2-D Modeling of Sediment Transport in Arkansas River at W.D. Mayo Lock and Dam

Andrey Shvidchenko, Senior Engineer, Northwest Hydraulic Consultants, Sacramento, CA, ashvidchenko@nhcweb.com
Brad Hall, Principal, Northwest Hydraulic Consultants, Sacramento, CA, bhall@nhcweb.com

Abstract

This paper presents results from a sediment modeling study undertaken by Northwest Hydraulic Consultants (NHC) to support the design of a proposed hydroelectric generating facility at the W.D. Mayo Lock and Dam on the Arkansas River. The sediment modeling was conducted using a 2-d AdH model of the 2.8-mile study reach of the river. The input parameters for the model were developed using available flow records, measured sediment data, and bathymetric surveys. The model was run for a range of flows for the existing and project conditions. The modeling results were used to assess the potential project impacts on sediment transport processes and to identify operational conditions for minimizing adverse sediment deposition in the vicinity of the lock and dam.

Introduction

The W.D. Mayo Lock and Dam is located at River Mile (RM) 319.6 on the Arkansas River (Figure 1). The lock and dam facilities were constructed in 1970’s as part of the McClellan-Kerr Arkansas River Navigation System and are owned and operated by the U.S. Army Corps of Engineers (USACE). The existing structure consists of a navigation lock and a gated spillway adjacent to the lock. The gates are operated to maintain navigable depths upstream of the dam during low flow conditions. At high flows exceeding approximately 125,000 cubic feet per second (cfs), the gates are fully opened to provide "open river" conditions.

Figure 1. W.D. Mayo Lock and Dam on Arkansas River at flow 110,000 cfs (aerial image from Google Earth).
The proposed hydroelectric facility includes the addition of a powerhouse adjacent to the dam's left descending abutment. The powerhouse approach and tailrace channels will be excavated in the river channel to provide efficient flow passage through the powerhouse and satisfactory channeling of the power plant discharges back into the main river. The powerhouse will generate power for all river flows up to approximately 105,000 cfs.

The primary objective of the numerical movable bed sediment modeling was to assess the potential impacts of the proposed hydropower project on sediment erosion and deposition patterns in the vicinity of the lock and dam facility, particularly in the lower lock approach (which is subject to chronic sedimentation and periodic maintenance dredging). This paper briefly describes the development of a numerical sediment model, derivation of model input parameters, key assumption, and main results from sediment transport simulations. For more detailed description and analysis see NHC (2012, 2018).

**Model Development**

The sediment modeling was conducted using the two-dimensional (2-d) Adaptive Hydraulics (AdH) computer program developed by the USACE. The 2-d model extended approximately 1.5 miles upstream and 1.3 miles downstream of the dam. The input parameters for the numerical model were developed using available bathymetric data, Light Detection and Ranging (LiDAR) surveys, project design drawings, flow records, and measured sediment data.

Separate models were developed for the existing and project conditions. The existing conditions model topography was developed by merging the bathymetric and LiDAR survey data collected in 2011. The project condition topography was developed by adding the project channel to the existing condition topography. The existing and project conditions topography in the vicinity of the lock and dam are shown in Figure 2.

Mesh spacing within the computational domain was developed from a series of preliminary runs to reasonably represent most topographic features and structures, and at the same time provide manageable model run times. Mesh spacing ranged from 20 feet (ft) near structures such as the dam spillway, gates, locks, and training dikes to 100 ft in relatively uniform channel areas to 300 ft in floodplain areas.

Given that sediment deposits in the study area are primarily composed of sand, a single sediment size of 1.5 millimeters, corresponding to the average median bed material size in the area, was used in the sediment models developed in this study. Available data suggest that significant portions of the channel in the vicinity of the dam are apparently scored to bedrock, with localized alluvial deposits, mostly along the banks. Therefore, the thickness of sediment layer in the models was set to 1.6 ft to initiate sediment transport computations and, at the same time, to prevent excessive bed scour (which is controlled by bedrock). After testing various upstream sediment inflow scenarios, equilibrium transport condition was specified at the upstream model boundary.

