



Modeling Sediment Concentrations during a Drawdown Reservoir Flush: Simulating the Fall Creek Operations with HEC-RAS

by Stanford Gibson and James Crain

PURPOSE: This U.S. Army Corps of Engineers (USACE) Regional Sediment Management Technical Note (RSM-TN) summarizes the history and objectives of the Fall Creek reservoir flushing operations and presents a one-dimensional (1D) morphodynamic model that simulates sediment dynamics during the flush. A USACE Institute for Water Resources (IWR), Hydrologic Engineering Center, River Analysis System (HEC-RAS), model was developed to simulate sediment flushing and was compared to downstream flush concentrations for three separate years (2012, 2013, and 2014).

BACKGROUND: Dam construction in the United States peaked approximately 50 years ago (Randle and Bountry 2017) with more than 60% of U.S. dams completed between 1950 and 1979. Therefore, most U.S. dams are approaching or have surpassed their design life. As reservoirs are managed beyond their planning time horizon, sediment deposition can impact project functions and downstream ecology. Other countries are addressing aging infrastructure by experimenting with sustainable reservoir management practices like drawdown flushing (Kondolf et al. 2014; Morris and Fan 1997). However, these management strategies are rare in the United States. Out of more than 450 water storage reservoirs in the USACE portfolio, only at Fall Creek, Oregon, is the reservoir pool drawn down annually to run-of-river conditions, thus flushing sediment from the reservoir. The USACE National Regional Sediment Management (RSM) Program funded a USACE Portland District (NWP) and Hydrologic Engineering Center (HEC) team to develop a sediment model of the Fall Creek drawdown. The study had four objectives:

1. Formalize lessons learned from the only regular USACE drawdown flush to inform other projects considering flushing as a management alternative.
2. Evaluate the sediment tools in HEC-RAS, including the USACE 1D sediment model for simulating a reservoir flush.
3. Improve modeling capabilities and invest in USACE software to make reservoir flush models more accurate and efficient.
4. Develop a management tool that NWP and its partners can use to test alternate flush approaches and optimize future drawdowns for morphological objectives.

Fall Creek is a large (115,100 acre-feet) reservoir on the western slope of the Cascade Mountains, approximately 20 miles southeast of Eugene, OR. The USACE constructed the dam in 1966 with flood risk management, water supply, water quality, navigation, and habitat missions.

Even before the annual drawdowns began in 2011, the reservoir elevation often varied more than 100 feet (ft), between 834 ft and 731 ft as the reservoir shifted between summer and winter pools. The USACE first drew Fall Creek down to near-run-of-river conditions (690.5 ft) in 2012 (Water Year 2013). The participating agencies have coordinated similar flushes annually since the 2012 event (Figure 1).



Figure 1. Pictures of the 2016 drawdown flush at Fall Creek Reservoir, OR, from upstream (top-left) to downstream (bottom-right) (from A to B to C to D).

While Fall Creek is the only USACE reservoir that draws down to run-of-river conditions and flushes sediment annually, these flushes are not motivated by sediment impacts. Historic deposition rates will not fill this large reservoir fast enough to substantially impact the flood risk management or water supply objectives for more than 100 years. Therefore, the USACE considers it a low-priority reservoir with respect to sediment impacts. The drawdowns at Fall Creek are motivated by fish passage. NWP draws down the reservoir so juvenile salmonids can pass through the dam without negotiating a severe pressure gradient between the pool and the river, which can affect their swim bladders and increase mortality. The drawdown improves salmonid survival and increases mortality of non-native lentic competitors. However, the drawdowns do flush sediment. As the only USACE project with a regular, run-of-river drawdown, Fall Creek provides an excellent opportunity to learn about the sediment processes associated with these events, as well as an opportunity to test and improve the modeling tools.

