Hydrodynamic modeling of the Colorado River between Glen Canyon Dam and Lees Ferry, Arizona

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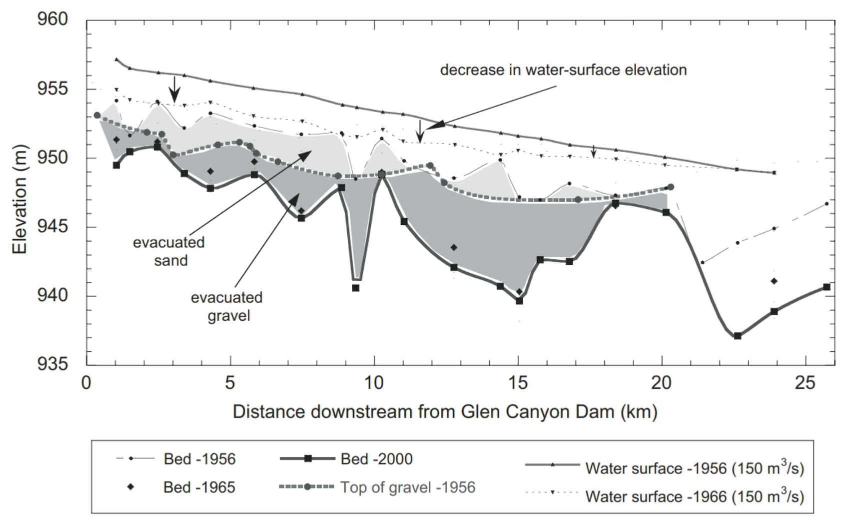
Introduction

A two-dimensional hydrodynamic model was constructed and applied for the 15.8 mile tailwater reach of the Colorado River between Glen Canyon Dam and Lees Ferry, Arizona. This reach is well suited for 2D hydrodynamic modeling because the boundary conditions (flow releases at Glen Canyon Dam, water-surface elevations at Lees Ferry, and channel bathymetry) are well constrained, flows throughout the reach are almost completely determined by outflows from Glen Canyon Dam, and the channel bed is primarily, rarely-mobilized gravel (Grams and others, 2007). The results produced by the model serve as a useful resource for researchers interested in water-surface elevations, shoreline extents, water depths, velocities, and other hydraulic characteristics across a range of discharges within the study reach.

Summary of Geomorphic Change

Closure of Glen Canyon Dam resulted in a 63% decrease in the magnitude of the mean annual flood and a 99% decrease in the annual sediment load in Glen Canyon. These changes resulted in sediment deficit, channel incision, and bed-sediment evacuation. The majority of bed lowering and sediment evacuation occurred during the channel cleaning flows of May 1965. The magnitude of incision in hydraulic controls, such as riffles, decreased with time and also decreased downstream, resulting in a lower post-dam reach-average gradient. The average bed-material grain size increased from ~0.25 mm to ~20 mm. The adjustment of bed-material grain size and reach-average gradient is consistent with the transformation of an adjustable-bed alluvial river to a stable channel with an infrequently mobilized bed. The dropping stage-discharge relations have decreased the inundation frequency of deposits leaving pre-dam channel-side sand deposits and portions of the exhumed gravel bed perched above the range of post-dam normal power plant discharges. This has caused in increase in the area of exposed alluvium and reduction of channel width by about 6%, despite the large magnitude of net sediment evacuation from the reach. Because the perched deposits are rarely inundated and stabilized by vegetation, erosion of these deposits has been limited and highly localized.

