Sediment Modeling of Hydraulic Flushing: General Guidelines

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Abstract

Reservoirs have been built on rivers to provide various benefits; undesirable consequences, however, have been resulted in. One of them is reservoir sedimentation – a large amount of inflowing sediment is blocked by the dam, causing deposition within the reservoir and sediment starvation downstream. Reservoir sedimentation reduces the reservoir storage capacity, increases the risk of plugging the water intake, and impacts the eco-system negatively.

Hydraulic flushing is an often-adopted method to remove deposited sediments in reservoirs by opening bottom outlets. In practice, reservoir managers need to determine the type, the optimum flushing schedule and water release rate. Numerical models are often used to make an informed decision. At represent, general guidelines are lacking on the proper use of numerical models for hydraulic flushing modeling – a gap this paper attempts to address. In this paper, various 1D, 2D and 3D numerical models are introduced and reviewed. General guidelines are presented on how to select a proper numerical model given a specific type of reservoir and flushing method, along with a discussion of the reliability of the model results. Three types of hydraulic flushing methods are relevant and discussed: drawdown flushing, pressure flushing and turbidity current routing.

Introduction

Reservoirs have been built on rivers to provide various benefits such as hydropower, flood protection, water supply, recreation, and navigation. A consequence is the issue of R*eservoir Sedimentation* by which a large amount of inflowing sediment is blocked by the dam and deposited in the reservoir (Annandale et al. 2016). Reservoir sedimentation reduces the reservoir capacity (Moriasi et al. 2018), increases the risk of plugging the water intake (Shelley et al. 2020), and alters ecology negatively (Shelley et al. 2016).

At Bureau of Reclamation (Reclamation), most dam facilities are approaching to the age of 100 years. The outlets of most dams were usually set at levels according to the 100-year sedimentation. This level is being reached and even exceeded at many reservoirs; it has impacted the Reclamation's ability to meet the agency mission of water delivery. For example, Paonia Reservoir in Colorado has had difficulty to meet water delivery as sediment and debris blocked its intake (Huang et al. 2019b). An appraisal level study is underway to develop measures to pass sediments through the reservoir, aiming to determine and then implement a sustainable alternative ultimately. Buffalo Bill Dam in Wyoming, a hydropower generation facility, is another example. The level of the two existing outlets - hydropower and river outlets – is being reached which threatens the power generation. The river outlet has been used for hydraulic flushing operation to pass sediment so that the hydropower intake may be cleared of potential sediment obstruction. However, the existing flushing operation is insufficient to slow down the reservoir sedimentation and new measures are needed if the power generation is not to be negatively impacted for the future. Other Reclamation reservoirs that are experiencing reservoir sedimentation issue leading to reduced project benefits may be cited, such as Black Canyon dam in Idaho, Elephant Butte reservoir in New Mexico, Summer reservoir in New Mexico, Arrowrock reservoir in Idaho, and Horseshoe Dam in Arizona, among others.

In this paper, hydraulic flushing is the primary focus, as it is one of the mostly adopted methods for reservoir sediment management (see reviews by Atkinson 1996 and Chaudhry 2012). The hydraulic flushing consists of three types: drawdown flushing, pressure flushing, and turbidity current routing (or venting). Drawdown flushing is carried out by lowering the reservoir pool elevation, partially or fully. Pressure flushing refers to the process where sediment removal is achieved by opening low-level outlets while the reservoir water is maintained at a constant level well above the outlets. Finally, turbidity current routing refers to the opening of a low-level gates at the right timing and location so that the near-bed traveling fine sediments generated during a large storm event are vented out of reservoir directly. The paper is further limited to the discussion of numerical modeling of hydraulic flushing.