HEC-RAS MODEL OF FALL CREEK: The study team generated a project report (NWP 2018) that describes multiple modeling approaches, the model data, transport algorithms, and system assumptions in detail. This section briefly summarizes these modeling decisions. The

modeling team developed the bathymetry from a 2012 lidar survey flown near the end of the first drawdown. Cross section locations are shown in Figure 2. Collecting lidar data during the drawdown generated a relatively complete reservoir sediment surface because the water level cut below the reservoir delta. However, the 2012 lidar already included significant incision from the flush. Therefore, the team updated the bathymetry for the 2012 flush, increasing the initial elevations in the incised channel to restore them to an approximate pre-drawdown condition.

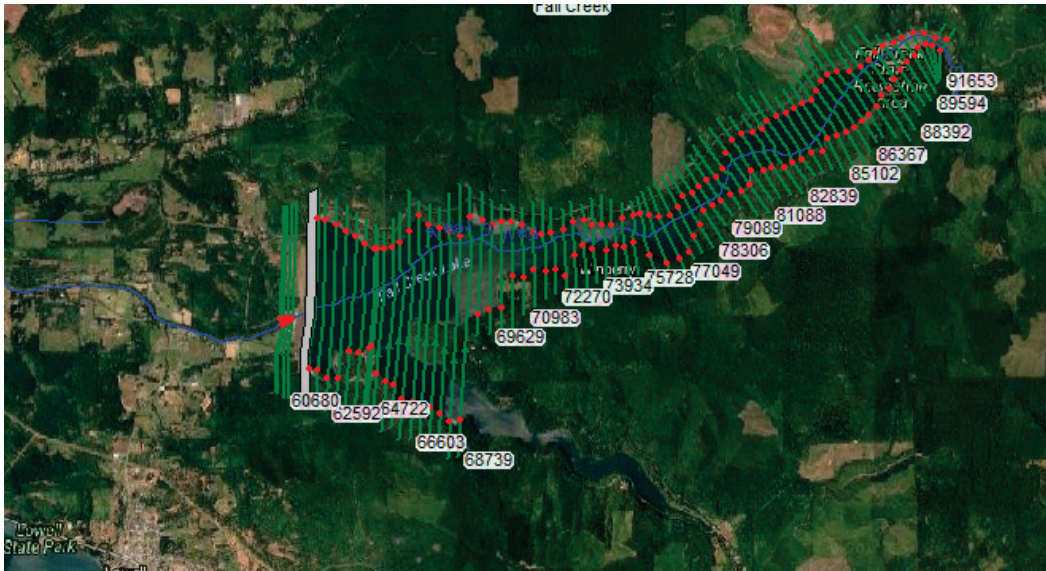


Figure 2. Schematic and cross-section layout of the Fall Creek model.

The U.S Geological Survey (USGS) collected 15-minute (min) flow records upstream of the reservoir on Fall Creek and on Winberry Creek, the southern tributary. USGS also collected suspended sediment data at the gage upstream of the reservoir. The final flushing model used 1-hour average flows at the upstream boundary condition and a lateral flow series to represent Winberry Creek. The study team applied a flow-load rating curve from the Middle Fork Willamette River at Lowell, OR, a similar, nearby basin with comparable climate and physiography, to both flow boundaries to compute upstream sediment flux during the simulation.

Flushing models, like dam removal simulations, are much more sensitive to the mass and gradation of the reservoir deposits than to sediment boundary conditions. The sediment eroded from the bed (including the reservoir deposits) represents many years of upstream flux. Reservoir erosion tends to overwhelm the boundary flux during the event, even if the flush corresponds with a large flow. The modeling team used four surficial bed-gradations collected from the reservoir delta during the 2012 flush to define the bed material. The model specified the base of these deposits with a fixed bedrock elevation, estimated from eight *as built* cross sections collected when the dam was constructed in 1966. These reservoir sediment samples were primarily fines downstream but all included gravel and fines. The samples distributions contained up to 60% silt and clay at the downstream end of the delta and over 10% cobble at the upstream end.

