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Cherry Creek Pressure Flushing: A 3D Modeling Approach

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ABSTRACT

A numerical modeling study of pressure flushing through outlet works is reported at the Cherry Creek Dam and Reservoir, Denver, Colorado. Specifically, a 3D numerical model is developed and applied. The project is a joint collaborative effort among the U.S. Bureau of Reclamation, US Army Corps of Engineers, and U.S. Geological Survey on the study of reservoir outlet maintenance activities. The 3D model is based on the solution of the Navier-Stokes equations along with sediment transport and mobile-bed modules. The numerical model results are compared with the field measurement results. Repeat land and bathymetric surveys, sediment sampling, and suspended sediment concentration measurement were made at the study site. The comparison allows us to evaluate the suitability of the numerical models for pressure flushing modeling. Model results may be used to evaluate whether improvements to gate operations may be made to increase the efficiency of sediment removal from the reservoir.

INTRODUCTION

Reservoir sedimentation is becoming an increasingly prominent issue as new dam construction is becoming less viable. It has led to an average annual loss of one percent of the reservoir storage capacity worldwide (Basson, 2007). As a result, reduction of reservoir sedimentation will be the key to achieve the sustainable use of reservoirs.

At Reclamation, most dam facilities are approaching to the design age of 100 years. Reservoir sedimentation is becoming a major concern; it will limit the agency to meet its future water delivery mission. Often, the intake elevation for penstocks to the hydroelectric facilities and for water delivery was set at an estimated value after 100 years of sedimentation. This level is being exceeded at many reservoirs. In fact, some Reclamation reservoirs have already been impacted by the sedimentation. Paonia Reservoir, Colorado, is an example where it has failed to meet water deliveries as sediment and debris have blocked its intake. Studies are under way to develop alternatives so sediments may be flushed through the reservoir. Buffalo Bill Dam in Wyoming is another example where the current pressure flushing practice is insufficient to remove the sediment to maintain unobstructed hydropower intake. Reservoir drawdown flushing is an effective alternative but may not always be feasible due to the need for power generation or water supply.

Various sediment removal measures may be used, such as upstream watershed management, hydraulic flushing, sediment bypass tunnels, density current venting, and mechanical dredging (Shen, 1999). Hydraulic flushing is one of the most attractive methods through which the deposited sediment in the reservoir may be removed by opening the bottom outlets (Shen, 1999; Madadi et al., 2017). Two types of hydraulic flushing may be used: drawdown flushing and pressure flushing. Drawdown flushing is carried out by lowering the reservoir pool elevation. However, it is not always possible for large reservoirs, as the stored water is needed for delivery commitments and/or power generation. For such reservoirs, pressure flushing is an alternative. Pressure flushing refers to the process where lower outlet is opened when the reservoir water is maintained at a constant level well above the outlet. Pressure flushing is not as effective as drawdown flushing; only sediment near the outlet is removed (Fan and Morris, 1992; Kantoush, 2008). In addition, pressure flushing schedule, such as timing, duration and release discharge, may have a significant impact on the flushing efficiency. Our understanding, however, is limited at present.

Past studies of pressure flushing are primarily experimental in nature in order to optimize the layout and design of the hydraulic structures. For example, Talebbeydokhti and Naghshineh (2004) conducted an experiment using the physical model and found that the amount of sediment flushed was a function of the release discharge, water level and flushing channel width. Meshkati et al. (2009; 2012) studied the time dependent process of the scour cone and developed a set of non-dimensional relationships for the temporal variations of the scour cone dimensions. The effect of the outlet cross-section size was investigated on the cone development. The cone size was found to be a strong function of the outlet diameter. Powell and Khan (2012, 2015) reported laboratory studies with circular outlets. The study focused on the flow characteristics such as vortices and the sediment transport at the outlet.

Using physical models is important to understanding processes and in the application to conditions similar to which the experiments were conducted, but the application to general field situations will be improved by developing numerical models that can be applied to a larger range of conditions. Few studies have been conducted in the numerical model area although free-flow drawdown flushing has been reported by many researchers (e.g., Chang et al., 1996; Liu et al., 2004; Lai and Greimann, 2012; Haun and Olsen, 2012). In this study, a new 3D model is developed to simulate pressure flushing. The model is then applied to simulate the flushing operation at the Cherry Creek Reservoir, Colorado. Model results are compared with the available field data and reported below.

