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Monitoring and Modelling of Sediment Flushing : A Review

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Abstract

With ever decreasing potential for suitable new dam sites, sustainable use of existing water reservoirs is of paramount importance. In absence of appropriate measures, reservoir storage is continually reduced due to sedimentation. One option to remove sediment deposits is hydraulic flushing. During the flushing operation, bottom outlets are open and water and sediment released. Whether flushing successfully removes sediment depends on a number of factors, such as bottom outlets' capacity, reservoir shape and water availability. Modelling is often used to assess viability of flushing for sediment management in the reservoir, as well as to design the operations and optimize their scheduling. One-dimensional numerical models are preferred for long term simulations, assessments on of a large number of scenarios, and optimization studies. Two- and three-dimensional numerical models and physical models can be used, each on their own or in combination as hybrid models, to understand local scouring near the gates and other details of operation. Monitoring of flushing operations can help improving their efficiency while at the same time limit downstream impacts. General monitoring of the reservoir and its catchment can help understanding the sedimentation problem and thus facilitate preparation of efficient sediment management strategies. Live monitoring of sediment concentrations is possible with modern equipment though not without challenges, and reservoir survey can be performed faster. Earth observation techniques are also an attractive option, allowing to monitor large areas and areas of difficult access, as well as to provide historical information going back several decades. This paper reviews monitoring and modelling approaches published in the literature, as well as presents some previously unpublished analyses.

Keywords: Dams and reservoirs; numerical models; earth observation

1. Introduction

Construction of dams to impound rivers and create space for water storage has been attested through history, going back several millennia. Some dams have served many generations and even several civilizations (Smith, 1972; Schnitter, 1994; Bildirici, 2001) confirming the possibility of their sustainable use. Proserpina and Cornalbo dams in Spain are examples of such constructions (Castillo, 2007). Yet also in Spain, Valdinferno dam became completely sedimented and had to be abandoned shortly after its completion (Brown, 1944). Apart from hydrological and sedimentological factors, (un)sustainability issues have possibly arisen by somewhat unfortunate economic doctrines of the previous century, which argued for a fixed life time of dams. In the present time, there is a strong preference towards sustainable design and operation of water reservoirs, as is the case with other projects aimed at exploitation of natural resources.

The aim of sustainable reservoir management is to tackle sedimentation and its adverse impacts by achieving an equilibrium between sediment inflow and outflow (Morris, 2015). One of the management strategies is hydraulic flushing of deposited sediment (Schleiss et al., 2016). This method uses forces of flowing water to remove and release sediment that is deposited between two flushing cycles. The most effective type of flushing is the drawdown flushing (Morris and Fan, 1997), where flow forces are maximised and flow is free from backwater throughout the reservoir. This is performed by opening bottom outlets and drawing down the water level in the reservoir. To what degree a reservoir is amenable to flushing depends on various geographic, hydro-sedimentologic and technical factors (White, 2001). Drawdown flushing requires emptying and refilling of the reservoir, which may not always be feasible. Among other limitations is the width of the flushing channel, which may be limited to part of the reservoir width if the reservoir is wide, and result in removal of only a small proportion of sediment deposits. Further review of limitations, and how to address them, is presented in Petkovšek et al. (2020).

Flushing is successfully practiced in reservoirs of various sizes, from less than 1 million m^3 to large storage reservoirs with capacity of more than 1000 million m^3 (Table 1). Flushing is practiced in countries where storage loss to sedimentation exceeds one percent (e.g. China) as well as in the European Alps where it is ten times lower.

