MORPHOLOGICAL COMPUTATION OF A CASCADE SYSTEM OF DAMS USING DELFT3D-FM COUPLED WITH A REAL-TIME CONTROL TOOL

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ABSTRACT

This paper presents detailed hydraulic and morphological study of a cascade system of dams, located in Marsyangdi River in Nepal. Firstly, severe morphological problem in one of the dams, namely Middle Marsyangdi Hydropower Project (MMHPP), was studied. We revealed one of the key reasons of the problem, which is related to the ignorance of large- and meso-scale morphological feature of the river while selecting the site. Secondly, the sedimentation process at the reservoir was replicated using a two-dimensional morphological model, namely Delft3D-Flexible Mesh (D-FM) coupled with Real-Time Control (RTC) tool to simulate reservoir gate operation. We attempted to incorporate downstream dam in the model, namely Marsyangdi Hydropower Project (MHPP), to simulate synchronized operation and its morphological impact. The effect of synchronized operation of two dams was assessed by simulating different synthetic flushing scenarios. Sensitivity of two different sediment transport formulae (Ashida-Michiue and Engelund-Hansen) on the model results was assessed as well. Given a rapid modelling exercise of such complex system using D-FM, the results can be regarded as satisfactory. They showed consistent model behaviour and observed trend despite the complexity involved in morphological modelling with synchronized operation of two dams. The study can further be improved in case more data and information are available. The model can also be applied to optimize dam operation considering morphological and ecological impacts on downstream reach.

Keywords: Delft3D-FM, cascade dams, morphology, Middle Marsyangdi Hydropower Project

1. INTRODUCTION

Himalayan rivers are high sediment-laden comparing to similar river basins around the world, since geology is rather young and fragile. Consequently, sediment-induced problems in dams and reservoir in such region is one of the most serious concerns for all kinds of existing and planned dam projects. This is particularly important for relatively smaller daily peaking reservoirs as their peaking storage volume is diminished very quickly (Mool et al., 2017). Furthermore, flow and sediment management become even more challenging when there is a cascade system of dams. Reservoir operation can have noticeable impacts on the mid- and long-term sediment management in Peaking Run-of-the-River hydropower projects (PROR HPP).

The main objective of this work is to investigate the model performance for a cascade system of dams, namely Middle Marsyangdi HPP (MMHPP) and Marsyangdi (MHPP). Following activities were performed within the scope of this work: (i) developing a hydrodynamic and morphological model of the cascade system of dams in D-FM (a newly developed unstructured modelling suite) coupled with Real-Time Control (RTC) tool (used to simulate reservoir operation), (ii) simulating sedimentation of upstream reservoir (MMHPP) using D-FM; (iii) application of Engelund-Hansen (1967) formula for fine sediment transport (total load) and comparison with Ashida-Michiue formula (1972, 1973) with different parameters (i.e. assessing sensitivity to sediment transport formula and parameters); (iv) assessing overall performance of D-FM coupled with RTC tool to simulate synchronized dam operation scenarios. The work is still in progress.

2. PROBLEM DESCRIPTION

2.1 Study area

The case study area is located in Marsyangdi basin in Nepal. The MMHPP is located about 140 km west of Kathmandu, and the MHPP is located about 40 km downstream of the MMHPP. The powerhouse of the MMHPP is located about 6 km downstream of the dam and tailrace discharge flows to the same river, which is utilized by downstream MHPP.

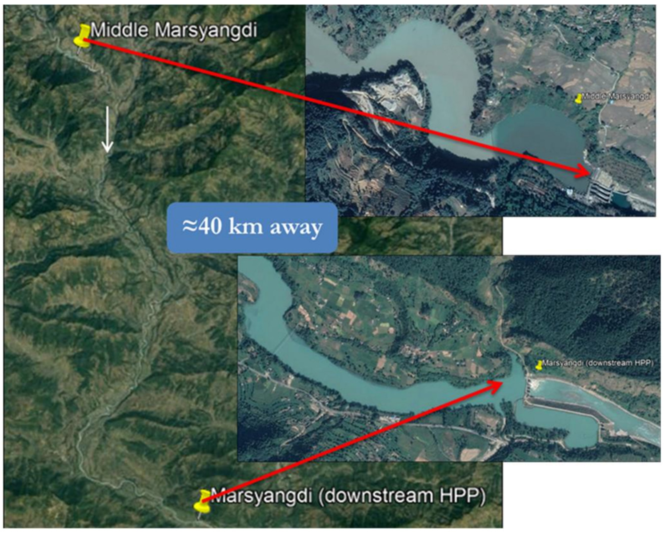

Figure 1. Location of MMHPP and MHPP with reservoirs (Image: Google Earth)