Hydraulic Flushing Analysis and Modeling

Drawdown Flushing

Drawdown flushing lowers the pool elevation, creating an increased flow velocity through the reservoir, and resulting in the entrainment and transport of deposited sediments from the reservoir. This technique is most effective among the three flushing types and has been widely used in reservoirs where water storage requirement allows sufficient water release. However, it may involve a large volume of water passing through the dam; sometimes the reservoir even has to be emptied (Atkinson 1996). When it is poorly managed, sediments from the upstream delta may move towards deeper portion of the reservoir and then deposit, rather than be routed past the dam (Dahl and Ramos-Villanueva 2019). Therefore, a careful study needs to be carried out for its proper use.

Favorable conditions to carry out the drawdown flushing are listed below (Morris and Fan 1998; Kondolf et al. 2014):

- steep longitudinal slope,
- narrow valleys with steep sides,
- river flow above a threshold to mobilize and transport sediment,
- low-level gates large enough to pass the needed flows, and
- strongly seasonal flow patterns.

Dahl and Ramos-Villanueva (2019) considered three factors: total reservoir capacity (CAP), mean annual runoff (MAR), and mean annual inflow of sediment (MAS). Low ratios of CAP/MAR (<0.1) and CAP/MAS (<30) were recommended for drawdown flushing to be successful. Kondolf et al. (2014) recommended that for drawdown flushing to be successful, the CAP/MAR ratio should not exceed 4%.

Pressure Flushing

Pressure flushing refers to the process where flushing is carried out when the reservoir water is maintained at a constant but relatively high level well above the low outlet. Pressure flushing has been widely used for reservoirs in the U.S. where water storage is important and the inflowing sediment rate is relatively small. A key benefit of the pressure flushing is that much less water is released than the drawdown flushing. The effectiveness of pressure flushing, however, is limited to the vicinity of the outlet in sediment removal (Kantoush 2008): Sediments eroded from the reservoir are usually limited to a cone area immediately upstream of the gates. Pressure flushing is often used to clean the sediments and debris near intakes and power generation gates to prevent the outlets from being buried or clogged. In general, pressure flushing schedule adopted – the timing, duration and release rate - impacts the flushing efficiency.

Our understanding of pressure flushing is limited at present and often the design of an efficient flushing schedule is mostly empirical. For a detailed discussion of the empirical relations developed for estimating the scour cone, readers are referred to Lai and Greimann (2020). It is commented that empirical equations will be useful in designing and evaluating expected scour in pressurized flushing scenarios. They have the following limitations:

- The equations may not apply outside of the range of parameters used in the development of these equations;
- The equations do not describe all the characteristics of a scour cone;
- The equations are applicable primarily to simple geometric conditions; other structural features added to increase scouring or more complex geometries will have an unknown effect on the accuracy; and
- The sediment size and cohesive properties are generally not scaled from the field to the laboratory. Therefore, the typical non-dimensional parameters related to sediment size will be much different in the laboratory than the field.

Turbidity Current Routing

Turbidity current may be formed if the incoming sediments are very fine while concentration is high. It is the result of a sediment-laden flow plunging beneath the clear water in the reservoir. It is very complex to determine whether a turbidity current would plunge or not, and often replying on empirical estimate or field observation. Once plunged, the turbidity current moves usually along the bed of the reservoir towards the dam face. Such bottom-moving turbidity current may be routed/vented out of the reservoir using low-level outlets opened at the right timing. Since turbidity current moves near the bed with a finite thickness, the routing/venting can be a very effective sediment management tool and has been studied extensively both in the field and through numerical modeling (e.g., Lai et al. 2015 and Huang et al. 2019a).

Earlier analyses of turbidity current were mostly empirical and analytical. Much information is available in the literature for understanding the turbidity current characteristics such as the plunging criteria, mixing rate, and entrainment from the upper clear water layer. The need to analyze and predict turbidity current characteristics has prompted the development of empirical and analytical models. Representative works in the area include those of Ford and Johnson (1983) and Imberger et al. (1978). A large amount of information contained in the work of Ford and Johnson (1983) was used to develop an empirical model named DCURL at Reclamation (Simoes 1999).

