MODELLING RESERVOIR SEDIMENTATION USING PHYSICS-BASED AND MACHINE-LEARNING TECHNIQUES : CASE STUDIES IN INDIA

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ABSTRACT

Complications related to sediment management at dams and reservoirs in India have become acute given their impact on water availability, the reliability of the infrastructure, and the safety of the downstream population. The multifaceted problem is challenging to address, quantify and manage. In this paper, we present several case studies of dams and reservoirs in India that evaluate sedimentinduced problems and possible mitigation measures. We used a physics-based (mathematical) model (Delft3D) to assess conditions on a reach scale and data-driven models for a generalized evaluation on a regional scale. We addressed the issues associated with complex flow, sediment transport, and fluvial morphology in two reservoirs located in different regions in India, namely Maneri Bhali-I dam in Uttarakhand, and Pillur dam in Tamil Nadu. The variation in scale and magnitude of the problems in these two reservoirs demonstrates the complexity and uniqueness of the problems, indicating needs for distinctive and tailor-made approaches to address them. A rapid assessment of these problems was made based on field reconnaissance and information, complemented by computational modeling, assuming some synthetic scenarios for the first assessment of the problems in both cases. This study demonstrates the applicability of a process-based modeling tool to address and analyze various aspects of sediment-induced problems. Furthermore, a machine-learning algorithm, based on an artificial neural network, was developed to quantify capacity loss of a reservoir on a regional scale. The model provides a high-quality fit to the assembled information and allows a straightforward calculation of the storage loss using easily-obtained data.

1. INTRODUCTION

1.1 Reservoir Sedimentation

Reservoir sedimentation is one of the major issues affecting not only reservoir storage capacity but also a number of adverse hydraulic, morphological and environmental effects in both upstream and downstream areas of river systems. Such effects could create increased flood levels in the up-stream areas, river bank erosion, bed incision and coastal erosion problems in downstream areas due to decrease in sediment supply as well as unfavorable conditions for agricultural lands due to lack of fertile silt supply. Furthermore, sediment deposition in the reservoirs might be a threat to the functionality, stability and safety of the dams and weirs, such as increase of dynamic loads, mal-functioning of flow control gates and outlets, erosion of hydro-mechanical equipment like hydro-power turbines and so on. Adverse environmental and ecological consequences, affecting the aquatic system with structural interventions, make these issues more complex to deal with. These problems are mainly caused by the alterations in flow regimes, interruption of sediment supply, unrestrained and random sediment removal operations. ICOLD has a number of publications that provide a wide range of information on sediment related problems and guidelines (ICOLD, 2009, 2007, 1996, 1989).

Despite all these adversities, the structural interventions are inevitable to create alternatives in order to fulfill the societal demand for water and energy resources. Consequently, these issues are supposed to be addressed in an integrated manner and with special care already from the beginning (i.e. during selection of the location and design) as well as during operation and rehabilitation of dam given that they are explicitly associated with dam life and safety.

1.2 *Sediment-induced problems in Indian dams*

There are concerns from various dam authorities in India with an urgent desire to explore the possibilities for adequate sediment management plan for some reservoirs, which are not only losing the storage capacity, but also under the threat of mal-functioning of intakes and sluices. Other complexities are associated with sediment removal activities given the cascade scheme of dams and reservoirs as well as the fact that some of the reservoirs are located in the neighborhood of the pre-served forest area. Besides, some of the reservoirs also serve for water supply, irrigation as well as recreational purpose. This implies that the upstream and downstream effects are of the major concerns, and thus the environmental, ecological and social compliances are supposed to be insured before carrying out such activities.

In this paper, our assessment on reservoir sedimentation issues as well as desiltation plan and approaches for two hydropower reservoirs, namely Pillur in south (Tamil Nadu) and Maneri Bhali I in north (Uttarakhand). The alteration in nature and magnitude of the problems in these two entirely different reservoirs demonstrates the complexity and uniqueness of the problems, indicating needs for distinctive and tailor-made approaches to address them. In addition to loss of reservoir storage capacity, the sedimentation seems to be leading to malfunctioning and dam-age of the structures and apparatuses, e.g. intakes, scour-sluices, spillway glacis, roller buckets, cut-off walls, gates etc. We have made an attempt to demonstrate the application of mathematical models to simulate some of the presumptions and synthetic scenarios associated with hydraulic and morphological impacts of different sediment management interventions and measures in both reservoirs. We carried out several studies in these reservoirs (Patra et al., 2019; Giri & Narayan, 2018; Giri et al., 2017; Giri et al., 2016a, Giri et al., 2016b).

2 COMPUTATIONAL MODELLING

2.1 *Pillur reservoir*

2.1.1 *Study area and sediment related problems*

Pillur reservoir is located in Kundah River 5 km downstream of the confluence between the rivers Bhavani and Kundah. The catchment area of the reservoir is 1191.40 km^2, which includes not only Tamil Nadu, but al-so Kerala state. The main rivers, contributing to the reservoirs are Bhavani, Kundah, Nirala Pallam and Katteri rivers. Besides, all upstream reservoirs, located in Nilgiris basin, contribute to this reservoir. Consequently, not only water but also sediment sources are diverse. The power plant is storage type, so sedimentation concerns are more relevant and important to be considered. Another important aspect is that the reservoir is being used for water supply to the city of Coimbatore. Therefore, the loss of storage capacity and deposition near water supply intakes could be of great concern in future.