The model used a normal depth boundary condition at the downstream end of a short reach below the dam and specified reservoir stage with an internal stage series (see Model Development Section), setting the model pool stages to the USGS measurements collected



during the flush. The modeling team constructed unsteady and quasi-unsteady sediment transport models in HEC-RAS.

Calibration. The USGS (Schenk and Bragg 2014) collected suspended sediment samples downstream of Fall Creek dam during each flushing event. Downstream concentration time series were available from the 2012, 2013, and 2014 flushing events. Figure 3 compares the quasi-unsteady model results against the measured concentrations.

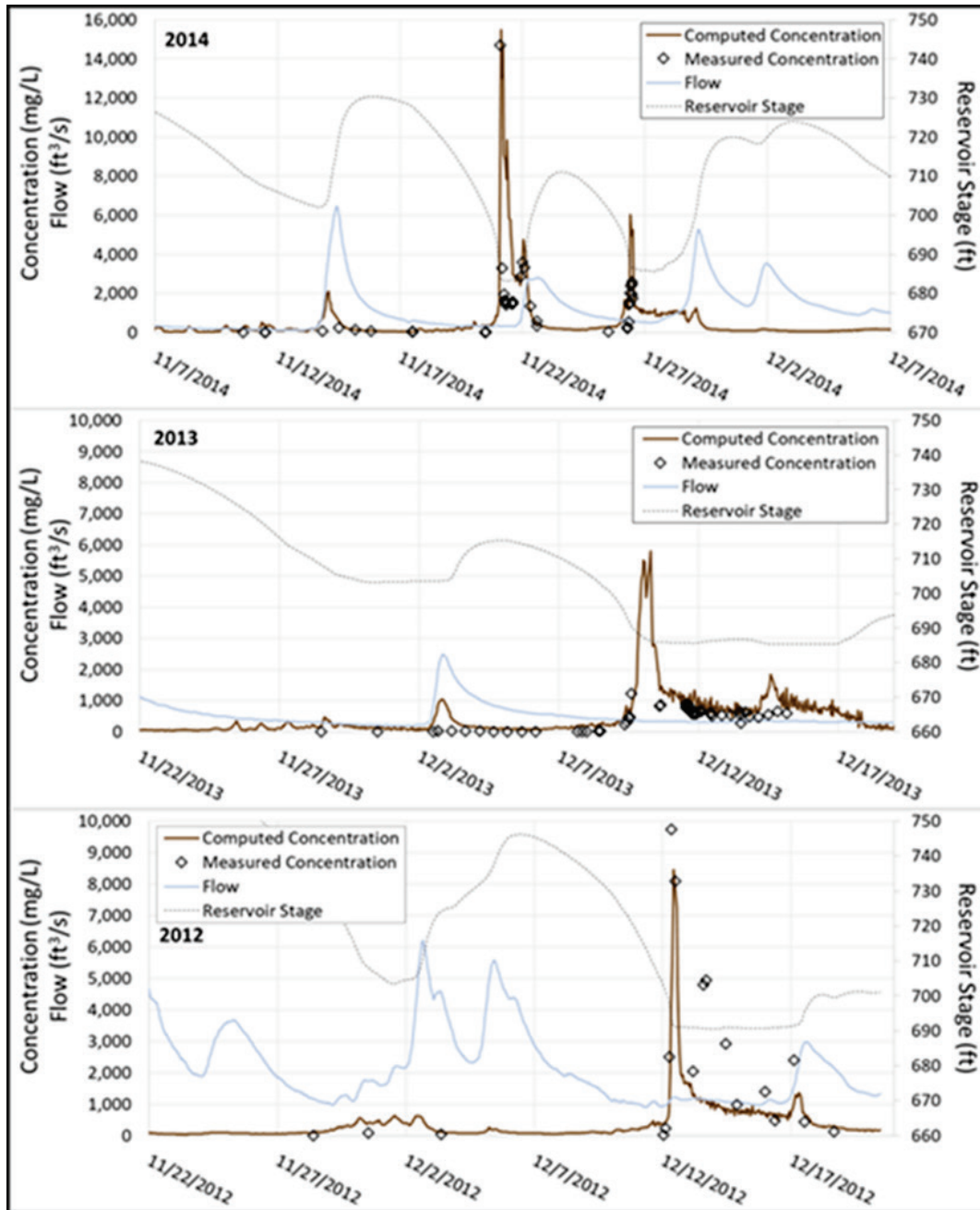


Figure 3. Modeled concentration downstream of Fall Creek during the 2012, 2013, and 2014 flushes, compared to observed concentrations and flow and stage time series.



The project report (NWP 2018) parameterized and calibrated each flush separately. The results in Figure 3 applied the same calibration parameters for all simulations. All three models used the Ackers-White transport function for sand and gravel transport and the active layer sorting and armoring method. The active layer thickness was set to $6 \times d_{90}$ (where d_{90} is the 90th percentile grain size at the cross section) to assure that the mixing method did not artificially limit scour by running out of sediment during morphologically active time-steps.