The model was calibrated to measured stages, velocity distributions, and sediment loads. The calibrated model was then used to simulate morphological changes in the study reach of the Arkansas River for a range of flows under existing and project conditions. The model hydraulic boundary conditions are summarized in Table 1. The comparison between the project and existing conditions modeling results was used to assess the potential project impacts on sediment transport processes in the vicinity of the lock and dam.
**Figure 2.** Existing (top) and project (bottom) conditions topography.
Table 1. Hydraulic boundary conditions.

<table>
<thead>
<tr>
<th>Flow (cfs)</th>
<th>Water surface elevation (ft NGVD29*)</th>
<th>Flow duration (USACE data)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>Powerhouse Above dam gates (RM 319.6)</td>
<td>Days in a year % time</td>
</tr>
<tr>
<td>30,000</td>
<td>30,000</td>
<td>412.0 394.8 281.2 77.00</td>
</tr>
<tr>
<td>60,000</td>
<td>30,000</td>
<td>412.0 399.8 38.9 10.7</td>
</tr>
<tr>
<td>105,000</td>
<td>30,000</td>
<td>412.0 405.9 23.1 6.3</td>
</tr>
<tr>
<td>150,000</td>
<td>0</td>
<td>412.8 (gates open) 410.8 19.3 5.3</td>
</tr>
<tr>
<td>200,000</td>
<td>0</td>
<td>418.1 (gates open) 415.4 1.6 0.4</td>
</tr>
<tr>
<td>250,000</td>
<td>0</td>
<td>421.2 (gates open) 419.4 0.5 0.1</td>
</tr>
<tr>
<td>300,000</td>
<td>0</td>
<td>424.8 (gates open) 423.2 0.6 0.2</td>
</tr>
</tbody>
</table>

*NGVD29 = National Geodetic Vertical Datum of 1929.

Results

The existing condition and project condition models were run for a range of constant flows with the same starting channel topography and the same initial thickness of movable bed material. The Van Rijn function was used to simulate sediment transport processes. All the simulations showed initially high sediment transport rates which then gradually reduced and approached a relatively stable value. Each simulation continued until an approximate equilibrium sediment condition (stable solution) was achieved in the model. The model runtime ranged from about 10 days (prototype time) at 60,000 cfs to 3 days at 300,000 cfs.

The modeling results included flow velocity distributions, depths, sediment loads, and bed changes (relative to the initial bed topography). Flow velocities and corresponding bed aggradation and degradation computed in the vicinity of the lower lock (which is of main concern for navigation) under the existing and project conditions are compared for selected flows in Figures 3-8. The main modeling results are briefly discussed below.

Existing Conditions

The movable bed simulations indicated significant sediment transport in the vicinity of the W.D. Mayo Lock and Dam at flows 60,000 cfs and greater. According to the historical flow record, this threshold flow is exceeded (and hence bed material is transported) on average about 23% of the time (or 84 days) in a year. The computed total sediment load at the dam ranged from less than 1 ton/day at 60,000 cfs to 120,000 tons/day at 150,000 cfs and 280,000 tons/day at 300,000 cfs. Suspended sediment load constituted about 94-96% and bed load constituted about 4-6% of the total sediment load. Computed sediment loads were in reasonable agreement with available measured sediment transport data.