Some studies regarding the capacity and sedimentation issues at Pillur reservoir were made by Institute of Hydraulics and Hydrology, Poondi. One of these studies has been carried out recently (in 2014). Earlier study was made in 1982 as de-scribed in the report (I.H.H. Poondi Report No. 4, 2014). Based on these studies, some plots have been made, revealing the storage loss over the reservoir level (as shown in Fig. 1). These studies show following evidences: (i) loss of reservoir storage = 41.64%, (ii) annual storage loss = 0.87%, (iii) trap efficiency = 68%, and (iv) annual rate of sedimentation = 1.4% (although this needs to be verified based on precise analysis of the data when proper field measurement is carried out). A first attempt of flushing was made only in 1991 (after about 30 years of dam operation). However, it ended up with a sediment disaster. Since the deposited amount was huge, the slurry got highly concentrated did not seem to behave like normal sediment-water mixture, but rather as a body of fluidized sediment mass that blocked the flow and eventually collapsed and allowed to flow away. At the same time, there was an unforeseen trouble with closure of scour sluice (apparently due to the hindrance, induced by debris), which led to this mass of sediment flowing towards power-house (which is located left side of the scour sluice at downstream area). Powerhouse area was covered with large amount of sediments, and thus the generation had to be stopped for considerable period.

2.1.2 ***Morphological modelling of sediment propagation***

A rapid morphological modelling was carried out to assess the propagation of released flow and sediments from the Pillur reservoir in downstream reach along Bhavani river. The study is based on a sediment removal plan that includes a proposal to discharge the removed material to the downstream with a controlled and limited amount. For example, start with 200 000 - 300 000 m^3 for first year (spread over the year) and monitor the erosion-sedimentation pattern and migration of sediment deposits in downstream river given the fact that there is another barrage in the downstream (Bhavani barrage).

2.1.2.1 Model set-up and conditions

A two-dimensional morphological model of the Bhavani River reach (downstream of the Pillur dam up to the Bhavani barrage) was developed using Delft3D to replicate a few synthetic scenarios of flow and morphology. The model incorporates various useful aspects such as consideration of floodplains including wet and dry processes, sediment transport over non-erodible layers and functionality for sediment management to assess dredging and dumping strategies etc. (Yossef et al., 2008, Giri et al., 2008).

The river reach in Google earth and the computational model is depicted in Figure 1. There are 722 and 12 computational cells in streamwise and transverse directions (total 8664 cells). Discharge and water level conditions have been imposed at upstream (Pillur dam) and down-stream (Bhavani barrage) boundaries, i.e. a constant upstream discharge equal to 200 m3/s and a downstream water level of 308 m. Since the data shows largest presence of coarse sand varying be-tween 0.2 - 0.6 mm, we have considered an average constant value of median grain size as 0.4 mm. An equilibrium sediment transport condition at the upstream boundary has been imposed.

Since there is no bathymetry data in this reach (it should be noted that available SRTM data is rather inaccurate and not applicable for morphological modelling of such a narrow river), we first assume a flatbed model with a constant slope based on the information on upstream and down-stream bed level. Furthermore, we run the morphological model for some time, which has created a bathymetry with certain morphological features. Those features have been assessed qualitatively and used as an initial bed for further assessment of morphological development with the sediment volume that is discharged downstream.

2.1.2.2 Results and analysis

Since the bathymetry data is not available and the SRTM data is largely inaccurate to represent the bed level of such a narrow river reach, we carried out computation of a synthetic scenario with a flatbed and constant slope. The morphological feature, simulated by the model, was qualitatively analyzed and compared with the Google earth images to make sure that the model is replicating qualitatively realistic morphological features. This is also useful to assess the model capabilities, since there is no data to calibrate and validate the model. The sedimentation and erosion pattern after simulation of about 20 morphological days is shown in Figure 2. As result shows, the model is able to replicate the realistic feature of the bend morphology, i.e. sedimentation in inner bend and erosion in outer bend, and also formation of alternate and mid-channel bars as well as creating deep water channel along the river planform. This can be inferred from some qualitative comparison with Google earth images of channel pattern as shown in Figure 3 (in Google image, a number of places with deposition have well developed and already been covered with vegetation, while numerical simulation results show still under developed pattern, which is obvious given the limited time used for the simulations). These results show that the channel patterns was replicated by the model satisfactorily considering such a simplified synthetic scenario. In Figure 4, it can be seen that the model replicates the mid-channel bars rather comparable to the current situation, but not yet fully developed (since the model simulation is too short).