The cohesive erodibility factors were the primary calibration factor in these simulations. HEC-RAS uses a piecewise linear erodibility model (Partheniades 1965) for cohesive sediment, with two erosion regimes: a lower shear erosion regime ($\tau_c = 0.03$, $M = 0.2$), and a *mass wasting* regime ($\tau_c = 0.08$, $M = 2.2$) (Figure 4). The model was not very sensitive to the lower regime thresholds because most of the erosion happened at very high shear stresses ($\tau_c > 0.08$) when the dropping pool exposed the high gradient channel. The model was calibrated to the 2014 event, and then the calibration was evaluated (i.e., validated) against the other two time series (Figure 3).

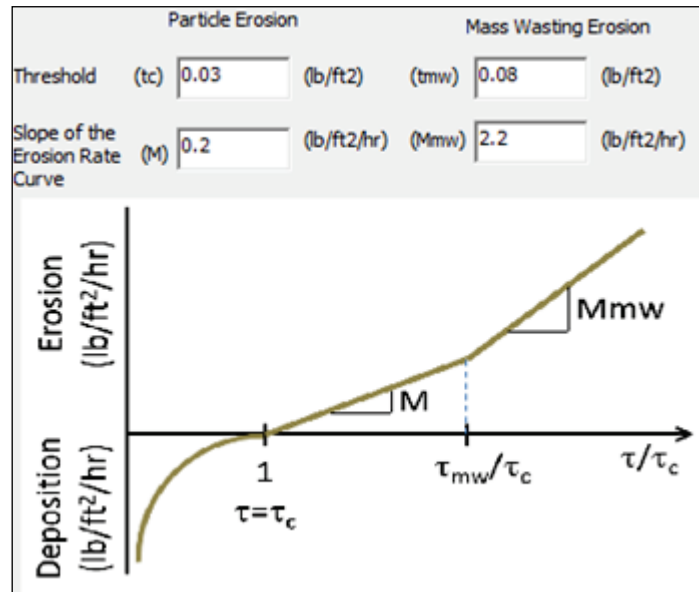


Figure 4. Partheniades (1965) parameters used to calibrate the model.

The largest apparent residuals (difference between observed and measured concentration) appear during the peak of the 2013 flush (Figure 3, middle). The peak simulated concentrations are substantially higher than the peak observed concentrations. However, the observed data only include one concentration on the rising limb of the sedigraph, and the concentration time series did not include any observations between December 9, 2013 14:16 and December 10, 2013 14:27, where the model predicted the peak sediment concentrations. The model actually performed very well where observations were available to compare against.