Table 1. Reservoirs where drawdown flushing has been practiced with success

Reservoir / Dam	Country	Year built	CAP (M m^3)	MAR (M m^3)	MAS (Mt) or *MAD (M m^3)	Source
Mangahao	New Zealand	1924	2	n/a	*0.03	Jowett (1984)
Zemo-Afchar	Georgia	1927	n/a	6600	5	UNESCO (1985)
Spencer	USA	1927	20.8	1500	*1	Boyd and Gibson (2016)
Barasona	Spain	1932	92	794	*0.25	Cobo (2008)
Jensanpei	Taiwan	1938	8.1	7	0.25	Wang et al. (2018)
Verbois	Switzerland	1943	15	10,000	0.33	Sumi (2008)
Gmund	Austria	1945	0.93	135	0.07	Morris and Fan (1997)
Genissiat	France	1948	53	11,000	0.73	Sumi (2008)
Lavey	Switzerland	1949	n/a	5700	*0.025	Bieri et al. (2012)
Palagnedra	Switzerland	1952	5.5	199	0.08	White (2001)
Agongdian	Taiwan	1953	36.7	54	0.38	Wang et al. (2018)
Cancano	Italy	1956	124	217	n/a	Espa et al. (2019)
Shuicaozi	China	1958	9.6	514	0.63	White (2001)
Heisonglin	China	1959	8.6	14.2	0.71	Morris and Fan (1997)
Barenburg	Switzerland	1960	1.7	3600	0.02	Sumi (2008)
Sanmenxia	China	1960	9,750	43,000	1600	Morris and Fan (1997)
Ferrera	Switzerland	1961	0.23	1300	0.008	Sumi (2008)
Uch-Kurgan	Kyrgyz Rep.	1961	56.4	15,000	13	UNESCO (1985)
Sefid-Rud	Iran	1962	1760	5000	50	Morris and Fan (1997)
Khashm El Girba	Sudan	1964	1300	12,000	85	Adam & Suleiman (2022)
Hengshan	China	1966	13.3	15.8	n/a	UNESCO (1985)
Cachí	Costa Rica	1966	54	1500	0.8	Morris and Fan (1997)
Fall Creek	USA	1966	140	520	0.05	Schenk and Bragg (2014)
Gebidem	Switzerland	1968	9	430	0.4	Morris and Fan (1997)
Rosegg	Austria	1973	19	6500	2	Steiner et al. (2004)
Santo Domingo	Venezuela	1974	3	450	0.2	Morris and Fan (1997)
Nanqin	China	1974	10.2	121	0.5	White (2001)

Table 1. Reservoirs where drawdown flushing has been practiced with success (continued)

Reservoir / Dam	Country	Year built	CAP (M m^3)	MAR (M m^3)	MAS (Mt) or *MAD (M m^3)	Source
Baira	India	1981	2.4	2700	0.3	White (2001)
Bodendorf	Austria	1982	0.9	1000	*0.04	Hartmann (2009)
Dashidaira	Japan	1985	9	1300	0.62	Sumi (2008)
St Egrève	France	1992	6.8	9500	2	Valette et al. (2013)
Fisching	Austria	1994	1.4	1500	*0.085	Harb (2013)
Angostura	Costa Rica	2000	17	3800	1.5	Hoven (2010)
Xiaolangdi	China	2000	13,000	41,000	1400	Ahn (2011)
Unazuki	Japan	2001	24.7	1800	0.96	Sumi (2008)

CAP = storage capacity, MAR = mean annual runoff, MAS = mean annual sediment yield, MAD = mean annual deposition

For flushing operation to be successful, it must be designed and planned carefully. Design and planning must be supported by flushing studies using evidence from field observation and monitoring. Hartmann (2009), White (2001) and others recommended use of physical and numerical models for flushing studies. Experimental studies, as well as monitoring and observation in nature can help closing gaps in knowledge, both in terms of general theoretical questions and to address and improve site-specific issues. Earth observation is a developing monitoring technique that is almost ready to be applied to aspects of reservoir flushing (e.g. the Hypos project). This paper reviews and analyses the selected modelling and some emerging earth observation monitoring approaches described in the literature and applied in practice.

2. Modelling

Natural processes can be modelled numerically, physically or through hybrid approaches. Each approach has its advantages and disadvantages.

Numerical models mathematically represent a set of ideas about natural processes and their relationships, proposed by experts. Although these ideas and models may not entirely correspond to the reality, they are still empirically known to be useful. Their performance is tested by comparing their numerical output with field or laboratory observations. If the two coincide satisfactorily, the model is accepted. This is often the case for simple and readily observable phenomena. Nevertheless, the degree of agreement between the model predictions and observations tends to decrease with more complex, more difficult to measure or uncommon phenomena. Some processes related to the reservoir sedimentation and flushing modelling fall into the latter category, for example bed load transport, sediment entrainment from bed, impact of sediment on turbulence of water flow etc. (Petkovšek and Kitamura, 2022). The main advantages of numerical models, compared to physical models, are fast execution and lower resource demand. They can cover large areas (e.g., coordinated flushing of reservoirs in chain, modelling of impacts on downstream reaches), use for optimization and trade-off analyses where a large number of runs over long time periods is required, easier coupling with habitat models for evaluation of environmental impact, etc.