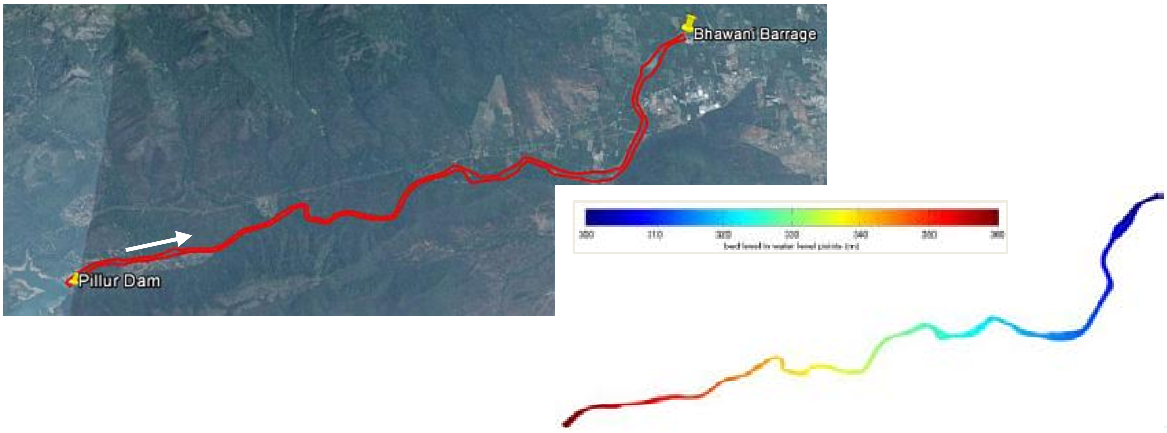

Figure 1. The model domain (color map shows the river bed elevation (m +datum))

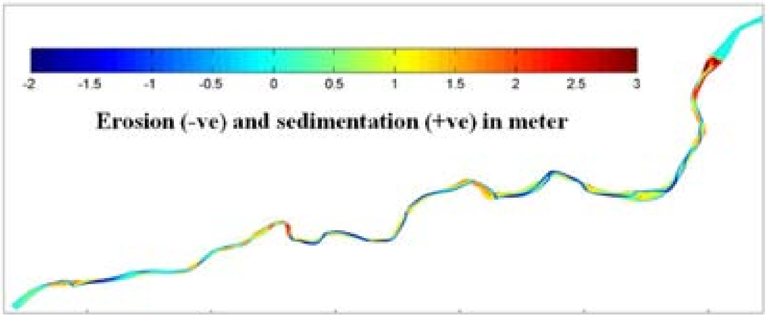

Figure 2. Sedimentation and erosion patterns after morphological simulation from initial flatbed condition

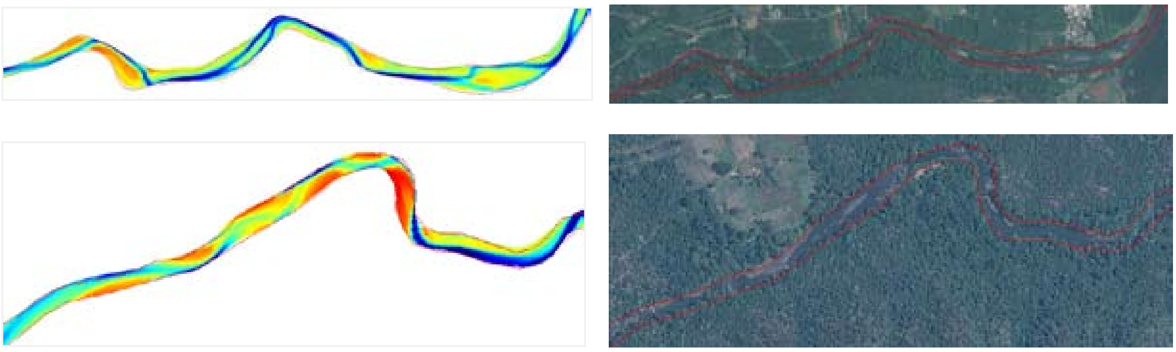

Figure 3. Comparison of erosion-deposition patterns between simulated results and Google earth images in some locations

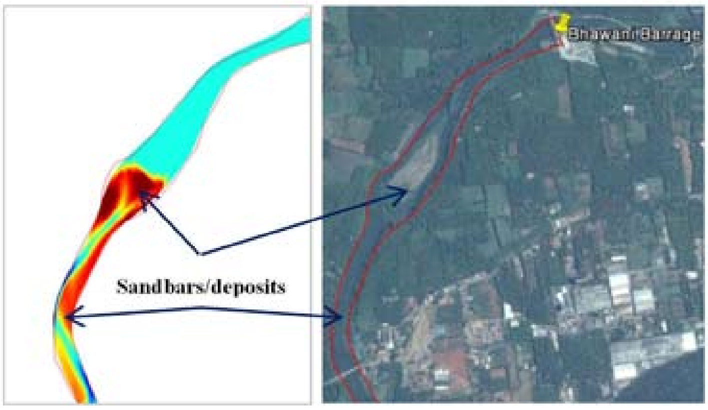

Figure 4. Comparison of formation of mid-channel bar between simulated result (not fully developed bar) and Google earth image (already developed bar) near the Bhavani barrage