Additionally, the HEC-RAS concentrations are based on total load while the USGS measurements approximately correspond to suspended load. The HEC-RAS concentrations downstream of the dam are almost 100% silt and clay, making this assumption appropriate. However, the USGS has observed some sand deposition downstream of the dam during these events, suggesting the models underpredict sand transport.



The year-to-year differences in model performance are likely a function of two main data deficiencies: (1) the antecedent bathymetry and (2) the bed gradation for each run. Because the 2012 event was the first flush, it would contain more relatively fine material than the later flushes, explaining why the 2012 model tends to underpredict transport while the others simulations slightly overpredict transport.

Considering the unmeasured variability in the initial delta thickness and gradation, and the limitations of the 2013 observations, the model performed well, reproducing reasonable concentration responses for three events with a single set of parameters.

During the drawdown, the model simulated gradual delta progression in the reservoir. As the water surface dropped, it exposed a high gradient channel at the upstream edge of the pool, which scoured the upstream end of the delta to bedrock. Most of these scoured sediments deposited relatively quickly in the backwater immediately downstream of their source. This process generated a slowly pro-grading sub-delta, advancing just ahead of the advancing pool-river transition, until the reservoir drew all the way down to the dam outlet reaching run-of-river condition. Because the delta moved gradually along the reservoir accumulating deposits from the entire reservoir, the reservoir flushed most of the sediment in a short period of time when the water level reached the outlet elevation. This sediment accumulation and transport in the sub-delta generated the abrupt concentration spike. The concentration measurements also included an abrupt concentration spike, suggesting that the model reflected the prototype process.

Unsteady Sediment Model. The study team also constructed an unsteady model of the 2014 event. While quasi-unsteady sediment models are more stable, they require user-specified reservoir stages, which limits their predictive flexibility. Because unsteady models conserve (flow) mass, modelers can modify them with alternative operations. The governing equations can simulate new reservoir stages associated with alternative operations. Invoking operational rules makes the model flexible for alternate operations based on specified flows, gate operations, or even responsive rules based on downstream concentrations (Gibson and Boyd 2016b). The unsteady model simulated reservoir stage with a very simple set of operational rules (Table 1), setting the reservoir stage to historic levels during the calibration. Historic stages were imported into the model as “gate elevations” for an isolated storage area connection with no connection to the main model.

Table 1. Operational rules that set reservoir to historic stage series.	
row	Operation
1	! Get the observed lake elevation
2	`ObsLakeElev` = Storage Area Connections:Gate.Opening(Gate, Gate #1, Value at current time step)
3	! Set XS elevation upstream of dam to observed lake elevation
4	Structure.Stage (Fixed) = `ObsLakeElev`

The unsteady hydrodynamics change the hydraulic parameters that feed the sediment transport, including depth and friction slope, both of which affect shear stress. Therefore, the unsteady flow model often computed higher transport, particularly transport associated with upstream flow. However, the unsteady flow peak (which was the target metric) was comparable to the quasi-



unsteady result with the same parameters (Figure 5) and the positive Nash-Sutcliffe Efficiencies were within 0.15 of each other.