The main advantage of physical models, over numerical models, is that they are governed by "true" natural processes. Physical models are however constructed at a scale, which requires certain degree of interpretation of their outputs, which is necessarily a human process. Furthermore, modelling of flushing requires modelling of many different processes in addition to flow of water, such as initiation of sediment motion, bedload, suspended load, secondary currents and bedforms. Each process has its different scaling laws which makes it difficult to select an overarching scaling approach. Olsen and Haun (2014) pointed out that as reservoirs are large, the scale used in a physical model must therefore be small, which makes modelling all relevant processes in a physical model more difficult.

To take advantage (and avoid disadvantages) of physical and numerical modelling, hybrid (also called composite) modelling was sometimes attempted.

2.1.Numerical Modelling

White (2001) suggested the use of 1D models to study feasibility of flushing. These models are the least complex and fastest to execute, while more resource demanding 2D or 3D models should be used where this is necessary (Figure 1). Examples include modelling of local impacts near outlets, simulation of wide reservoirs and reservoirs with complex geometries where flow direction and magnitude varies throughout the reservoir. Olsen and Haun (2014) suggested that 3D models are better suited to model flushing flows in reservoirs with training works or for flushing channels with bends, because they can simulate secondary currents, which by its nature is a 3D phenomenon. Alternatively, some 2D models can simulate sediment transport under secondary currents indirectly (Begnudelli et al., 2010), although they were not specifically tested for flushing channels with bends. A comparison of a 1D, 2D and 3D models that form the same modelling suite TELEMAC-MASCARET was performed by Valette et al., (2013). For a long and narrow St. Egrève reservoir in France, they used two separate flushing events to calibrate and validate each model. All three models were able to accurately predict the mass of sediment flushed during a typical flushing event and confirmed that for a linearly shaped reservoir, concluding 1D modelling was sufficient for most practical purposes.

There are some specific 2D or 3D phenomena related to reservoir sedimentation and flushing. Boyd and Gibson (2016) reported that discrepancies between observed values and HEC-RAS 1D model results were found due to the model not being able to represent lateral widening. Others include vertical sediment concentration distribution for simulation of sediment release through outlets or ingress into intakes. Approaches for modelling of these phenomena have been incorporated in 1D models to make them fit for these specific tasks. Fruchard and Camenen (2012) used the RubarBE 1D model developed at IRSTEA to simulate environmentally friendly flushing, where release was made through outlets at different heights with different sediment concentrations, in order to keep downstream sediment concentrations below the maximum permitted value. In addition to vertical concentration profile at dam, this 1D mode also takes into account slope stability concept to model slope instability during the development of flushing channel. HR Wallingford developed the 1D RESSASS model (Petkovšek and Roca, 2014) specifically for reservoir sedimentation, by incorporating modelling approaches to the vertical gradient of sediment concentration at dam with outlets at multiple levels, widening of flushing channel, slope stability, sediment compaction and turbid density currents. The RESSASS model can also simulate multiple reservoirs, as can GSTARS model (Ahn, 2011). For flushing, the most important property of a model is the ability to model channel widening and slope instability, which both mentioned models can do, as well as can the Courlis model (Valette et al., 2013).

Figure 1. An example of a long narrow reservoir suitable for modelling with a 1D model, while the details near dam and intake are modelled with a 2D model

The use of 3D models has been increasing as their higher demand on computational resources is matched by more capable hardware. Harb (2013) modelled sediment flushing of two reservoirs in Austria, one with SSIIM and another with TELEMAC-3D. The former model was also used by Hoven (2010) to study flushing of a reservoir in Costa Rica, while the latter was used by Aliau et al. (2016) to model eco-friendly flushing of a reservoir in France. Omer et al. (2016) used Delft3D for a reservoir in Japan. A special 3D model for pressure flushing was developed by Sawadogo et al. (2019).

In addition to models that discretise the domain to a particular set of model nodes linked into a numerical mesh (1D, 2D and 3D), meshless models have been, although to a lesser degree, used to study sediment transport and flushing (Maneti et al., 2012; Zubeldia et al., 2018). In both cases, the Smoothed Particle Hydrodynamics (SPH) approach was used. With this approach, the computational points are not ordered in a particular system but follow the movement of fluid. The approach is well suited to cases where the area occupied by fluid(s) changes rapidly, such as rapid erosion of sediment from the reservoir bed during flushing.