Subsequently, the final bed level (quasi-equilibrium) simulated from a flatbed condition (as shown above) has been used as initial bed level for further computations in order to replicate the morphological development of deposited material at the downstream reach. For this purpose, few synthetic scenarios with different upstream discharge were simulated considering maximum 1 m thick sediment layer, deposited at the upstream part of the river as shown in the left plot of Figure 5. This supposedly replicates the deposition of the sediment, discharged over the dam through slurry pipe, since initially most part of the discharged sediments is expected to be deposited (or replenished) at the upstream reach unless the transport capacity of the flow is enough to have active morphological development caused by migration of these deposits towards the down-stream reach. Computational simulations for two scenarios with discharge of 200 m^3/s and 50 m^3/s were carried out. The result is depicted in the right plot of Figure 5 showing width-averaged cumulative erosion and sedimentation along the river for different instantaneous time for the case of 50 m^3/s. For the case of 200 m^3/s, the sediment propagation is faster. The simulation result depicted in Figure 6 shows the propagation of deposited material at downstream river under the condition of 200 m^3/s upstream discharge. From the result, it can be inferred that the part of the sediment deposits along the river in the form of sandbars (some of them appears to be trapped in the bends and pools). The result also shows that a part of sediment reaches Bhavani barrage after 20 days of morphological simulation. The propagation speed of bed sediment depends on the upstream discharge (which is released from the spillways and powerhouse tailrace in this case), sediment characteristics and other model parameters as well, which can be explored further in case of availability of more precise data and information.

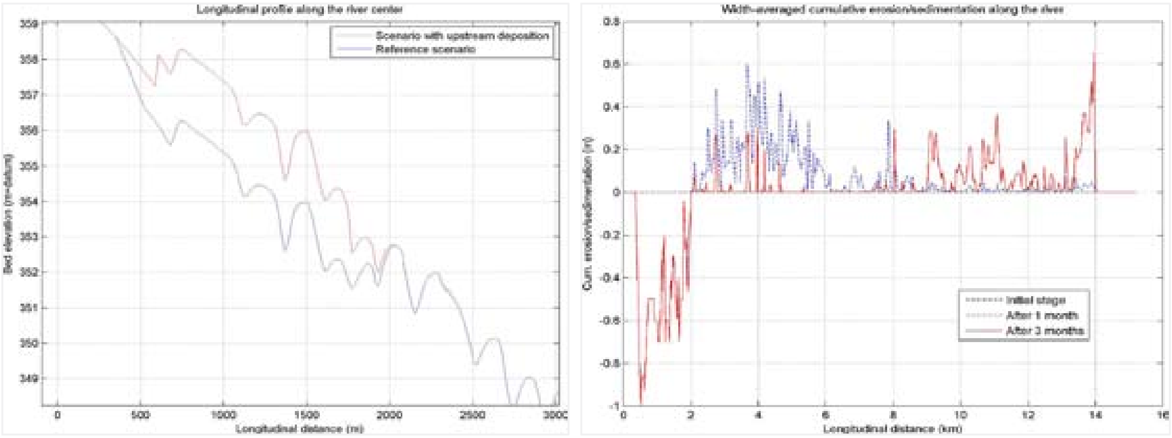

Figure 5. Left plot: Comparison of initial longitudinal profiles at upstream area for two simulation scenarios (higher bed level represents the scenario with deposition at upstream reach caused by sediment replenishment from the reservoir); Right plot: Sedimentation (+ve) and erosion (-ve) of the deposited material and their spatial and temporal evolution for Q = 50 m^3/s.

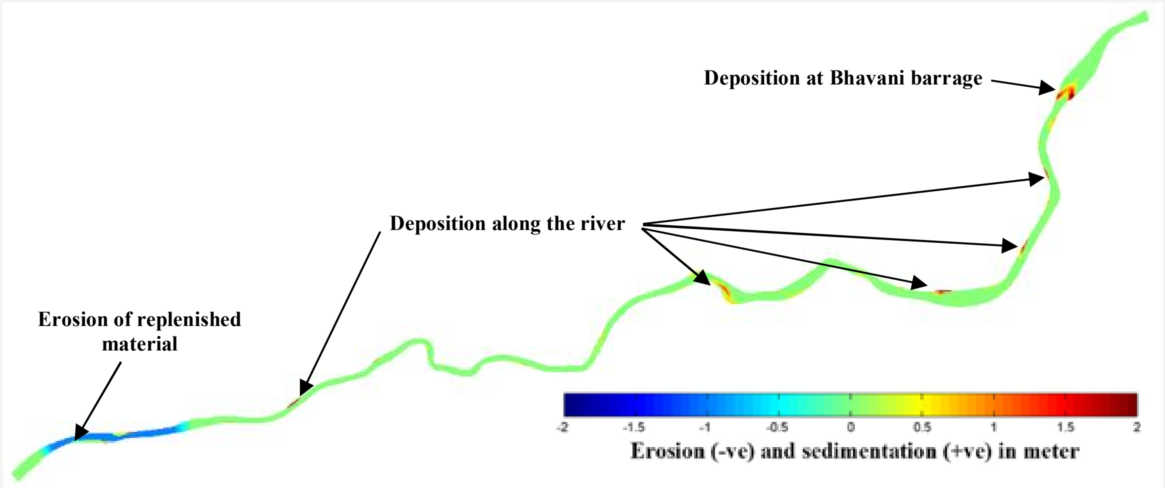

Figure 6. Erosion and deposition patterns of removed sediment at the upstream and its propagation towards downstream of the river (after 20 days of morphological simulations under Q = 200 m^3/s)