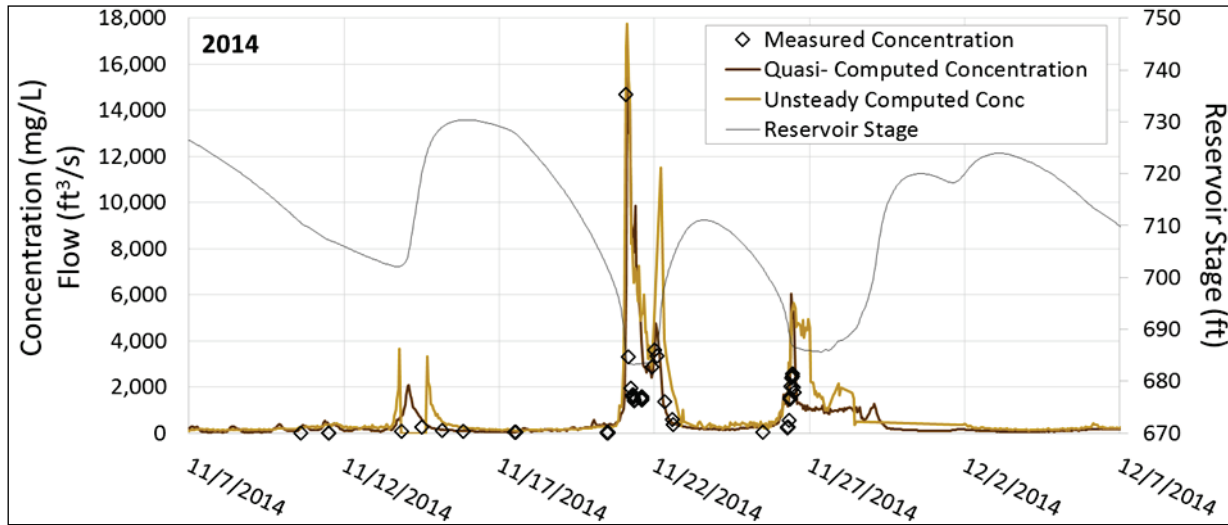


Figure 5. Unsteady concentration results from 2014 simulation plotted with quasi-unsteady results.

Model Developments. HEC-RAS 5.0.3 (and earlier versions) could not control water surfaces behind a dam in the quasi-unsteady flow mode. Modelers could only control a reservoir pool by making the reservoir stage a downstream boundary condition, which excluded the structure from the model. This limitation made it impossible to simulate sediment dynamics upstream and downstream of a dam, or a multiple-structure reservoir cascade, in a single model. As part of this RSM initiative, HEC added internal stage boundary conditions to the HEC-RAS quasi-unsteady hydrodynamic model (Figure 6).

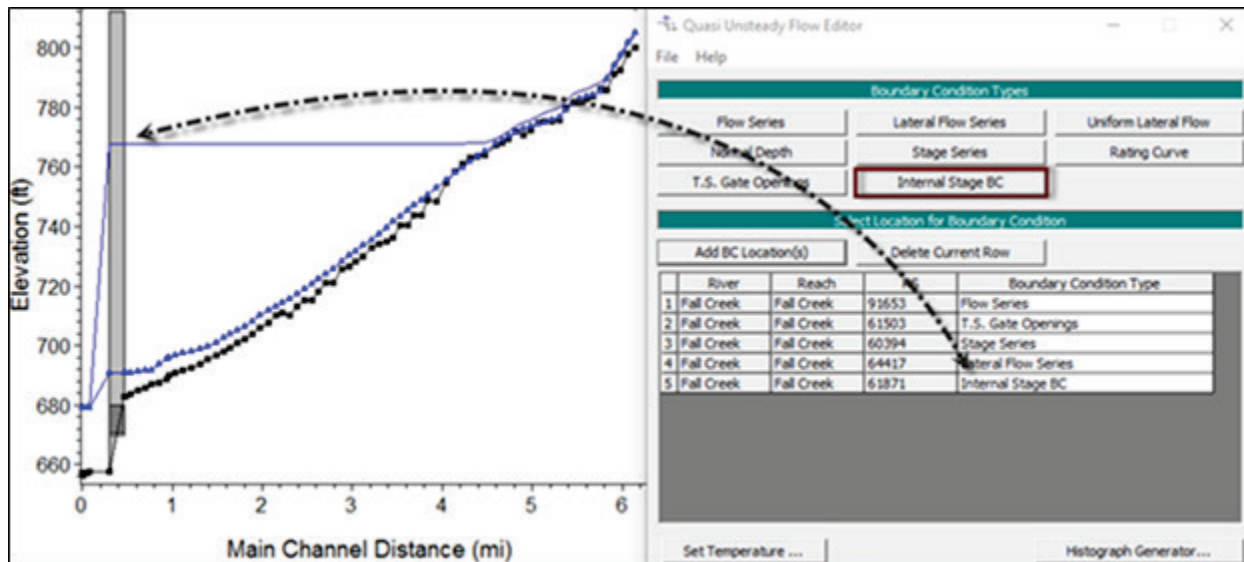


Figure 6. Internal stage boundary condition added to simulate reservoir operations in a quasi-unsteady model.

