is around 600 mg/L (not shown because out of the scale) and is much higher than the sediment concentration that would occur with a low-flow of 1,900 cfs (53.8 m^3/s). These results show that opening of the spill gate during a low-flow period would move significantly less sediment than a flood of approximately yearly recurrence with the gate closed.

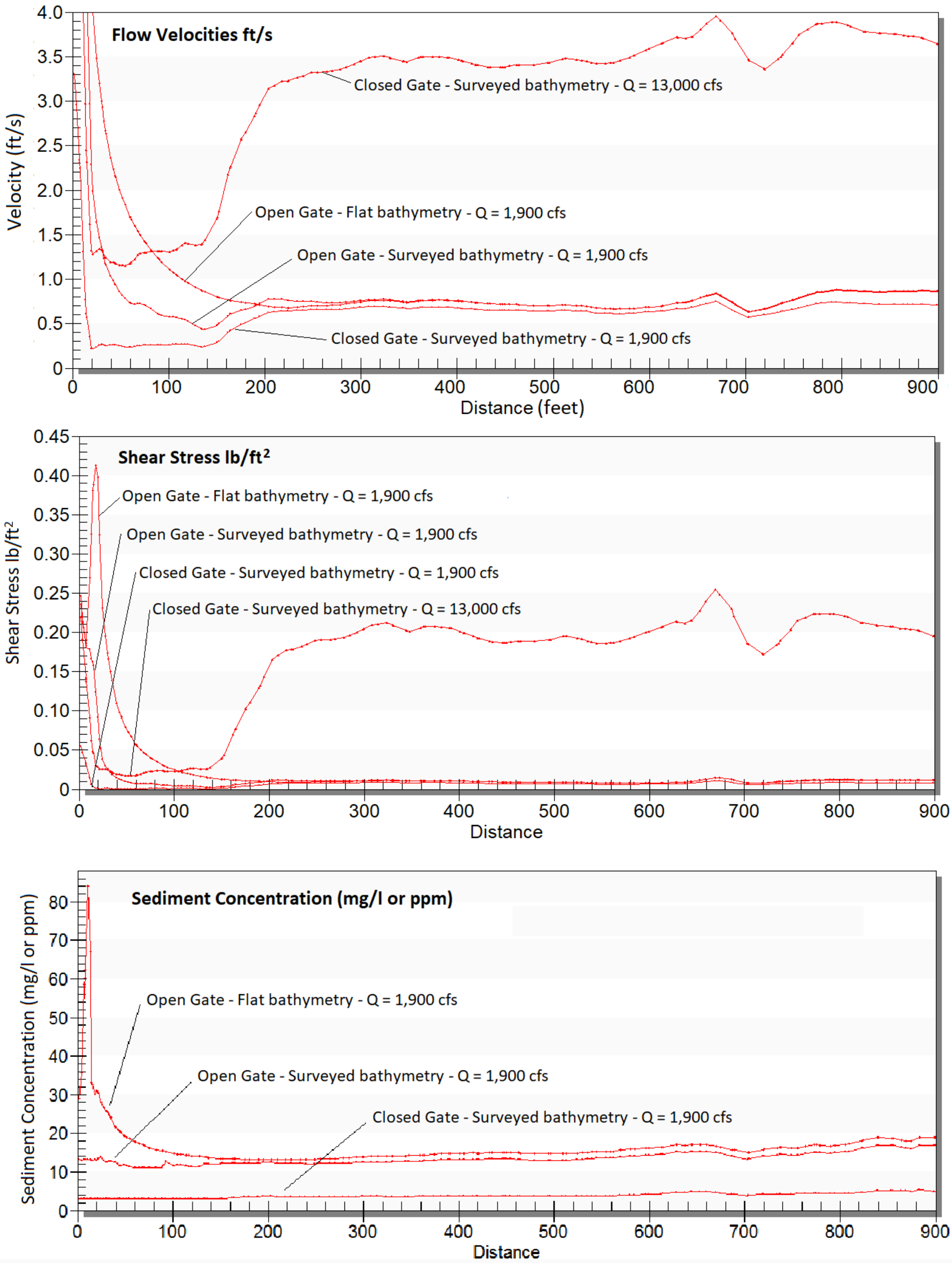

Figure 8. Flow Velocity, Shear Stress and Sediment Concentration along Nolichucky Reservoir thalweg

3.4 *Sediment Erosion and Scour Depths at the Gate*

The sediment transport induced by the opening of the gate will tend to scour the area in front of the gate. However, because of the low values of shear stress and sediment concentration, the model results indicate that the amount of scour will be only a few feet. Figure 9 shows the scour depth contours in front of the gate and Figure 10 shows the time evolution of the scour depth. The maximum scour after three days was estimated to be 1.9 feet (0.6 m). The amount of sediment scoured in this area is around 11 cubic yards (8.4 m^3). This volume of sediment is significantly less than the 9,500 cubic yards (7,263 m^3) of sediment that would be moved in 24 hours during a high-flow of 13,000 cfs (368 m^3/s), which occurs on approximately a yearly interval.