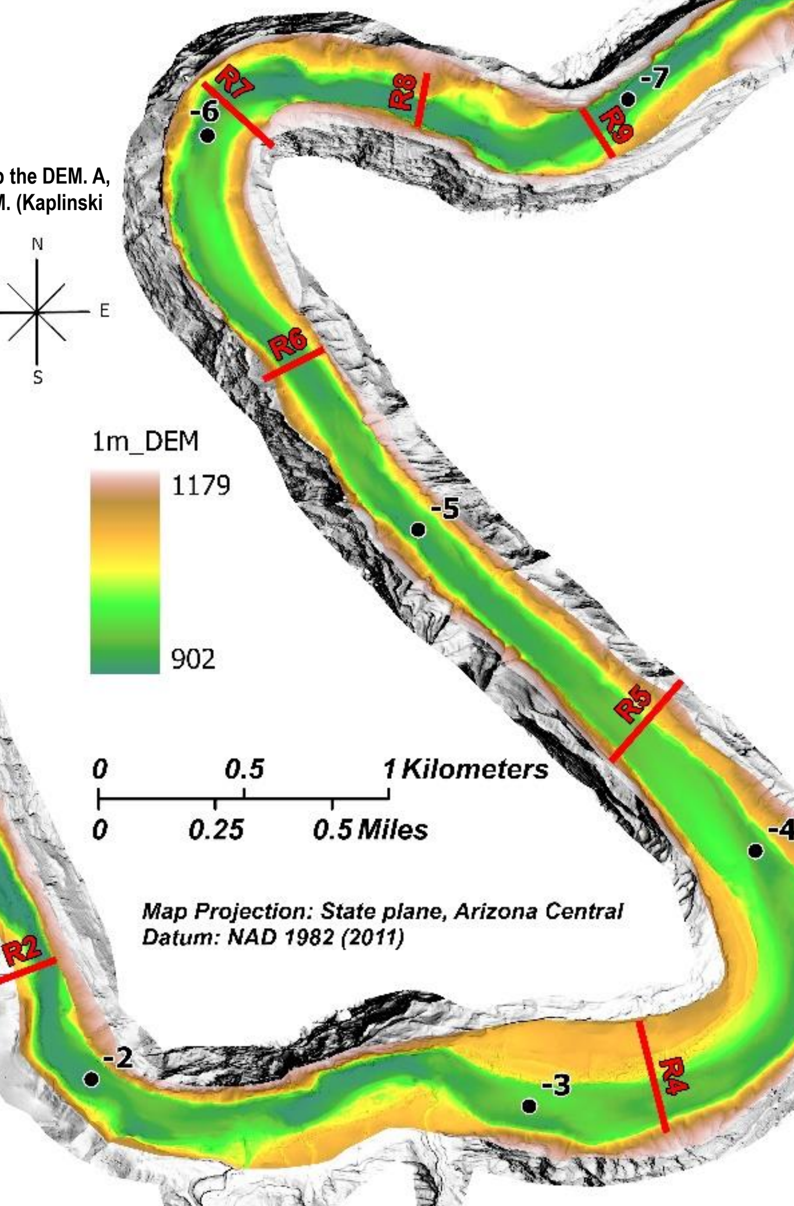


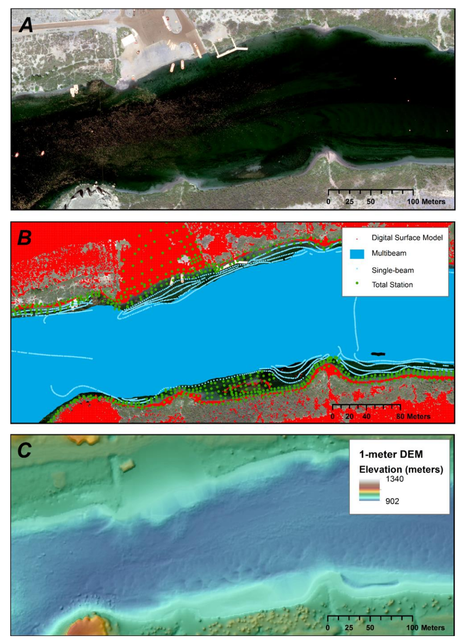
Longitudinal profile showing thalweg elevation for each of the Bureau of Reclamation surveys and elevation of the top of the gravel layer determined by borehole and jet probe measurements by the Bureau of Reclamation in 1956. Water-surface profiles for a common discharge of 150 m³/s (5,300 ft³/s) are also shown. From Grams and others (2007).