2.2 *Maneri Bhali - I*

2.2.1 *Study area and sediment related problems*

The Maneri Bhali Stage - I, located in north hilly region of Uttarakhand in Bhagirathi River, is a Run-of-the-river hydropower plant. The hydrological and geomorphological characteristic of the region is very different from the region where Pillur dam is located. Bhagirathi River carries large amount of sediments/debris during monsoon period. Particularly, during 2012 and 2013 flood events, there were landslides, bank erosion and significant morphological changes in the river causing disaster and fatality in upper Ganga basin. Significant changes in river planform and channel shifting were occurred in a number of locations along Bhagirathi River as well including just upstream of the reservoir. Large amount of debris containing rubbles, boulder and gravels, transported over the spillway during flood events causing abrasion and damages of the spillway as well as other structures and apparatuses like roller buckets, cut-off walls, gates etc.

Sedimentation leading to loss of storage capacity is another major issue which is interrelated to the structural damages as well. Even though the HP is a run-of-the-river type, sedimentation has reached up to crest level of the spillway creating an unfavorable flow and sediment transport condition over the spillway during flood passage, and thereby causing its abrasion. Besides, asymmetric opening of the gates may cause complex flows over and in the vicinity of the spillway (both upstream and downstream) given bend planform of the river reach at this lo-cation. This also causes sedimentation in front of the gates (at right side near inner bend), which are closed most of the time.

2.2.2 *Modelling of effects of proposed measures*

2.2.2.1 Model set-up and conditions

The basic computational model (Delft3D) is same as used in case of Pillur reservoir (see above). Two model domains were developed, i.e. first model includes upstream river reach to simulate general morphological feature, while second model has shorter upstream reach but includes immediate downstream reach of the dam and used mainly for hydrodynamic analysis. Figure 7 shows the Google earth image and computational domain for the upstream model. The second model is not shown here (only results are shown).

Approach is the same as in case of Pillur reservoir, since there is no bathymetry measurement. A flatbed condition with constant slope has been assumed as an initial bed (Fig. 7) given the bed level information at upstream and downstream (reservoir is considered to be silted up to the crest level). The morphological feature, simulated by the model, has been qualitatively analyzed and compared with the Google earth images to ensure that the model is able to replicate qualitatively realistic features.

Discharge boundary at the upstream (200 m^3/s, i.e. minimum discharge when all gates have to be open) and 1290 m (water level equal to MDDL) at the downstream have been imposed as representative values for the formation of bed morphology (for the model with upstream reach). While, for hydrodynamic analysis of some scenarios like effects of sediment removal and gate opening (using second model with downstream reach), the maximum discharge during 2013 flood, i.e. 1200 m^3/s has been used (the water level boundary at downstream reach has been imposed as 1270 m). It must be noted that the power intake discharge has not been incorporated in this study. For these simulations, a representative sediment size of 5 mm has been considered (future detailed study should consider graded sediment transport approach).

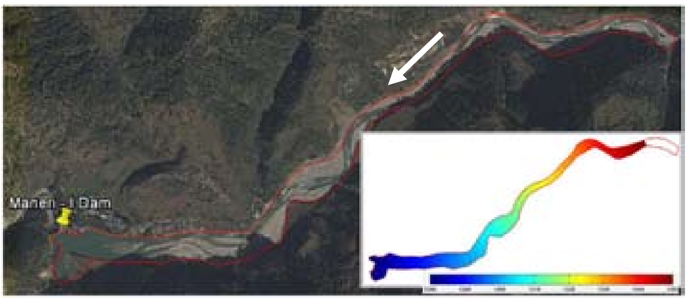

Figure 7. Computational model domain in Google earth image and in initial bed level in Delft3D model (color legend denotes bed elevation)

2.2.2.2 Results and analysis

Morphological simulation under an initially flatbed with a constant slope condition replicates development of channel pattern as well as propagation of deposition front towards the reservoir. A qualitative comparison of sedimentation, erosion and channel formation patterns, simulated by the model and the Google earth image, provides an impression about performance of the model. As result reveals (depicted in left plot of Fig. 8), even the modelling with such assumptions replicates realistic feature of morphological development. As the model result (and also Google earth image) shows, the sediment front is propagating towards the reservoir. The right plot of Figure 8 shows width-averaged bed level evolution in the reservoir area (within 1 km upstream of the dam) replicating propagation of delta front towards the dam. As a field experiment, a sediment (mainly rubbles) trap was proposed to be installed near the reservoir. It must be soft trap that should not cover whole river width and shall be permeable. However, in our modelling exercise, we schematized it as an impermeable obstruction along whole river width to see the effect of trapping finer sediment as well. Test computations with synthetic scenarios have been carried out. Figure 9 shows two-dimensional morphological feature (left plot) as well as a comparison of width-averaged longitudinal profiles between the simulation scenarios with and without sediment trap (right plot). It is evident that there is effect on erosion-sedimentation pattern, and the most obvious effect is the sedimentation at the upstream of the structure while erosion at the downstream. These results must be considered as qualitative assessment.