Specifying a reservoir stage allows modelers to simulate the reservoir and the downstream reach, as well as multi-reservoir systems in the same quasi-unsteady model. The Fall Creek quasi-



unsteady sediment model was replicated with the classic (downstream stage) and new (modeled dam and internal boundary condition) methods and produced very similar results. See Gibson et al. (2017) for more information on this feature.

While unsteady flow modeling is more flexible than quasi-unsteady flow modeling, it also can be less stable. HEC-RAS presently computes each unsteady flow time-step faster than each quasi-unsteady time-step. Previous versions of HEC-RAS required a single unsteady time-step for the whole simulation. Running the entire simulation at the minimum stable time-step generated long unsteady run times. A single unsteady time-step can be particularly limiting for an unsteady mobile bed model of a drawdown flush simulations because drawdown models often require very small time-steps to resolve a brief time window when the dropping pool exposes the delta.

HEC introduced a variable time-step feature for unsteady flow simulations in HEC-RAS version 5.0.4. HEC-RAS can now automatically compute appropriate time-steps throughout the simulation based on the Courant number or can subdivide time-steps during user-specified time windows. The latter method was added specifically for drawdown flushing simulation and was first applied to this model of Fall Creek. Variable time-steps (Table 2) allowed the model to simulate most of the flush at stable 30 min time-steps but dropped to 30-second time-steps during several critical simulation days where the falling pool transitioned into a run-of-river regime. Variable time-steps improved unsteady model run time by up to an order of magnitude, simulating the drawdown in 11 min (for a 77-day simulation).

Table 2. User-specified time-step adjustment in HEC-RAS.			
• Adjust Time Step Based on Time Series of Divisors			<input type="button" value="Verify Dates..."/>
	Time Step	Date(ddMMMyyyy hhmm)	Divisor
1	30.00 sec	20Nov2014 2000	60
2	10.00 min	26Nov2014 2000	3
3	30.00 min	30Nov2014 2000	1
4			
5			
6			
7			
8			

CONCLUSIONS: Several USACE reservoirs are facing more severe sediment challenges than Fall Creek. For reservoirs with the necessary infrastructure (e.g., low level outlets), or reservoirs which the USACE could retrofit with the necessary infrastructure, drawdown flushing is often the most effective method to reclaim reservoir capacity and restore sediment continuity. Fall Creek presents a precedent for large-scale reservoir flushing. These flushes demonstrate that drawdown flushing can be consistent with USACE missions and partner agency objectives. Additionally, this modeling study increased confidence that a 1D sediment model like HEC-RAS can credibly approximate flushing concentrations downstream. This is a conclusion similar to the work of Gibson and Boyd (2016a,b), who applied HEC-RAS to Spencer Dam on the Niobrara River. However, the Fall Creek morphology is fundamentally different from the Niobrara River. The



Niobrara River is a low-gradient sand-bed river with a fine-sand reservoir delta while Fall Creek is a high-gradient bedrock river with a reservoir delta composed largely of cohesive sediment with significant cobble content. HEC-RAS simulated reservoir flushing effectively in both settings, demonstrating the flexibility of USACE modeling tools for these analyses.

ADDITIONAL INFORMATION: This RSM-TN was prepared for the USACE National RSM Program, a Navigation Research, Development, and Technology Portfolio program administered by Headquarters, USACE, and the U.S. Army Engineer Research and Development Center.