NUMERICAL MODEL

A 3D model is developed for simulating the pressure flushing process. The flow hydrodynamics solver is based on the U^2RANS model developed by Lai et al. (2003). The model solves the unsteady Reynolds averaged Navier-Stokes (RANS) equations as:

$$\frac{\partial \rho}{\partial t}+\frac{\partial \rho U_j}{\partial x_j}=0 \tag{1}$$

$$\frac{\partial \rho U_i}{\partial t}+\frac{\partial \rho U_i U_j}{\partial x_j}=\frac{\partial}{\partial x_j}\left(\mu \frac{\partial U_i}{\partial x_j}+\tau_{ij}\right)-\frac{\partial P}{\partial x_i}+\rho g_i \tag{2}$$

where t is time; x_j is the j-th Cartesian coordinate; ρ is the water-sediment mixture density; U_j is the mean velocity components along the Cartesian coordinate x_j; $\tau_{ij}=-\rho\overline{u_i u_j}$ is the turbulence stress with u_j the j-th turbulent fluctuating velocity component; P is the mean pressure; μ is the mixture viscosity; and g_i is the i-th component of the acceleration due to gravity.

The standard k-ε model of Launder and Spalding (1974) is adopted to relate the Reynolds stresses to the mean strain rate by:

$$\tau_{ij}=\mu_t\left(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i}\right)-\frac{2}{3}\rho k \delta_{ij} \tag{3}$$

$$\mu_t=C_\mu \rho \frac{k^2}{\varepsilon} \tag{4}$$

The turbulence kinetic energy k and the dissipation rate ε are governed by:

$$\frac{\partial \rho k}{\partial t}+\frac{\partial \rho U_j k}{\partial x_j}=\frac{\partial}{\partial x_j}\left((\mu+\frac{\mu_t}{\sigma_k})\frac{\partial k}{\partial x_j}\right)+G-\rho\varepsilon \tag{5}$$

$$\frac{\partial \rho \varepsilon}{\partial t}+\frac{\partial \rho U_j \varepsilon}{\partial x_j}=\frac{\partial}{\partial x_j}\left((\mu+\frac{\mu_t}{\sigma_\varepsilon})\frac{\partial \varepsilon}{\partial x_j}\right)+C_{\varepsilon 1}\frac{\varepsilon}{k}G-C_{\varepsilon 2}\rho\frac{\varepsilon^2}{k} \tag{6}$$

where $G=\tau_{ij}\frac{\partial U_i}{\partial x_j}$ is the turbulence generation rate. The model constants are:

$C_\mu=0.09;\ C_{\varepsilon 1}=1.44,\ C_{\varepsilon 2}=1.92,\ \sigma_k=1.0,\ \sigma_\varepsilon=1.30$

Suspended load sediment transport is simulated. The 3D transport of a suspended load is governed by the following advection-diffusion equation:

$$\frac{\partial C}{\partial t}+\frac{\partial UC}{\partial x}+\frac{\partial VC}{\partial y}+\frac{\partial (W-\omega)C}{\partial z}=\frac{\partial}{\partial x}\left(D_t\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(D_t\frac{\partial C}{\partial y}\right)+\frac{\partial}{\partial z}\left(D_t\frac{\partial C}{\partial z}\right) \tag{7}$$

In the above, C is the sediment volume concentration, ω is the fall velocity, and D_t is the turbulence diffusivity. The diffusivity is made to be the eddy viscosity in this study. The fall velocity is computed by (van Rijn, 1993):

$$\omega_k = \frac{(\gamma-1)gd_k^2}{18\nu} \qquad 65\mu m < d_k \le 100\mu m$$

$$\omega_k = \frac{10\nu}{d_k}\left(\sqrt{1+\frac{0.01(\lambda-1)gd_k^3}{\nu^2}}-1\right) \qquad 100\mu m < d_k \le 1000\mu m \tag{8}$$

$$\omega_k = 1.1\sqrt{(\gamma-1)gd_k} \qquad 1000\mu m < d_k$$

γ = specific gravity of sediment ($=\rho_s/\rho_w$)