Numerical Modeling Review

Numerical models have been developed and widely used in hydraulic flushing studies. The model complexity, however, varied significantly - ranging from 1D, 2D and 3D models. An overview was reported by Teal et al. (2015), and a review has been provided by Anari et al. (2020). Herein a summary is provided with our own review.

1D numerical models have been used the most due to two reasons: (a) it requires the least amount of computing power and is probably the only option for long-term simulation, and (b) various 1D models have been developed and freely available to the public. A primary limitation users need to be aware is that 1D models are appropriate primarily for run-of-the-river or narrow reservoirs where flow is highly channelized and transverse mixing is well accomplished (Teal et al. 2015). Some of the 1D models adopted in the past studies are listed below:

- HEC-6: It was used, e.g., by Morris and Hu (1992) to simulate sediment flushing in the Loíza Reservoir in Puerto Rico.
- FLUVIAL: Chang et al. (1996) used the model to evaluate the drawdown flushing during a flood event at a series of reservoirs on the North Fork Feather River in Northern California.
- GSTAR4: It was adopted by Ahn (2012) and Ahn et al. (2013) to simulate the sediment flushing in Xiaolangdi Reservoir of the Yellow River, China, as well as in Lewis and Clark Lake of the Missouri River.
- HEC-RAS 1D: This model has been widely used for many hydraulic flushing simulations. For example, Boyd and Gibson (2016) reported simulating 2014 fall flush of the reservoir of Spencer Dam, 40 miles upstream of the confluence of the Niobrara River and the Missouri River. It was reported that the model underpredicted the delta scour by about 50% and over-predicted the peak sediment concentration downstream of the dam. The authors attributed the difference to the channel widening process which could not be simulated correctly by 1D models. In another study by Gibson and Crain (2019), the drawdown sediment flushing was simulated at Fall Creek Reservoir, Oregon.
- SRH-1D: It is another model that has been variously used for hydraulic flushing modeling. For example, Brignoli (2017) simulated the controlled sediment flush in Isolato and Madesimo Reservoirs in Italy. The model predicted the sediment impact in the downstream of the two dams and at the downstream of the conference. The author found that a satisfactory agreement between the computed and the observed depositional pattern was obtained. In another example, Huang et al. (2019) reported the use of the model to evaluate a specific sediment flushing plan for the Paonia reservoir on Muddy Creek in western Colorado. The model was first calibrated with 3 years of field data and then used to predict short-term sediment management under different reservoir operations.

2D depth-averaged numerical models are more general than the 1D models and being adopted extensively due to the availability of several federal agency developed models and the advancement of desktop computers. For example, reservoirs having relatively large width-to-depth ratio or complex shapes may be simulated by 2D models more accurately. A primary constraint of the 2D models is that the computer run time may be high and viable primarily for event-based simulations. Some of the previous 2D modeling studies are summarized below involving the use of various models:

- SSIIM: It is a widely used model for open channel sediment transport simulation. For example, the model developer himself (Olsen 1999) presented a 2D modeling study of the reservoir hydraulic flushing study at the Kali Gandaki Hydropower Reservoir, Nepal. Note that SSIIM is primarily a 3D CFD model to be discussed later.