Photographs of pre-dam (left, photo by Tad Nichols, NAU special collections 19785) and post-dam Glen Canyon (right, author unknown).

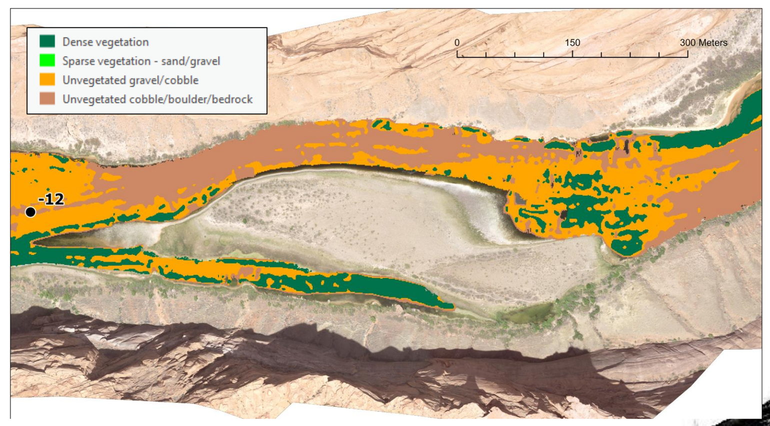
Digital Elevation Model

Bathymetric and topographic data were collected from May 2013 to February 2016 along the 15.8-mile reach of the Colorado River from Glen Canyon Dam to Lees Ferry in Glen Canyon National Recreation Area, Arizona (Kaplinski and others, 2022). Channel bathymetry was mapped using multibeam and singlebeam echo sounders; subaerial topography was mapped using a combination of ground-based total stations and aerial photogrammetry. These data were combined to produce a digital elevation model (DEM), spatially variable estimates of DEM uncertainty, and bed-substrate distribution.

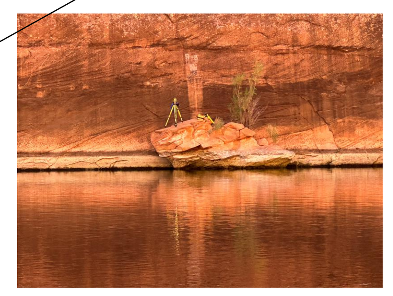




Maps of Lees Ferry area showing data used to develop the DEM. A, Orthophoto of area. B, DEM input data. C, 1-meter DEM. (Kaplinski and others, 2022).



Map of bed-substrate distribution (Kaplinski and others, 2022).



Photograph of Shannon Sartain surveying at river left side of cross section R8. photo by Matt Kaplinski.

Photograph of multibeam survey near dam. photo by Joe Hazel, Jr..

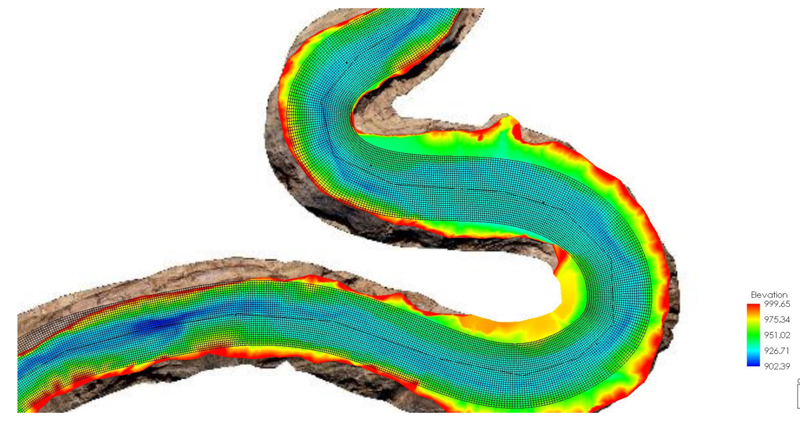
Photograph of Ryan Seumptewa surveying near dam. photo by Matt Kaplinski.