ν = kinematic water viscosity (m^2/s)

At reservoir bed, net sediment flux reflects the net sediment exchange between those in water column and bed. It is non-zero unless the flow is in equilibrium. The net sediment flux is computed by:

$$\omega C + D_t\frac{\partial C}{\partial z} = D - E \tag{9}$$

The deposition rate is computed by $D = \omega C$ and the entrainment rate for the non-cohesive sediment is computed by $E = \omega C_{b*}$. Here, the entrainment rate is proportional to the local near-bed equilibrium concentration based on the equation of Zyserman and Fredsøe (1994) as follows:

$$C_{b*} = \frac{0.331(\theta-0.045)^{1.75}}{1+\frac{0.331}{0.46}(\theta-0.045)^{1.75}} \tag{10}$$

$$\theta = \frac{{u_\tau}^2}{(\gamma-1)gd} \tag{11}$$

In the above, d is the sediment diameter and u_τ is the bed friction velocity.

For cohesive sediment, the entrainment rate is calculated differently as:

$$E = \varepsilon(\tau_b - \tau_c) \tag{12}$$

where ε is the erodibility, τ_b is bed shear stress, and τ_c is the critical shear stress of the cohesive sediment.

Finally, bed elevation change is allowed while bed is eroded or deposited. The change in bed elevation (z_b) follows the following equation:

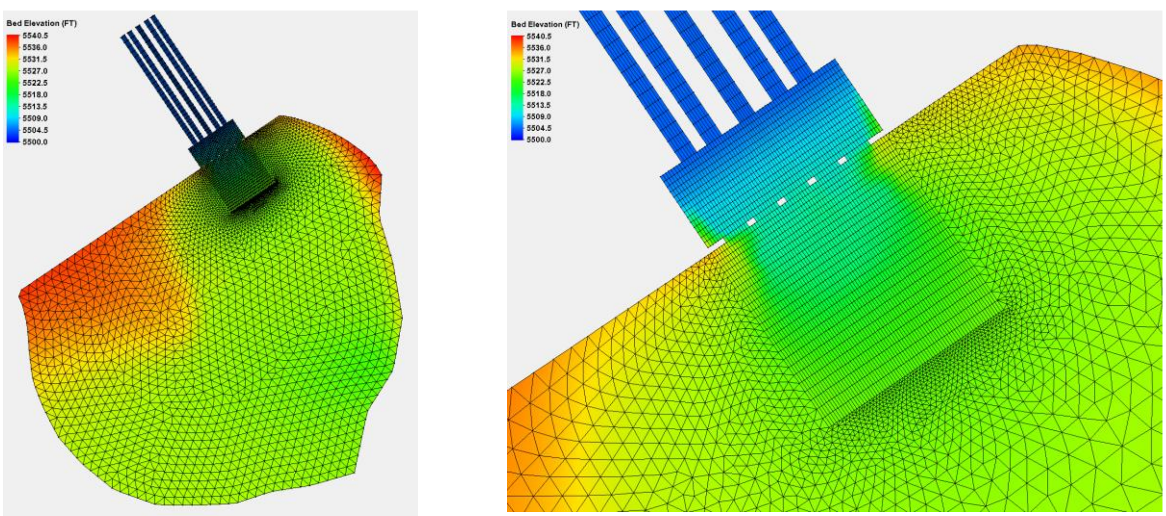
$$(1-\sigma_a)\frac{\partial z_b}{\partial t} = E - D \tag{13}$$

where σ_a is the porosity in the bed layer.

MODEL VERIFICATION AND APPLICATION

The above 3D model is applied to simulate the pressure flushing process of the Cherry Creek Reservoir, Denver, Colorado. Model inputs and simulation results are discussed below.