- WOLF-2D: Dewals et al. (2004) used the 2D model to simulate sediment flushing in a reservoir in India. The model predicted that only a narrow channel was generated by the flushing.
- Delft3D: It is another popularly used sediment transport model which has a 2D component. For example, Boeriu et al. (2011) presented hydraulic flushing case studies using the 2D capability of the model. The studies were related to the sediment erosion in an unnamed reservoir in Sri Lanka where multiple 5 to 10 days of flushing operations were implemented; in another, the Koga reservoir in Ethiopia was simulated with a 35-day drawdown.
- BASEMENT: Iqbal et al. (2019) reported the use of the 2D model to simulate two sediment flushing cases: (a) a 1:40 physical model of the reservoir of the Gulpur Hydropower Plant, Poonch river, Pakistan-administrated Kashmir; (b) laboratory flushing experiment of Lai and Shen (1995).
- MIKE21: It is a commercial 2D model widely used for sediment transportation simulation. For example, Chaudhary et al. (2019) reported using the model to simulate hydraulic flushing of a proposed reservoir on the Dibang River in east Asia. The numerical modeling estimated how much sediment could be flushed out with various flushing discharges and durations.
- SRH-2D: It is a freely available model developed at Reclamation. The use of the model at Reclamation for sediment flushing studies have been reported. For example, it was used to simulate sediment management at the Robles diversion dam on the Ventura River, California (Lai 2008b); it was also used for drawdown flushing of the Copco 1 dam on the Klamath River, Oregon (Lai and Greimann 2012). Other studies have also been reported using the model. Example studies in recent years include the work of Wang et al. (2020) who investigated different reservoir drawdown scenarios at Agongdian Reservoir, Taiwan, and the study of Stillwater Sciences (2021) who used the model to simulate sediment processes under dam removal scenarios at the Matilija Dam within the Ventura River watershed in southern California.

It is noted that special models have also been developed to simulate turbidity current routing, as such a model is complex and difficult to develop. Most existing models are inadequate to simulate turbidity current transport within reservoirs once the current plunges to the bottom. Turbidity current models range from 2D laterally averaged model, 2D layer-averaged model, and 3D models, although 1D models have also been developed. We believe layer-averaged 2D models have the best potential for engineering applications and they are discussed below:

- Bradford and Katopodes (1999) studied turbidity undercurrents in deep sea environment. They developed a finite-volume numerical model to capture the current front with the predictor-corrector time-stepping scheme.
- Groenenberg (2009) developed a 2D model that used a combination of the explicit fractional-step MacCormack scheme and a high-resolution shock-capturing technique.
- At Reclamation, a comprehensive 2D layer-averaged turbidity current model is developed into SRH-2D; the model was successfully applied to several typhoon events at the Shihmen Reservoir, Taiwan. Lai et al. (2015) reported the theory and model validation; Lai and Wu (2018) reported the application of the model for assessing the effective of bypass tunnels; and Huang et al. (2019a) reported the validation of the model for several typhoon events in the field.

3D numerical models have rarely been used for hydraulic flushing modeling, and only a few studies were reported for field applications. We note that it is important to distinguish the hydrostatic-assumption 3D models (e.g., Delt3D) and the non-hydrostatic model based on the solution of full Navier-Stokes equations – named 3D CFD models in this paper. We believe only 3D CFD models are beneficial in the adoption of 3D models for hydraulic flushing study in order to achieve the maximum benefits of 3D modeling. Some of the past studies are discussed below:

- Ghoreishi and Tabatabai (2010) used a 3D CFD model to simulate the reservoir flushing case of Lai and Shen (1995). The model predicted the channel erosion near the dam well; however, it did not reproduce the observed eroded channel developed longitudinally upstream.
- Haun and Olsen (2012) applied the 3D model SSIIM to predict reservoir flushing processes. The model was applied to a physical model of the Kali Gandaki hydropower reservoir in Nepal. Later, Olsen and Haun (2018) updated the model to include the bank failure algorithm. The model reproduced the number and magnitude of the slides well, but the locations were not always correct. The SSIIM model was also used by Saam et al. (2019) to simulate the flushing efficiency of the Schwarzenbach reservoir in the Black Forest, Germany.
- Esmaeili et al. (2015) employed the 3D SSIIM to simulate the 2012 sediment flushing operation in Dashidaira Reservoir, Japan. Sediment flushing operation has been performed through the bottom outlets every year during the first major flood event in the rainy season since 1991. The results showed that the 3D model properly simulated the flushing channel evolutionary pattern. Esmaeili et al. (2017) presented additional calculations using the same model.
- Ermilov et al. (2018) used the TELEMAC-MASCARET model to simulate the pressure flushing scenarios. The 3D model was capable of simulating the sudden sediment removal processes in a schematized reservoir. The model also reproduced the typical scour cone shape upstream of the flushing gate, along with the locally varying flow features.
- Reclamation has developed a 3D CFD model to simulate pressure flushing processes at the Cherry Creek Reservoir, Denver, Colorado (Lai and Greimann 2020). The model results were compared with the field data and satisfactory predictions were reported.