In order to assess the effect of the reservoir dredging on flow-field, the model was extended to downstream reach (but shorten the up-stream reach). In this way, the spillway has been modelled as a weir with the crest level of 1280.2 m. The bed level in case of reference situation is kept only 20 cm below the crest level, while for dredging scenario the reservoir bed was lowered 5 m near the spillway and linearly extended up to the upstream boundary, which leads to the change in the bed slope (left plot of Figure 10). The upstream discharge condition is 1200 m^3/s (which replicates the flood of 2013). Under the same flow conditions at upstream and downstream boundaries, the lowered bed level leads to lowering of the water level as depicted in the simulation result (right plots of Figure 10). Moreover, lowering the reservoir bed level is found to be resulting in additional backwater effect from the spillway. This leads to decrease in velocity in reservoir area. The plots of velocity field depicted in right plots of Figure 10 shows that the flow velocity magnitude is much lower in the reservoir near the spillway and intake area in case of lowered bed. This implies that bed lowering creates a favourable condition for the spillway. Besides, lowered bed will be an extra trap for boulders preventing them from transporting over the spillway, thereby minimizing the damage.

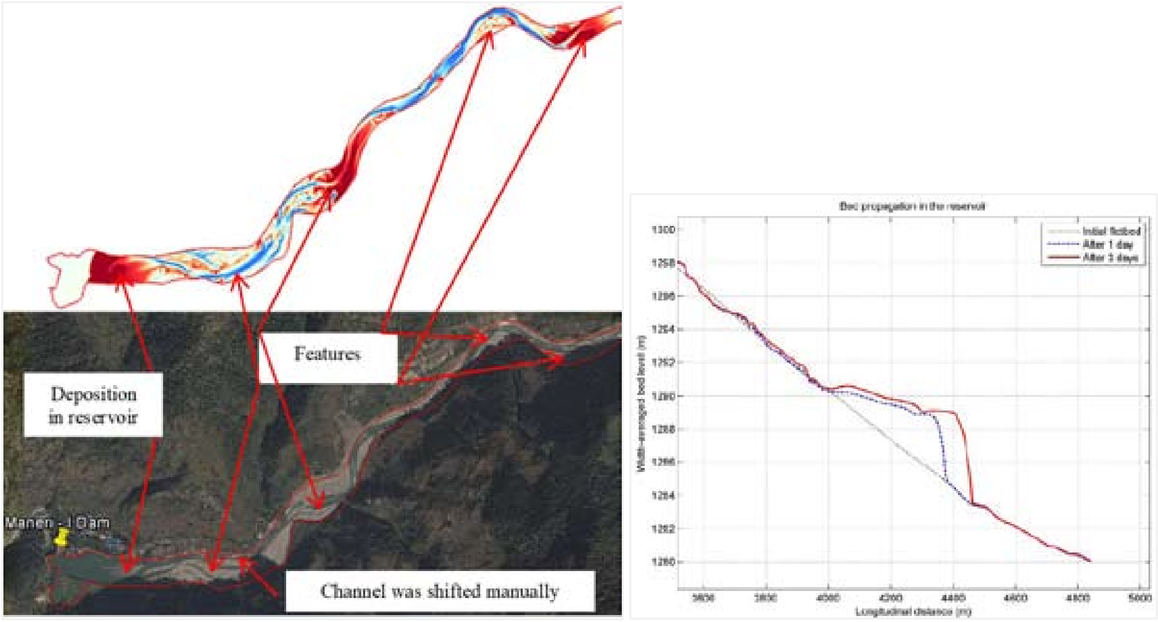

Figure 8. Qualitative comparison of sedimentation, erosion and channel formation patterns, simulated by numerical model (left plot) and simulated width-averaged bed propagation in the reservoir (right plot)