3D Mesh. The unstructured physical coordinate (UPC) sigma mesh of Lai (2018) is adopted. A UPC sigma mesh uses unstructured polygonal cells in the horizontal plane and an equal number of mesh points in the vertical direction. For the modeling of Cherry Creek pressure flushing, the model domain, the 2D horizontal mesh and the reservoir terrain are shown in Figure **1**. The reservoir terrain is based on the pre-2018 flushing survey carried out by Collins et al. (2019). The number of vertical mesh points is maintained at 47 covering the deepest depth between 5504 and 5550 ft.



(a) Model Domain (b) Close-up view in the intake

Figure 1. The model domain, the horizontal mesh and the terrain of the reservoir.

Model inputs. Simulation is carried out to match the pressure flushing carried out on May 23, 2018 at the Cherry Creek Reservoir. The maximum nominal discharge is 1,300 cfs. The flow release is through opening one of the five gates and following the sequence of 3, 1, 2, 4, 5 (the gates are numbered from right to left looking towards the intake). The actual release is shown in Figure **2** which is used for modeling.

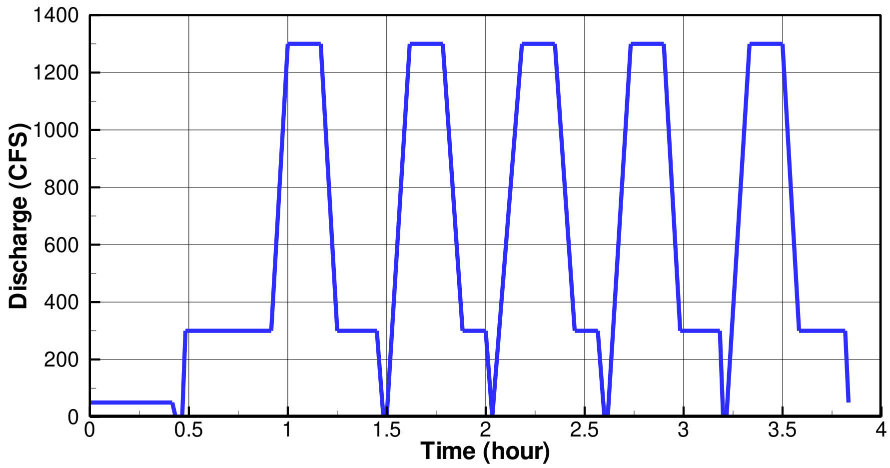


Figure 2. The 2018 pressure flushing release rate.

The sediments in the Cheery Creek Reservoir consists of clay, silt and sand. According to the measurement data of Armstrong (2017), the fractions for clay, silt and sand are 45%, 50%, and 5%, respectively. In this study, therefore, only cohesive sediment is simulated. The sediment properties are based on the measured data reported by Armstrong (2017). They include: average sediment specific density of 2.51, bulk density of 520.6 kg/m^3, the critical shear stress of 0.62 Pa, and the erodibility of 3.547×10^{-4} m/s-Pa.

Results and Discussion. The model predicted sediment concentration during the 2018 pressure flushing is compared with the field measured data of Dombroski (2018). The numerical model concentration is right after the exit of the numerical gates (within the outlet works), while the measured sediment concentration was made further downstream within the Cherry Creek, about 0.25 mile downstream of the dam outlet (Dombroski, 2018).

The predicted sediment concentration is compared with the field data in Figure **3**. It is seen that the numerical model agrees with the data reasonably well. Overall, the concentration is under-predicted over the first period of about 1.2 hours, while it is over-predicted over the remaining period. The total amount of sediment release is close to the measured data. It is possible that the initial concentration was measured to be too high as sediments stored downstream of the release outlet in the channel upstream of the measurement site may contribute to the measured concentration.