POINTS OF CONTACT: This RSM-TN was prepared by the USACE Portland District (NWP) as part of the USACE NWP RSM Program and was written by Stanford Gibson, USACE IWR, HEC, and James Crain (NWP). Additional information regarding the USACE National RSM Program may be obtained at <http://rsm.usace.army.mil>.

Questions regarding this RSM-TN or the National RSM Program may be addressed to the following:

Stanford Gibson: Stanford.Gibson@usace.army.mil
(HEC RSM POC)

Katherine E. Brutsche: Katherine.E.Brutsche@usace.army.mil
(USACE National RSM Program Manager)

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REFERENCES

- Gibson, S., and P. Boyd. 2016a. "Monitoring, Measuring, and Modeling a Reservoir Flush on the Niobrara River in the Sandhills of Nebraska." *Proceedings, River Flow 2016. International Conference on Fluvial Hydraulics. St. Louis, Missouri*. Edited by G. Constantinescu, M. Garcia, and M. Hanes, 1448-1455. Boca Raton, FL: CRC Press.
<https://www.bing.com/search?q=Gibson,+S.+and+P.+Boyd.+2016a.+Monitoring,+measuring,+and+modeling+a+reservoir+flush+on+the+Niobrara+River+in+the+Sandhills+of+Nebraska.+Proceedings,+River+Flow+2016&src=IE-SearchBox&FORM=IESR3A>
- Gibson, S., and P. Boyd. 2016b. "Designing Reservoir Sediment Management Alternatives with Automated Concentration Constraints in a 1D Sediment Model." *Proceedings, 13th International Symposium on River Sedimentation, Stuttgart, Germany*. Edited by S. Wieprecht, S. Haun, K. Weber, M. Noack, and K. Terheiden, 1000-1006. Boca Raton, FL: CRC Press.
- Gibson, S., A. Sánchez, S. Piper, and G. Brunner. 2017. "New One-Dimensional Sediment Features in HEC-RAS 5.0 and 5.1." *Proceedings, World Environmental and Water Resource Congress*. Edited by C. Dunn and B. Van Weele, 192-206. Sacramento, CA: American Society of Civil Engineers, Environmental and Water Resources Institute. <https://doi.org/10.1061/9780784480625.018>
- Kondolf, G. M., G. Yongxuan, G. W. Annandale, G. L. Morris, E. Jiang, and J. Zhang. 2014. "Sustainable Sediment Management in Reservoirs and Regulated Rivers: Experiences from Five Continents." *Earth's Future*, 2(5): 256-280.



- Morris, G. L., and J. Fan. 1997. *Reservoir Sedimentation Handbook: Design and Management of Dams, Reservoir and Watersheds for Sustainable Use*. New York, NY: McGraw-Hill.
- Partheniades, E. 1965. "Erosion and Deposition of Cohesive Soils." *Journal of the Hydraulics Division*. 91(HY1):105-139. Reston, VA: American Society of Civil Engineers.
<http://cedb.asce.org/CEDBsearch/record.jsp?dockkey=0013640>
- Randle, T. J., and J. Bountry. 2017. *Dam Removal Analysis Guidelines for Sediment*. Washington, DC: U.S. Department of the Interior, Bureau of Reclamation, Advisory Committee on Water Information, Subcommittee on Sedimentation. https://www.bing.com/search?q=DamRemovalAnalysisGuidelines2017_508.pdf&src=IE-SearchBox&FORM=IESR3A
- Schenk, L. N., and M. Bragg. 2014. *Assessment of Suspended-Sediment Transport, Bedload, and Dissolved Oxygen during a Short-Term Drawdown of Fall Creek Lake, Oregon: Winter 2012–13*. Open File Report 2014. Reston, VA: U.S. Geological Survey.
- U.S. Army Corps of Engineers, Portland District (NWP). 2018. *Calibration of HEC-RAS Quasi-Unsteady Sediment Transport Model for Fall Creek Reservoir Drawdown*. Portland, OR: U.S. Army Corps of Engineers, Portland District.

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