Hydrodynamic Model Development

The Flow and Sediment Transport with Morphologic Evolution of Channels (FaSTMECH) solver was used for this study. FaSTMECH is a 2D hydrodynamic model contained within the International River Interface Cooperative streamflow modeling package (Nelson and others, 2016). The 1-m resolution DEM (Kaplinski and others, 2022) was used to map elevations to the 5-m by 5-m model grid. FaSTMECH computational grids utilize a curvilinear orthogonal coordinate system that follows a user-defined channel centerline. Boundary Conditions: 1) steady discharge at the upstream boundary (Glen Canyon Dam); and 2) constant water-surface elevation at the downstream boundary (Lees Ferry).

Model Calibration

Good agreement between predicted and measured water-surface elevations (described in Model accuracy section) was achieved using two parameters that influence the flow solution: Bed roughness height (z_0) = 0.01 m in all grid elements and lateral eddy viscosity = 0.1 m/s² across the entire model domain and for all discharges. Using these parameters, the model was run for upstream discharges ranging from 1,000 to 40,000 ft³/s in 1,000 ft³/s increments and from 40,000 to 70,000 ft³/s in 5,000 ft³/s increments.



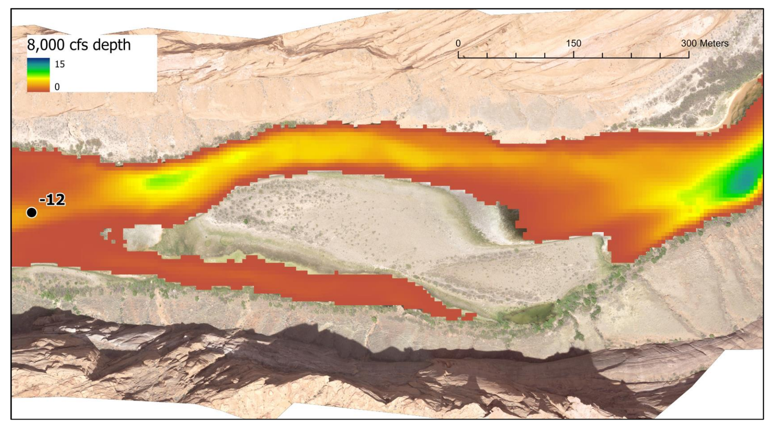
Example of the FaSTMECH model grid through a bend in the project reach.

Model Results

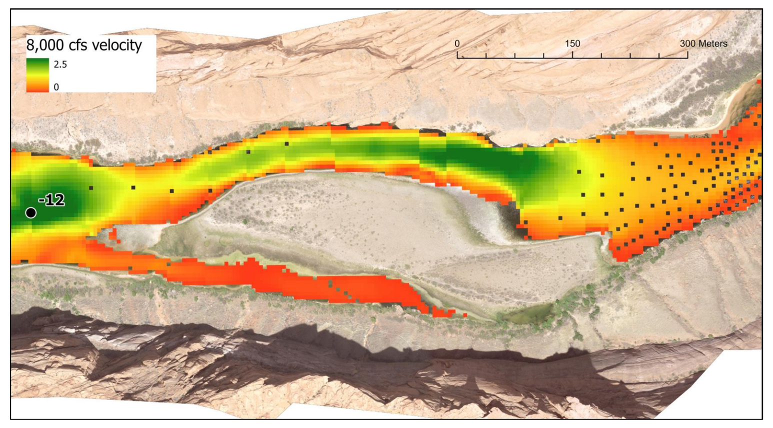
The results for each model run are stored in tables that list, for each grid cell, the predicted water surface elevation, depth, bed elevation, and velocity and shear stress solutions. An example of the output table is shown at right and figures below of depth, flow velocity, and shear stress of model results for a flow of 8,000 ft³/s.