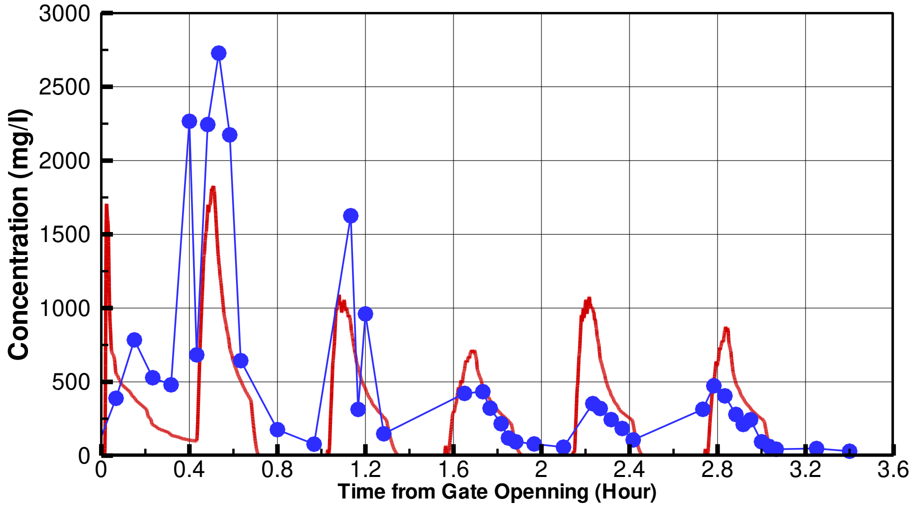
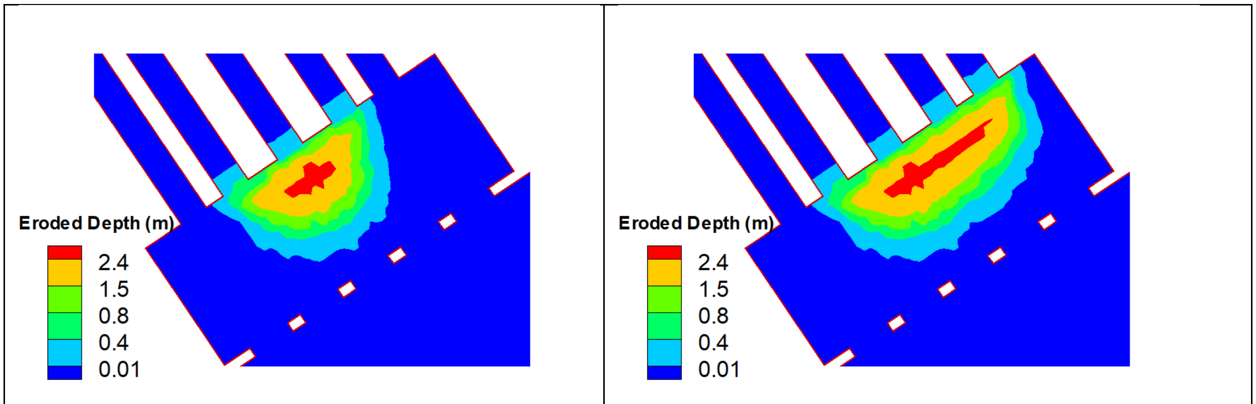


Figure 3. Numerical mode predicted (red) and field measured (blue) sediment concentration downstream of the release gate.

It is interesting to investigate the erosion pattern produced by the pressure flushing. The erosion pattern (scour zone) development due to the 2018 pressure flushing is displayed in Figure **4**. The numerical modeling results show that the scour zone is limited to near-gate areas and within the intake. This is qualitatively confirmed by the fact that the 2018 field survey in the reservoir was unable to detect measurable erosion upstream of and outside of the intake tower. Quantitative comparison, however, is not possible as the field measurements were not able to reach inside the intake.