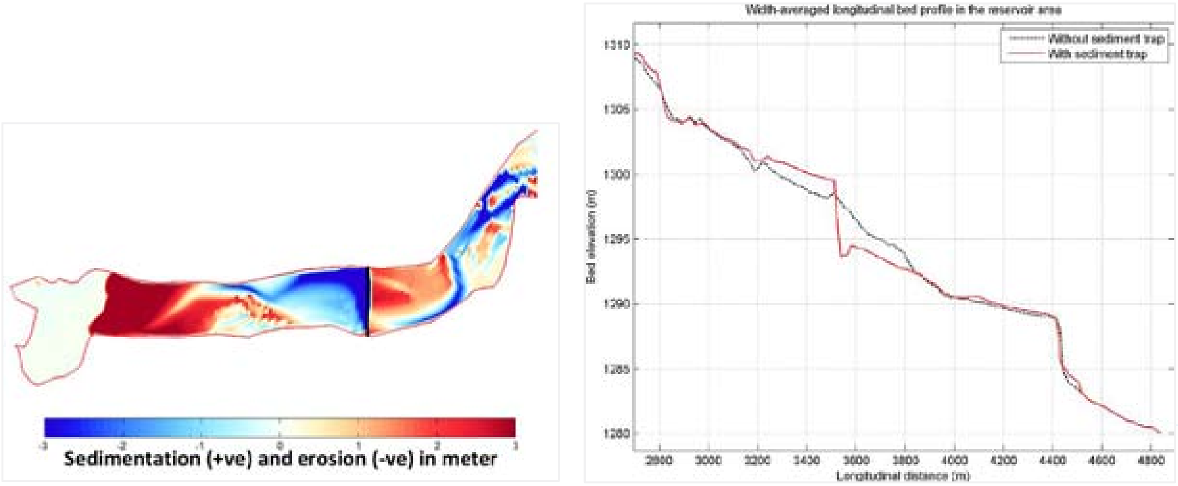

Figure 9. Morphological effect of a sediment trap (left plot) and comparing width-averaged longitudinal profiles between the scenarios with and without a sediment trap

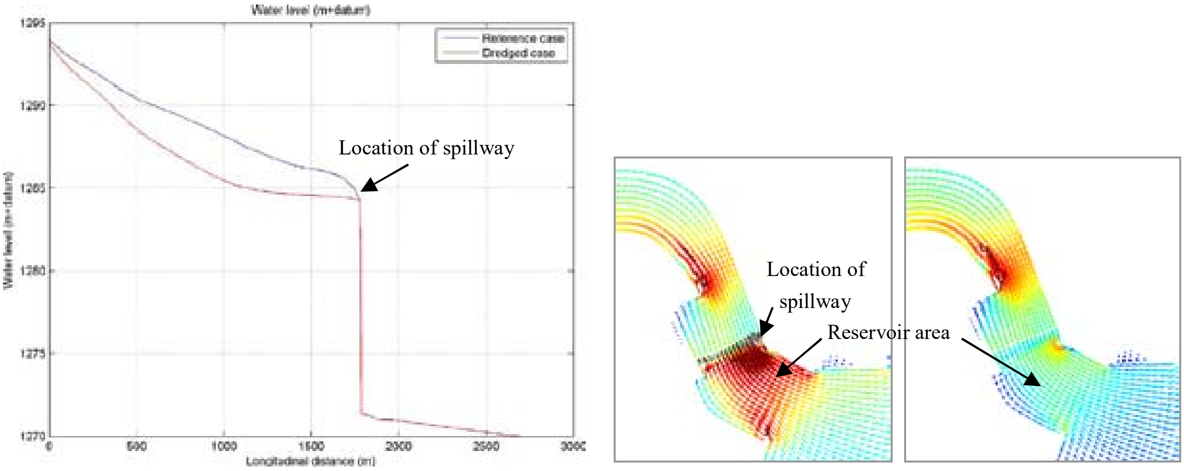

Figure 10. Comparison of longitudinal water level profiles between the scenarios with and without lowering the reservoir bed (left plot) and velocity vectors in the reservoir area and downstream of the spillway for scenarios without (middle plot) and with (right plot) reservoir bed lowering

3 MACHINE LEARNING APPROACH

3.1 *Artificial Neural Network*

A multilayer perceptron network with one hidden layer of nodes and a single output was used to evaluate the capacity loss of India's reservoirs caused by sedimentation (Froehlich & Giri, 2019). A hyperbolic tangent activation function was applied to the hidden layer and a linear transfer function to the output layer. The JMP (Version 14) statistical software neural network platform (SAS Institute, 2018) was used to fit the model parameters. The inputs Neural networks are flexible models that tend to overfit data – that is, they generate weights and biases that predict the dependent variables of the training data with high accuracy, but that predict the values for additional information with reduced efficiency. Validation is the process of using part of a data set to estimate model parameters and using the other part to assess the predictive ability of the model. The data from sediment compendium, published by Central Water Commission (2015) was used for developing the model. Further details can be found elsewhere (Froehlich & Giri, 2019).

3.2 *Calculation of reservoir half-life*

The project life (also called the useful life) of a reservoir is the period during which it can reliably satisfy the purposes for which it was built. When the impoundment can no longer achieve its intended use because of sediment accumulation, it has reached the end of its designed project life. However, the operation of the reservoir may continue with a revised or a scaled-down performance expectation. Severe interference with the original design often occurs by the time half the storage capacity has been lost because of sediment deposition. In some cases, sediment accumulation affects reservoir operation considerably sooner. Standard practice is to estimate reservoir half-life ($T_{50\%}$) by halving the time needed to lose all storage capacity to sedimentation found by dividing the available storage volume by the average amount sediment deposited annually. However, the efficiency of sediment trapping declines as the reservoir capacity is reduced, i.e. the annual sediment deposition rate decreases with time. For this reason, an accurate calculation of the half-life is more complicated (Froehlich & Giri, 2019).

A comparison between measured and predicted (by using the ANN model) reservoir capacity loss for eastward and westward flowing rivers in India is depicted in Figure 11.