For long term simulations, the quasi-steady modelling approach is attractive due to its ability to handle long time steps and generally being numerically more stable than the fully unsteady approach. However, it disregards the local acceleration term and wave propagation through a reservoir during drawdown and infill. This may have some impact on the results. Gibson and Crain (2019) compared the two approaches and the measured values of released sediment concentrations at the Fall Creek Dam, USA. Both approaches predicted similar peak values that were also coherent with the measurements, but overall, the unsteady approach predicted higher values than the quasi-steady approach. Ahn (2011) compared predicted and measured bed level changes in cross sections and longitudinal sections of the Xiaolangdi reservoir. They found that the unsteady approach performed better in the case of cross sections, while quay-steady approach performed better in the case of the longitudinal section.

Flushing can have large impacts on downstream environment. To analyse and ultimately minimise these impacts, the outputs of the sediment models can be coupled with environmental assessment. Moridi and Yazidi (2017) modelled suspended sediment concentrations during flushing operations for Dez Dam in Iran and applied the model results to consider social, environmental and water resources impacts in the study area. Impacts of flushing can be also evaluated by habitat models, for example CASiMiR (Jorde, 1996; Schneider et al., 2001).

2.2.Physical Modelling

Physical modelling supports both theoretical investigations of reservoir flushing processes as well as case-specific flushing studies.

Lai and Shen (1996) theoretically investigated the flushing channel evolution and the amount of sediment released. Kantoush and Schleiss (2014) investigated the effects of the reservoir geometry on sediment deposition and flushing with a series of systematic laboratory experiments. The authors found that both deposition and flushing rates can be well related to a shape factor that they formulated based on geometric properties of the reservoir. Sindelar et al. (2016) investigated the effect of weir height and reservoir widening at the dam on sediment continuity for run-of-river hydropower project on small and medium sized gravel bed rivers. Guillén-Ludeña et al. (2022) performed ninety laboratory experiments to study the efficacy (released sediment to water ratio) of flushing with respect to the volume of stored water, bed slope and sediment size. Only the stored water was used for flushing without any additional inflow. They found that the efficacy increases with slope and decreases with water volume. There was little difference in flushing efficacy between coarse and medium sand, while efficacy for fine sand was somewhat lower, which the authors attributed to the apparent cohesion.

Physical models have been developed to study feasibility and support design of flushing operations in real reservoirs. Examples include Ratnayesuraj et al. (2015), who used a scaled model (1:250) for studies at the Rantambe Reservoir, Sri Lanka. A physical modelling at 1:70 scale for Chamera Hydro-Electric Project in India was constructed to study performance of the reservoir, including sediment flushing (Isaac et al. 2014). For the Cerro del Aguila dam in Peru, a physical model was constructed covering the area from 1000 m upstream of the dam to 350 m downstream from the dam (Sayah et al., 2014). Harb (2013) reported on a physical model of the Schönau reservoir on the river Enns in Austria in 1:40 scale and using lightweight material to represent fine deposits, alongside a 3D numerical model, to study flushing.

2.3.Hybrid Modelling

Hhybrid models use both physical and numerical models. The aim is to take advantage of the respective strengths of each model and to avoid their respective weaknesses. Typically, the numerical model covers the whole domain of interest in space and time at a 1:1 scale, while the physical model is used to add specific information where it is deemed necessary. Possible links between the numerical and physical models are shown in Figure 2.

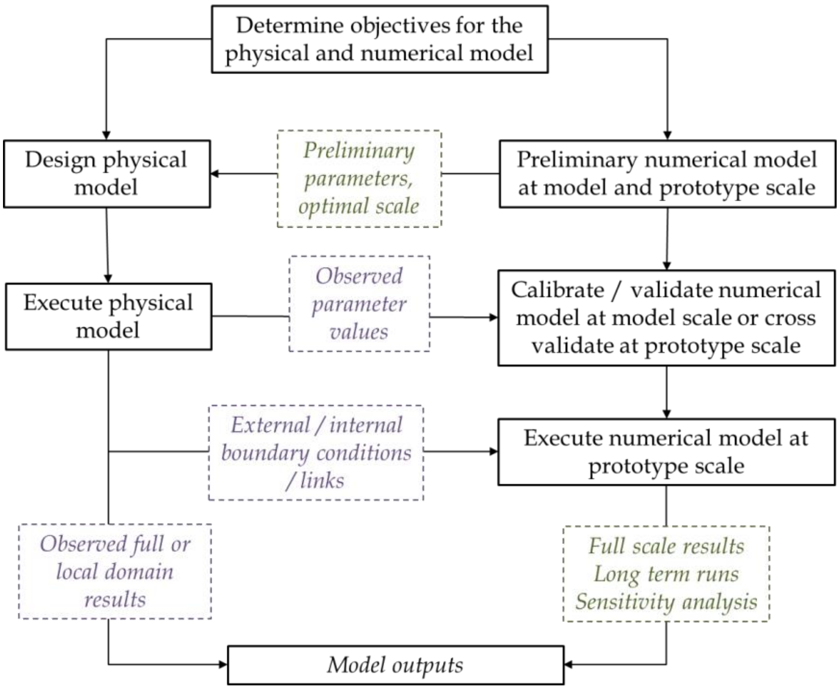

Figure 2. Possible links between a physical and numerical model in the hybrid modelling approach