The model results indicated active bed degradation along the central portion of the channel both upstream and downstream of the dam. The existing training dikes concentrate the flow along the central part of the river (particularly downstream of the dam), which resulted in the erosion of bed material at these areas in the model. Such model behavior indicated that significant portions of the prototype channel in the vicinity of the dam are likely degraded to bedrock, which agrees with the field observations.
Figure 3. Velocities computed near downstream lock approach for flow of 105,000 cfs for existing (top) and project (bottom) conditions.
Figure 4. Bed aggradation and degradation computed near downstream lock approach for flow of 105,000 cfs for existing (top) and project (bottom) conditions.
Figure 5. Velocities computed near downstream lock approach for flow of 150,000 cfs for existing (top) and project (bottom) conditions.
**Figure 6.** Bed aggradation and degradation computed near downstream lock approach for flow of 150,000 cfs for existing (top) and project (bottom) conditions.
Figure 7. Velocities computed near downstream lock approach for flow of 250,000 cfs for existing (top) and project (bottom) conditions.
Figure 8. Bed aggradation and degradation computed near downstream lock approach for flow of 250,000 cfs for existing (top) and project (bottom) conditions.
The simulated bed changes demonstrated sediment deposition in the ineffective flow areas at the upper and lower lock approaches, which is consistent with the field observations and dredging records. The computed sediment deposition in the upper lock approach ranged from about 1-2 ft at 105,000 cfs to 2-3 ft at 150,000 cfs and 3-5 ft at 200,000 cfs and greater flows. The depositional area extended about 2,000-3,000 ft upstream of the lock. The computed deposition in the lower lock approach ranged from 0.5-1 ft at 60,000 cfs to 2-3 ft at 105,000 cfs and 3-5 ft at 150,000 cfs and greater flows. The depositional area extended about 1,500-2,000 ft downstream of the lock.

The model also showed potential sediment accumulation in the slow flow areas between the training dikes. Sediment was brought in and deposited between the dikes by eddy action of currents from the main channel. The maximum computed deposition between the dikes ranged from 0.5-1 ft at 60,000 cfs to 2-3 ft at 105,000 cfs and 5-7 ft at 200,000 cfs and the greater flows.

**Project Conditions**

The total sediment load computed at the W.D. Mayo Lock and Dam for the project conditions was similar to the existing conditions load. However, the powerhouse operation changed the lateral distribution of the sediment load. During powerhouse operations, from 80% (at 60,000 cfs) to 30% (at 105,000 cfs) of the total sediment load was conveyed through the powerhouse, which altered the sediment transport pattern in the downstream reach. During high flows, when the powerhouse was closed, sediment load over the spillway was similar to the existing conditions load.

Channel morphological patterns computed for the project conditions upstream of the dam were similar to the existing conditions results. However, the project significantly altered sediment transport, erosion, and deposition patterns in the reach extending about 3,500-4,000 ft downstream of the dam.

During powerhouse operations, sediments were conveyed through the powerhouse and deposited in the lower part of the tailrace channel. The model computed about 0.5-1 ft of deposition in the tailrace channel for 60,000 cfs and 1-2 ft of deposition for 105,000 cfs. During open river flows (when the powerhouse was closed), sediment was brought from the main channel into the recirculating flow area that formed at the downstream end of the tailrace channel, as well as with overtopping flows over the northeast embankment at the dam. The computed maximum sediment deposition in the tailrace channel was about 2-4 ft for 150,000 cfs and 3-5 ft for 200,000 cfs and 300,000 cfs. The depositional area in the tailrace channel progressively increased for higher flows, which indicated there may be a need for periodic dredging within the tailrace channel.

The project did not affect computed sediment deposition upstream of the lock, while its effect on deposition downstream of the lock varied with the river discharge. For 60,000 cfs, the diversion through the powerhouse reduced the flow in the main channel to below the threshold conditions for bed material movement and, as a result, the model showed no changes in bed elevations downstream of the lock. For 105,000 cfs, the diversion through the powerhouse reduced flow velocities in the main channel downstream of the dam (see Figure 3), which reduced sediment transport capacity and significantly increased the depositional area downstream of the lock compared to the existing conditions (see Figure 4). For the open river flows of 150,000 cfs and 200,000 cfs, the powerhouse was closed and most of the flow was conveyed through the main channel. As a result, the flow velocity pattern and magnitude downstream of the dam were
similar to the existing conditions (see Figure 5) and there was no significant impact on sediment deposition in the lower lock approach under the project conditions (see Figure 6). The range of flows 150,000-200,000 cfs represents an approximate bankfull (or channel forming) discharge and therefore has a dominant long-term effect on shaping the overall channel morphology. For the flows of 250,000 cfs and 300,000 cfs, the powerhouse was closed, but the tailrace channel effectively intercepted and conveyed overbank flows into the river, which reduced flow velocities in the main channel (see Figure 7) and increased depositional area at the lower lock approach under the project conditions compared to the existing conditions (see Figure 8).