Figure 9. Scour depths near the gate

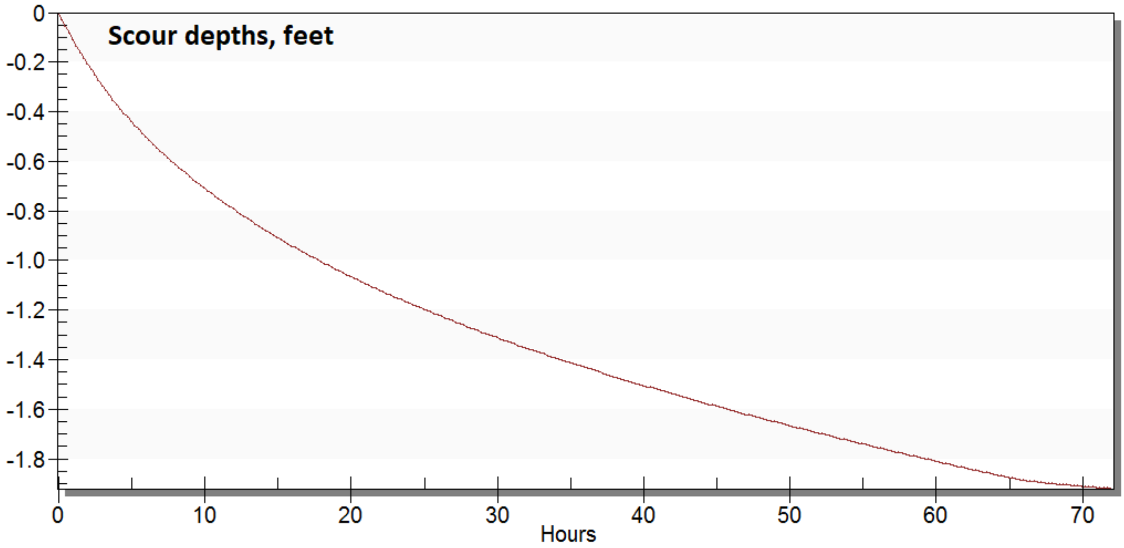

Figure 10. Scour depth evolution in front of the gate

4 CONCLUSIONS

WEST developed a two-dimensional numerical model using SRH-2D (USBR, 2017) to evaluate sediment transport through Nolichucky Reservoir on the Nolichucky River in eastern Tennessee, USA, upstream of Nolichucky Dam. The purpose of this study was to provide scour and sediment loading predictions for spillway operations that TVA was planning for upcoming gate replacement and operation.

The model results indicate that the existing velocities and shear stresses in the reservoir are very low and are not strong enough to move significant amounts of sediment for a flow rate of 1,900 cfs (53.8 m^3/s). Sediment concentrations for existing conditions with the gate closed were found to be around 3 mg/L across the lake thalweg and would reach a value of about 20 mg/L after the gate is open for 24 hours. Because of the limited predicted sediment transport, only a small amount of scour was identified, with a maximum scour of about 1.9 feet (0.6 m) immediately in front of the gate. The resulting volume of sediment scoured was approximately 11 cubic yards (8.4 m^3), a significantly lesser volume than the 9,500 cubic yards (7,263 m^3) expected to be moved with the gate closed during a flow of 13,000 cfs (368 m^3/s), a flowrate that occurs at the site approximately yearly.

Because the bathymetry near Nolichucky Dam (within about 80 feet (24.4 m) of the face) was uncertain, a simulation was also performed with an artificial flat bed in this area at an elevation equal to the existing sediment accumulation upstream. In the presence of the flat bathymetry, the resulting sediment concentration at the gate was on average 30 mg/l, with a peak of about 160 mg/l during the initial transient period after the gate is fully open. Because of the increased sediment transport, the maximum scour after a flow duration of 2 days was 6.6 feet (2 m) in front of the gate. This scour hole is about 33% of the actual scour hole that is currently in front of the gate, indicating that a period longer than 2 days would be necessary to scour the flat bathymetry to match the existing bathymetry.

The flat bathymetry scenario can be considered as representative of a situation in which stratification effects (cold, dense water at the bottom) prevent water from flowing freely in the deepest lake section closest to Nolichucky Dam. The stagnant water at low elevations would have the effect of reducing the flow area, thereby increasing flow velocities. In the model, however, the flat bed consists of sediment which can be mobilized and produces higher concentrations than would be observed if flow were over a stagnant body of water in front of the dam.

An additional simulation representing a flow of 13,000 cfs (368 m^3/s, an event expected to occur yearly) over the dam with the gate closed was run in order to compare the sediment transport results with the condition of an open gate and a flow of 1,900 cfs (53.8 m^3/s). The comparison indicated that a flow of 13,000 cfs (368 m^3/s), would induce a much higher shear stress and the sediment concentration would reach a value of about 600 mg/L along the lake thalweg. Given these results, the small amount of sediment directly above the gate that could potentially move in response to gate operations is inconsequential compared to the larger volume of sediment moved by existing processes at an approximately yearly interval.

5 REFERENCES

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