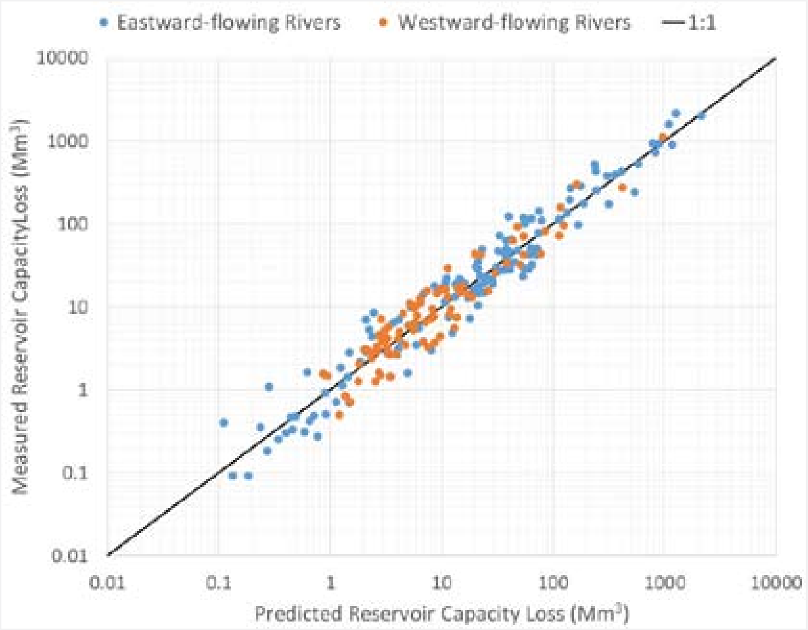

Figure 11. Comparing measured and predicted (by ANN model) storage loss in some Indian reservoirs

4 CONCLUDING REMARKS

As this study reveals in two different examples, the issues associated with reservoir sedimentations can be rather different in their nature, magnitude and severity depending on the location with specific topographical, hydraulic and morphological conditions. Therefore, a tailor-made approach is desirable to address specific concerns related to each reservoir. Nevertheless, approach to address and analyze such concerns by using physics-based tools and knowledge, supported by brief field reconnaissance can be similar and helpful, particularly for pre-feasibility assessments. On the other hand, the machine learning approach, which is not a physics-based approach, also appears useful as it delivers a straightforward and rapid means of estimating the loss of reservoir storage capacity. Dam owners and operators will benefit from such model to identify those reservoirs at higher risk of filling soon so that problems can be anticipated, and countermeasures can be explored and implemented.

REFERENCES

Central Water Commission 2015. Compendium on Silting of Reservoirs in the Republic of India. Ministry of Water Resources, Watershed and Reservoir Sedimentation Directorate, New Delhi, Delhi, India.

Froehlich, D. C. & Giri, S. 2019. Neural Network Prediction of Reservoir Sedimentation. 14th International Symposium on River Sedimentation, Chengdu, China.

Giri, S., Omer, A.& Dahal, S. 2019a. Sediment Removal and Beneficial Use (Part-2): Morphological Modelling of Dakpathar Barrage. International Dam Safety Conference 2019, India.

Giri, S., Narayan, P., Kumar, M. & Sharan, S. 2019b. Handbook for Assessing and Managing Reservoir Sedimentation. Doc. No. CDSO_GUD_DS_04_v1.0. Prepared for Central Water Commissions.

Giri, S. & Narayan, P. 2018. On Sediment-Induced Problems under the Dam Rehabilitation and Im-provement Project in India. Hydrolink, IAHR publication, Issue 3: 83-86.

Giri, S., Nabi, M., Cleyet-Merle, P., & Pillai, B.R.K. 2017. Reservoir sedimentation issues in India as a part of

Dam Rehabilitation and Improvement Project (DRIP): Field reconnaissance and modelling, River Sedimentation – Wieprecht et al. (Eds), Taylor & Francis Group, London, ISBN 978-1-138-02945-3.

Giri, S., Raman, S., & Chetan, M. 2016a. Reservoir Desiltation: Case Studies of Kundah Palam and Pil-lur Dams in Nilgiris Basin, Compendium of Second National Dam Safety Conference, Bengaluru, India.

Giri, S., Yossef, M., Raman, S., Cleyet-Merle, P., & Pillai, B.R.K. 2016b. Reservoir sedimentation issue in Pillur reservoir in Nilgiris basin (India): Field reconnaissance and numerical modelling using Delft3D, River Flow 2016 - Constantinescu, Garcia & Hanes (Eds), Taylor & Francis Group, Lon-don, ISBN 978-1-138-02913-2.

ICOLD 2009. Sedimentation and Sustainable Use of Reservoirs and River Systems. Draft Bulletin 147.

ICOLD 2007. Mathematical Modelling of Sediment Transport and Deposition in Reservoirs. Guidelines and case studies. Bulletin 140.

ICOLD 1996. Dealing with Reservoir Sedimentation. Guidelines and case studies. Bulletin 115.

ICOLD 1989. Sedimentation Control of Reservoirs. Guidelines. Bulletin 67.

Patra, B., Giri, S., Narayan, P. 2019. Reservoir Sedimentation in Indian Dams: Trends and Challenges. International Dam Safety Conference 2019, India.