Hybrid modelling was proposed for flushing studies (Reisenbüchler et al., 2020) and implemented by some authors, e.g. Harb (2013) and Sayah et al. (2014). Schleiss et al. (2011) used a hybrid model of a pressure flushing operation at Räterichsboden reservoir in Switzerland. Numerical modelling was performed by the FLOW-3D software and a 1:35 scale physical model was constructed, used them for cross-checking as well as tested them against one field observations during an annual bottom gate functional testing. The authors concluded that the results were of sufficient similitude to make the cross-checked models suitable for prediction of sediment flushing, including prediction of released sediment concentration as function of outlet gate opening height. Peteuil et al. (2017) presented a hybrid model of the Champagneux reservoir. They applied a numerical model TELEMAC-3D to the whole reservoir, constructed a physical model at a 1:35 scale for the area near dam, and a CFD numerical model of spillway section at both scales. The main aim of modelling was to accurately represent bottom shear stress, which is the main factor in assessment of sediment erosion.

3. Earth Observation Assisted Monitoring

Earth observation has been used extensively in water related research as well as practical application. While not as accurate as the direct on-the-ground observations, earth observation has its advantages, mainly due to large (full) spatial coverage, as well as typically lower processing effort and cost (Peterson et al., 2018).

Flushing channel is the central feature of flushing that also determines how much sediment can be flushed from the reservoir, given the available water discharge, as well as sediment characteristics and slopes. Observations of the final width of flushing channels at different conditions was performed in the past and an empirical relation between the two was proposed (White, 2001). Earth observation data offer an opportunity to enhance this database using historical data for reservoirs where flushing has been practiced purposely as well as where a flushing channel has formed spontaneously in the sediment delta during periodic drawdown. Historical outflows are usually measured and recorded, sediment characteristics are also known, while the width of the flushing channel at different times and locations can be estimated form satellite imagery (Figure 3).