It is note that commercial CFD models, such as ANSYS FLUENT and FLOW-3D, have also been used for various sediment modeling studies. For example, Castillo et al. (2015) adopted the FLOW-3D for sediment simulation at the initial stage of the gate-opening during a flushing operation.

General Guidelines

General recommendations on how to select a 1D, 2D depth-averaged, or a 3D CFD model are presented below. They are based on an extensive case studies carried out with projects at Reclamation.

1D Models

A key advantage of 1D models is that they require a minimal amount of computing time among all models. Therefore, 1D models are most widely used; in particular, they are still recommended for long-term simulation (e.g., more than 10 years). 100-year scenario modeling study has been routinely carried out with 1D models.

Example study questions that may be answered by 1D models may include the following:

- reservoir sedimentation and storage loss,
- long-term flushing efficiency among different flushing alternatives,
- reservoir sustainability impact of reservoir operation,
- sediment concentration released from the reservoir,
- long-term sediment impact on the downstream, and
- quantification of the uncertainty of the model results, among others.

A key limitation should be kept in mind in applying 1D models: 1D results may have high uncertainty when a reservoir geometry is wide and/or lateral (along cross-sections) variation is not uniform. In general, the width ratio of the largest reservoir cross section to the narrowest or drawdown section is not to exceed 4 to 5. The reliability of the 1D model results increases when the width ratio is decreasing and the pool level is lowered. The highest accuracy may be achieved when the flow through the reservoir pool during flushing is similar to the run-of-the-river type. 1D models are not recommended for pressure flushing or turbidity current routing simulation.

2D Depth-Averaged Models

2D models are more general and results are more accurate than 1D models. However, they usually take much longer to complete than the 1D models, and therefore, may be limited in the selection of the spatial extent and time scale of the model. 2D models are the choice if computer run time is not a concern for the study questions.

Scenarios where 2D modeling may be warranted include the following:

- 2D models are recommended if the total longitudinal length of the model domain is less than, e.g., 10 miles, and time scale of the simulation is limited to a few drawdown events or less than 1 to 2 years.
- 2D models are applicable to both drawdown flushing and turbidity current routing.
- 2D models are recommended if the width of the reservoir is wide (e.g., the width ratio is more than 4 to 5) or highly sinuous, or the assumption of a constant water level variation laterally breaks down.
- 2D modeling is highly recommended if the delta evolution is to be simulated where the delta would move into lateral tributaries and margins.
- 2D models are highly recommended for flushing cases where multiple gates are available and they are distributed across the dam face.

Note that a widely-held view that 2D modeling setup and calibration are more time consuming than 1D models may not be valid due to the recent-year advancement of the latest 2D models.

Some potential limitations of the 2D models include:

- 2D models are not recommended for use for pressure flushing modeling;
- 2D model results are usually not right at the initial stage of the flushing when the reservoir level is high relative to the flushing gates;
- flushing-induced channel formation may be underpredicted significantly if the bed consists of cohesive materials, unless the cohesive properties are properly calibrated and; and
- eroded sediment from the channel may be under-predicted due to the failure of a model to handle the bank erosion properly.

3D CFD Models

3D CFD models are the most general and applicable to all types of hydraulic flushing studies, whether it is drawdown flushing, pressure flushing, or turbidity current routing. It is stressed again that 1D and 2D models are not appropriate to use for pressure flushing, as these models assume that the velocity is uniform throughout the pool depth. 1D and 2D models may produce high uncertainty if or when the drawdown is only partial.