The flow of 250,000 cfs is equaled or exceeded only for about 0.3 % of the time (or about 1 day) in a year. Sediment deposits formed by these high flows will likely be re-worked during receding stages by subsequent bankfull flows (150,000-200,000 cfs), which will re-shape the channel and eliminate the project effect on sedimentation at the lower lock approach. Since navigation through the lock is feasible up to 150,000 cfs, sediment deposited during the rare flow events will likely pose no significant problem for navigation. However, the modeling results indicated that sediment deposited at the lower lock during powerhouse operations at flows around 105,000 cfs will unlikely be re-worked by subsequent lower flows and, therefore, may have implications to navigation and could lead to additional dredging.

**Sensitivity Analysis**

A series of sensitivity tests were conducted to ascertain that the computed morphological trends are reasonable. The sensitivity tests were performed with different sediment size and thickness of sediment layer. The test simulations indicated that while the computed magnitude of bed changes was affected by the sediment size and initial thickness of the sediment layer in the model, the effects of the project on the sediment transport and morphological processes were comparable.

Additional test simulations were conducted to evaluate the combined morphological effects of changing flow conditions (selected high flows followed by lower flows). The test simulations demonstrated that morphological processes in the study reach depended on a particular combination of flows. For river flows up to the bankfull flow (150,000-200,000 cfs), the main project effect on sediment deposition in the lower lock approach was produced by the higher flows in a flow sequence, especially by river flows around 105,000 cfs with the powerhouse in operation. Sediment deposited at the lock by very high, rare flow events was generally re-worked by subsequent bankfull flows.

An additional sensitivity test was conducted to evaluate the possibility of reducing sediment deposition at the lower lock approach during powerhouse operations. The test demonstrated that periodic closures of the powerhouse would be an effective means of flushing sediment below the dam and reducing the project impact on sediment deposition at the lower lock approach.

**Summary and Conclusion**

The main objective of this sediment modeling study was to evaluate the potential long-term impacts of the proposed hydropower project on sediment erosion and deposition in the vicinity of the W.D. Mayo Lock and Dam on the Arkansas River. The sediment modeling was conducted using a 2-d AdH model of the 2.8-mile study reach of the river. The model was developed using available bathymetric and topographic surveys, flow records, and measured sediment data. The model was calibrated to measured stages, velocity distributions, and sediment loads. The
calibrated model was run for a range of flows for the existing and project conditions. The comparison between these conditions was used to assess the potential project impacts on sediment transport processes in the vicinity of the lock and dam.

The numerical modeling results obtained for the existing conditions demonstrated sediment deposition at the upper and lower lock approaches, which is consistent with the field observations. The computed annual sediment deposition ranged from about 1-3 ft at low to moderate gated flows to 2-5 ft at high open river flows. The depositional areas in the model extended several thousand feet both upstream and downstream of the lock.

The addition of the powerhouse in the model changed the lateral flow distribution, which altered sediment transport, erosion, and deposition patterns, particularly downstream of the dam. Sediments tended to deposit in the powerhouse tailrace channel for most of the flows evaluated. The computed annual deposition in the tailrace channel ranged from about 1-2 ft during powerhouse operations to 2-5 ft during open river flows.

The project did not affect computed sediment deposition upstream of the lock, while its effect on deposition downstream of the lock varied with the river discharge. The project did not increase sediment deposition at the lower lock approach for relatively low sediment moving flows (around 60,000 cfs) and for bankfull flows (150,000-200,000 cfs). However, the project increased the depositional area at the lower lock approach for high gated flows with the powerhouse in operation (around 105,000 cfs) and very high open river flows with the powerhouse closed (250,000 cfs and greater). The observed flow statistics were used to evaluate the long-term contribution of the computed flow-specific project impacts. Based on the numerical modeling results, operational conditions were identified to minimize adverse deposition in the lower lock approach and reduce dredging requirements.

References