(a) Time = 1.0 Hour (b) Time = 1.5 hour

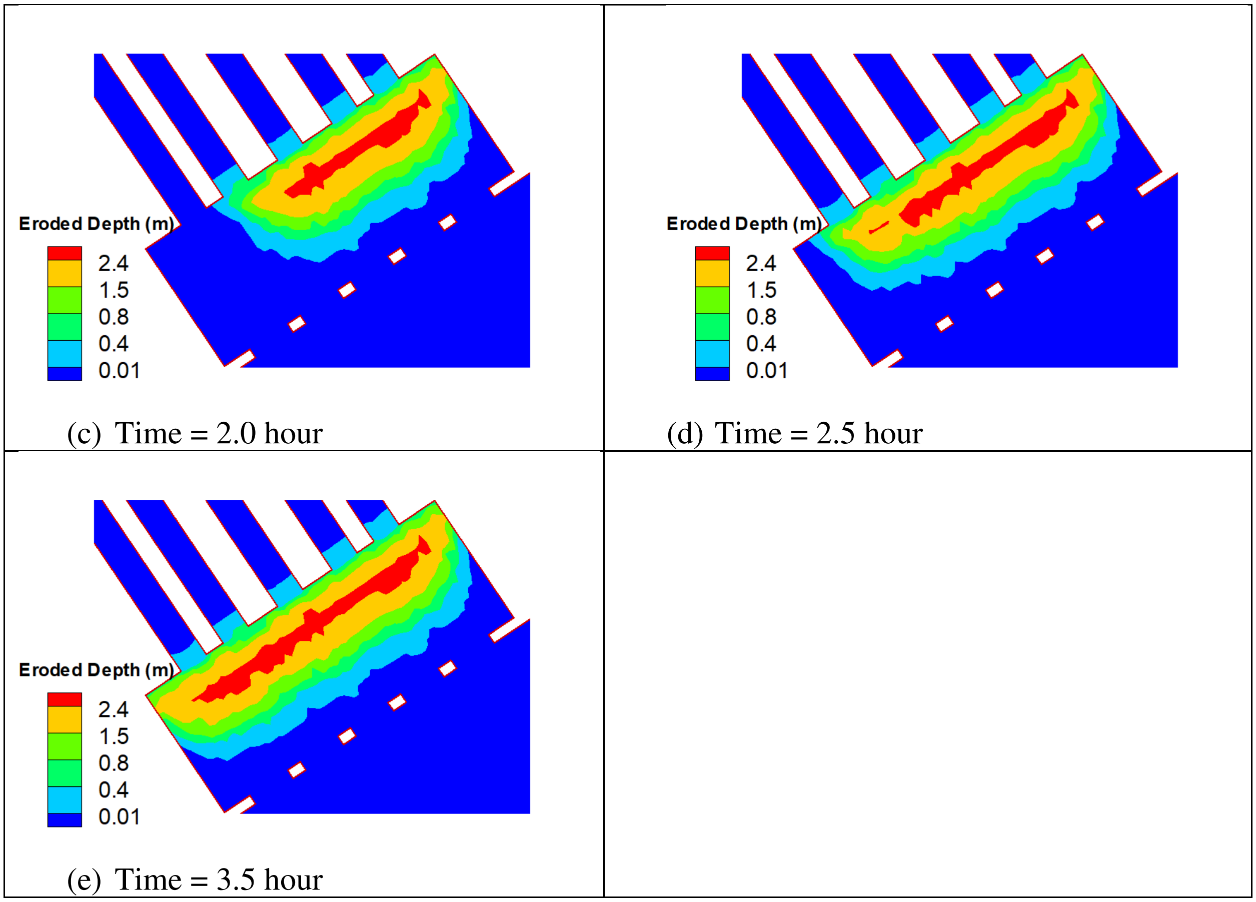


Figure 4. Predicted scour zone development in time during 2018 flushing (contours represent the eroded depth in meter).

CONCLUSION

A 3D numerical model is developed to simulate the pressure flushing at the Cherry Creek Reservoir. The study shows that the model works well for such applications. The specific modeling of the 2018 pressure flushing at the reservoir leads to the following key findings:

- The predicted sediment release concentration is compared with the measured data downstream in the river. The agreement is reasonable and points to the potential of the 3D model for future pressure flushing applications.
- Pressure flushing is not an efficient means to remove large volumes of sediment in reservoirs. Both the numerical and field results showed that pressure flushing failed to remove sediment deposits outside the intake in the reservoir.
- Pressure flushing does produce scour cones upstream of the gates but limited to within the intake. Pressure flushing thus is effective if the objective is to clean up the sediment deposits within the intake tower and prevent clogging from occurring in front of the gates.

The numerical model may be used to develop an effective strategy of flushing. For example, based on the above results, a 3-gate release - gates 3, 1 and 5 - would be more efficient than the current 5-gate schedule.

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