A benefit of 3D models is that the adjustable model parameters are only a few and they include mesh resolution, turbulence model, and sediment specific parameters. A key drawback of 3D CFD modeling is that it is very time consuming to simulate, if not prohibitive. Both the spatial extent and the time scale, therefore, should be limited. Some of considerations for 3D modeling are listed below:

- 3D model results may be sensitive to mesh resolution; in general, therefore, a mesh sensitivity study should be carried out.
- The selection of turbulence models is not deemed critical and may be regarded as a secondary issue. However, literature often cites the importance of it. We found that most uncertainties of 3D modeling were related to the mesh resolution and the sediment solver component of the model.
- Accuracy of the scouring results is dictated primarily by the empirical equations of the sediment solver – similar to typical 2D sediment modeling. Therefore, the sediment input parameters need to be carefully selected and calibrated.
- The bed sediment in front of low-level gates is often cohesive for reservoir management simulation; care should be taken to ensure the model has the cohesive modeling capability and the erosion properties of the cohesive sediment are adequately obtained - usually through field measurement - with known uncertainty ranges. Proper model calibration is critical in obtaining statistically meaningful results.

Summary of 1D, 3D and 3D Models

A comprehensive reservoir management/sustainability study may need to adopt the so-called “nested approach” in which all models, 1D, 2D and 3D, are applied. In this approach, the 3D model may be a small zone of the 2D model, and the 2D model may be a subset of the 1D model domain. Often, different study questions are inherently tied to different spatial and time scales and may be answered with different-resolution models. For example, reservoir sedimentation and downstream morphological impact are of the long-term nature and 1D models may be adequate, while the rapid erosion processes at the start of gate-opening for a hydraulic flushing are short-term and may require high-resolution 3D simulation. Castillo et al. (2015) provided such a nested approach example to study the changes expected in the Paute River, Ecuador, after the Paute-Cardenillo Dam is constructed. In the modeling, 1D model was used to estimate the long-term reservoir sedimentation, 2D model was used to simulate the 72-hour hydraulic flushing operation, and 3D model was applied to investigate the sediment transport details when the bottom outlets were opened. It was reported that the 2D modeling of the 72-hour period took about 24 hours of computing time while the 3D modeling of the period required 1,600 hours for the entire reservoir. We estimate that a 1D model may require only a few hours to run a 100-year simulation.

For pressure flushing modeling, only 3D models may be applicable, and 1D and 2D models are not recommended unless the specific case study question warrants their use. Additionally, only a portion of the reservoir pool surrounding the pressure flushing low outlets needs to be simulated – not the entire reservoir. The reason is that the scour cone during the pressure flushing is relatively small and limited to the front portion of the outlets.

For drawdown flushing modeling, 1D or 2D models are recommended for most reservoirs, unless the drawdown water level remains high and sediment processes are more similar to the pressure flushing. The choice between a 1D or 2D model should consult the guidelines above. Note that 2D models have no requirement of the narrowness of the reservoir pool. However, the reliability of the 2D results is still related to the amount of pool level lowered: lower the pool level, higher the accuracy. 3D modeling may be needed for the early stage of drawdown flushing, particularly if the amount of early erosion is significant or it is the study question. It is also commented that two channel erosion types may exist during drawdown flushing: progressive or retrogressive (or knickpoint process) (see Lai and Greimann 2012 for more information). Progressive type is easier to simulate than the retrogressive type.

For the turbidity current routing modeling, it is commented that not all turbid water entering a reservoir would plunge to the bottom and travel as an undercurrent. Field observation and the relevant data or empirical analyses may be needed to make such a determination. 2D layer-averaged model is recommended for turbidity current simulation, as the availability of 2D layer-averaged models makes the use of 1D models less necessary, and turbidity current routing is mostly event-based. 3D CFD models may be applicable and accurate; however, the runtime of 3D models may become prohibitive; 3D models are yet to become practical.

Finally, an extensive number of case studies carried out at Reclamation have been documented in a recent report by Lai and Huang (2022) and may be consulted in the use of 1D, 2D and 3D models for hydraulic flushing simulation. These case studies are not reported herein due to the page limitation of this paper. Readers may also refer to Anari et al. (2020) for more case studies carried out at other agencies.

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