I	J	X	Y	IBC	FMIBC	Depth	Water Surface Elevation	Elevation	Shear Stress Divergence	Velocity X	Velocity Y	Velocity (magnitude)	ShearStressX	ShearStressY	ShearStress (magnitude)
4435	9	448998.09	4078082.5	1	-1	1.47	926.60	925.13	-0.0002	0.022	0.023	0.032	0.006	0.007	0.009
4436	9	448996.34	4078087.25	1	-1	1.72	926.60	924.88	-0.0001	0.005	0.034	0.035	0.001	0.010	0.010
4437	9	448994.56	4078092.25	1	-1	1.94	926.60	924.66	-0.0001	-0.009	0.039	0.040	-0.003	0.012	0.012
4438	9	448992.75	4078097	1	-1	1.57	926.60	925.03	0.0000	-0.021	0.039	0.045	-0.008	0.014	0.016

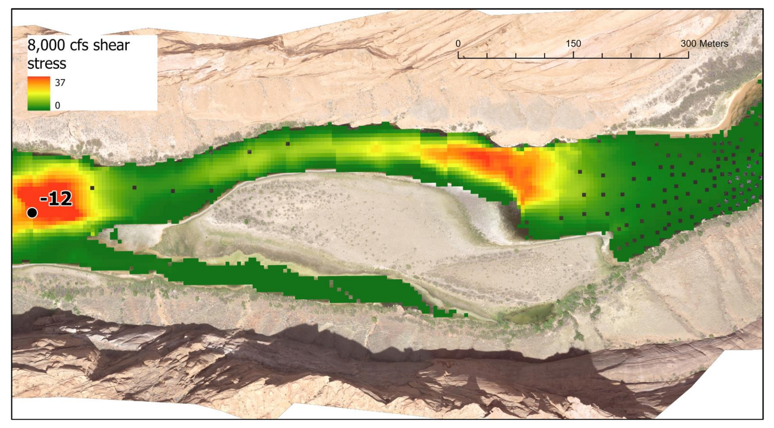
Example of the model result output table



Map of 8,000 ft³/s model output of depth (water surface elevation – elevation of DEM) near mile -12.



Map of 8,000 ft³/s model output of current velocity magnitude near mile -12.



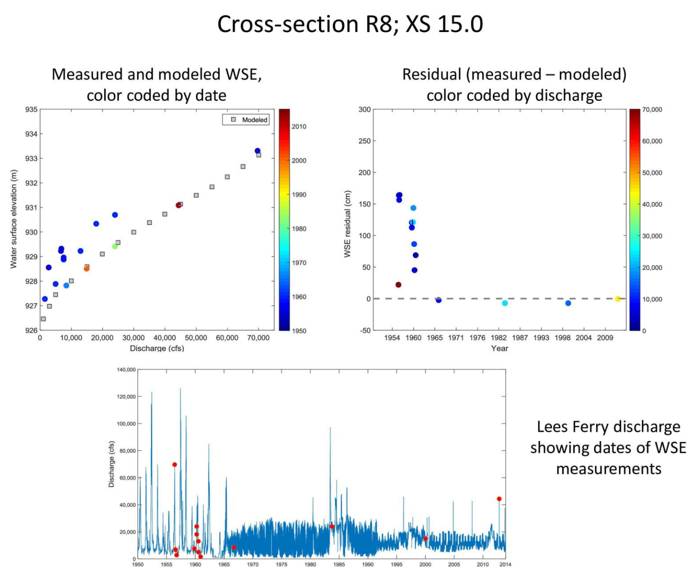
Map of 8,000 ft³/s model output of shear stress near mile -12.