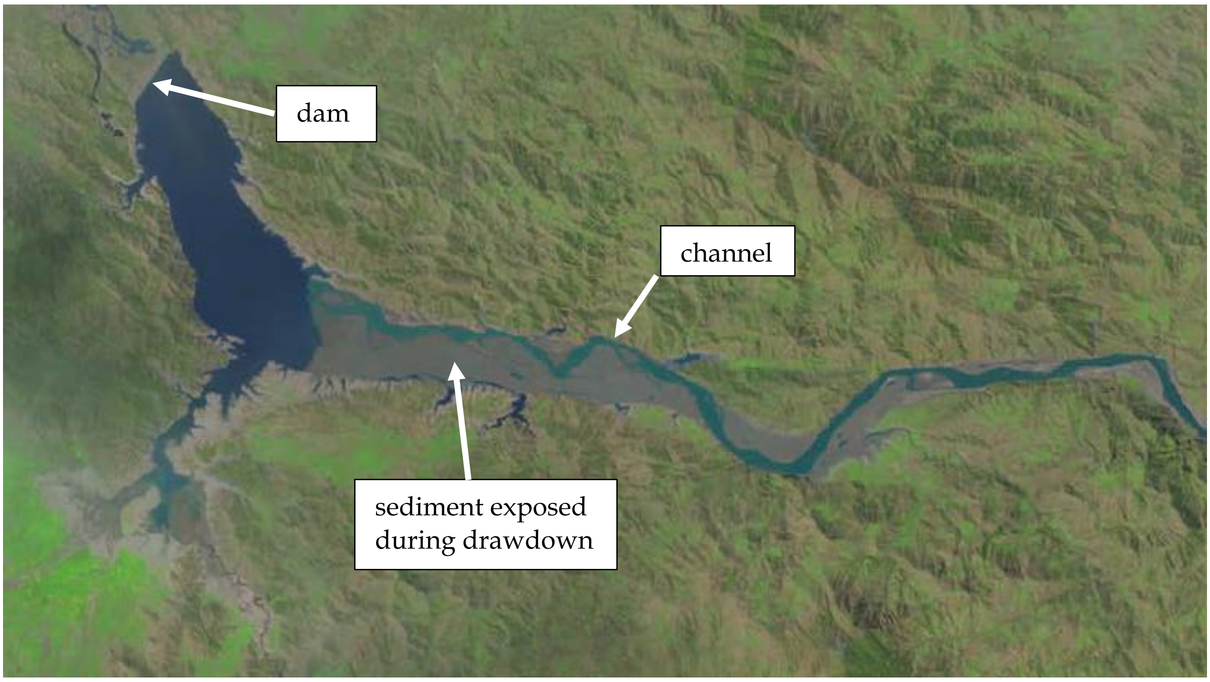

Figure 3. : Scouring channel in Tarbela reservoir sediment delta during the drawdown season shown in a Landsat 7 satellite image from 26/03/2000.

Another application related to flushing and fate of released sediment transport is related to monitoring of sediment concentration in the reservoirs and rivers. In large reservoirs, monitoring based on satellite imagery had been reported already in 1970s (Ritchie et al., 1976). With better spatial resolution and development of assessment techniques, the scope of application can now be extended to smaller reservoirs and longer river reaches. Zhang et al. (2022) used the multispectral imagery and two-stage non-linear relationship between suspended sediment concentration and reflectance in various bands, valid for the range 2-850 PPM, and applied it to the whole mainstream Yangtze River.

The rate of flushing depends on the compaction rate of fine sediment, to some extent (White, 2001). The compaction rate is usually determined from undisturbed samples obtained by in-situ coring. An earth observation-based approach to study compaction rates could be carried out by employing the remote InSAR (interferometric synthetic aperture radar) technology. This method uses radar imagery provided by satellites and can, under certain circumstances, measure surface movements with precision of a few millimeters. In principle, this enables relatively fast and efficient scanning of wide areas, as was done at a large scale, for example for the Meghna River delta in Bangladesh (Higgins et al., 2014). However, there are certain points to note and challenges at present state with the method as it is usually applied. Firstly, the method requires a more or less continuous dataset of 30 images over a period of one year, without major changes to the tracked points on surface (e.g. points can move/subside but they should not be covered by water or other material). This is challenging in many dams where sediment is only exposed during short period of time. Secondly, the measurement is in the line-of-sight (LOS) of the satellite. As it can be safely assumed that the compaction movement is in the vertical direction only, this is not a particular concern. Thirdly, the usually applied method of persistent scatterers works well for solid types of surfaces (buildings, rocks, firm ground) but struggles with coherence (consistent points) in vegetated areas or over water. If sediment is frequently covered by water, the third challenge is related to the first. When sediment is exposed for long periods, it may also be overgrown by vegetation. This again restricts the application of InSAR.

4. Conclusions

Loss of storage due to sedimentation is an important challenge to the sustainable use of water resources. Sediment flushing is potentially a very efficient sediment management strategy that must be carefully designed. Numerical and physical modelling can contribute to the design. Knowledge gaps can be filled through experimental investigation and observation in nature, including through earth observation.

Different modelling methods can be used for assessment of different aspects of flushing operations. For the detailed studies of water and sediment flow near outlets, in particular where vertical component of flow is important, 3D numerical models are most suitable. Further assurance can be obtained by the hybrid approach where numerical modelling is combined with physical modelling in order to benefit from the advantages of each approach: real processes on a physical model and a prototype scale on a numerical model. In time, these models are typically used for the flushing operation itself or its most critical part during drawdown. For long term simulations, scenario exploration or optimization, taking into account the whole reservoir or even the river system impacted by flushing, the use of 3D (or 2D) models is likely to be computationally too expensive. Lighter 1D models can produce satisfactory results, especially if the reservoir is long and narrow. Apart from shorter run times, these models also require less input parameters, that relate to well tested quantities and processes, which is not always the case with the parameters required for the more complex 3D models.

Earth observation is becoming popular but still underused data source for flushing studies. Wealth of information could be obtained from earth observation sources to fill the knowledge gaps with respect to formation of flushing channel and its width. Monitoring of sediment concentrations in rivers is becoming more feasible with higher resolution of satellite imagery and its multispectral characteristics. Sediment compaction can be studied through InSAR techniques, although some important limitations related to the persistency of observed points (scatterers) remain a challenge.

Author Statement

The author confirms sole responsibility for the following: data collection, analysis and interpretation of results, and manuscript preparation.

Conflict of Interest

The author declares no conflict of interest.

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