Model Accuracy

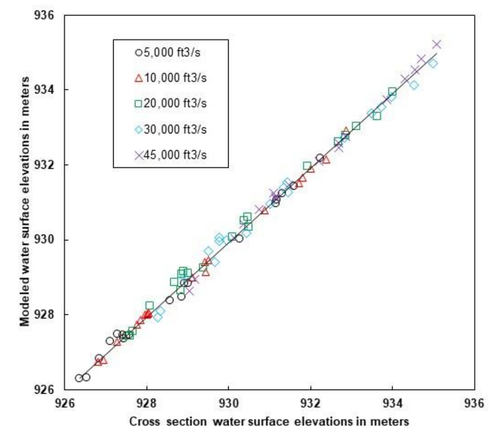
FaSTMECH tracks the convergence a model solution based on the "mean error in discharge", which is a measure of how well the model has conserved water volume over the entire domain. The mean error in discharge was below 2% for all model runs, and below 1% for 39 of the 44 runs. The runs that exceeded 1% error were all for discharges less than 10,000 ft³/s, likely due to the fact that lower discharges include more complex flow patterns around bars along the shoreline that become completely submerged at higher discharges (i.e. at higher discharges the flow is more unidirectional).

Comparison of modeled and measured water-surface elevations

Predicted water-surface elevations at five discharges (5,000 ft³/s, 10,000 ft³/s, 20,000 ft³/s, 30,000 ft³/s, and 45,000 ft³/s) were compared to measured water-surface elevations and elevations derived from stage-discharge relationships to evaluate the accuracy of the model. Grams and others (2007) developed stage-discharge relationships at 19 historical cross-sections established by the U.S. Bureau of Reclamation that span the length of tailwater reach. The stage-discharge data available for Glen Canyon span a period of approximately 50 years. During this time period, the elevation of the bed changed considerably, with the majority of erosion occurring immediately following dam construction in the early 1960s (Grams and others, 2007). Because the model is based on recent terrain surveying, only the more recent water-surface elevation data were used to fit stage-discharge curves to compare with model predictions. Table 1 contains information on the model residuals for each of the discharges, shown as mean (signed) values, mean absolute values, and maximum absolute residuals. The means were computed from all cross-sections over the reach (N = 19) for each discharge. The mean residuals ranged from -0.03 to -0.12 m and the mean absolute residuals ranged from 0.08 to 0.18 m, indicating good agreement. Maximum absolute residuals were below 0.5 m for all cross-sections for all discharges.



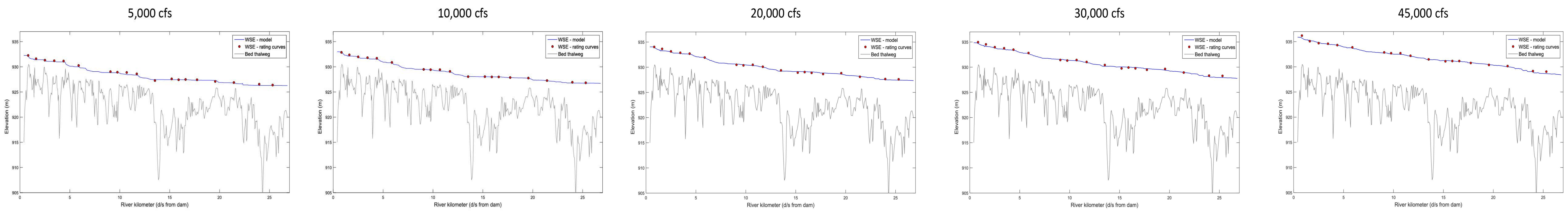
Comparison of model to stage and discharge measurements at each cross-section R8.



modeled versus measured water-surface elevations from all cross-sections for all five discharges.

Table 1. Summary of water-surface elevation residuals for a range of discharges

Discharge (ft³/s)	Mean residual (m)	Mean absolute residual (m)	Maximum absolute residual (m)	Cross-section with maximum residual
5,000	-0.12	0.15	0.41	R11A
10,000	-0.07	0.08	0.29	R11A
20,000	-0.03	0.14	0.38	R19
30,000	-0.08	0.18	0.38	R19
45,000	-0.07	0.13	0.47	R20
Averages	-0.08	0.14	0.38	



modeled and measured water-surface elevation profiles for five discharges that span the typical range of releases from Glen Canyon Dam (5,000; 10,000; 20,000; 30,000; and 45,000 ft³/s), along with the bed thalweg elevation profile. The figure panels demonstrate that the modeled profiles track the measured profiles well over the range of discharges.

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Acknowledgements

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