2.2 Sedimentation at MMHPP

The upstream reservoir (MMHPP) has been suffering from severe sedimentation problems since its commissioning in 2006 as shown in Figure 2. There could be a few reasons for this problem, the most obvious of which, is the ignorance of the large-scale and meso-scale morphological behaviour of the river when choosing the dam site. The reservoir planform (with strong bends and protrusion leading to inner-bend deposition and outer-bend erosion) and location of the intake do not appear to be appropriate from the morphological point of view. This demonstrates how important it is to consider morphological aspects when selecting a reservoir location. Huge sedimentation near the intake was revealed already in 2010 (see a picture shown in Figure 2, a part of which was dredged to allow operation of the hydropower.

Figure 2. The reservoir of MMHPP showing narrow and almost armoured river bed before exploitation (left image) and formation of sandbars along the reservoir with severe deposition near the dam after 5 years of exploitation (right image) (Images: Google Earth)

3. MORPHOLOGICAL MODELLING

3.1 Model set-up

Two reservoirs are included in a single model domain (as depicted in left plot of Figure 3). The computational grid was constructed for both reservoirs that are connected by the river reach (the size is varied 10 to 50 m with 2917 and 31 cells in longitudinal and transverse direction respectively with reasonably good orthogonality and smoothness). The measured bed elevation of the pre-construction period was used for the initial bed level of the MMHEP. However, there is no bed level data for the river reach and lower reservoir (MHPP). Therefore, we imposed a rectangular cross-section with a longitudinal slope based on available reservoir level data and valley slope. The bathymetry, used in the current study for both reservoirs, is depicted in right plot of Figure 3. The weirs for the MMHEP are schematized as per collected information, while the weirs for the MHEP was assumed to have one opening, due to the lack of data. This will be improved in future in case more data and information are available.

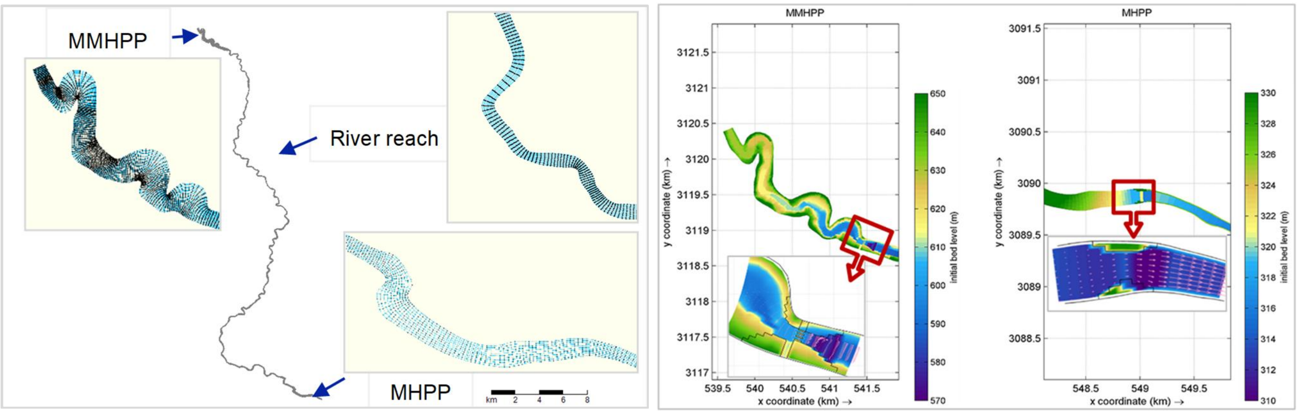

Figure 3. D-FM (2D) model extent with the grid (left) and details of weirs and reservoir bathymetry (right)

3.2 Boundary and reservoir operation conditions

3.2.1 Boundary conditions

Based on the analysis of available annual flow data of 2013, we used the high-flow monsoon period as a boundary condition. This selection is meant to limit the simulation to the period when the river and reservoirs are morphologically active, viz. the high flow period. The discharge is repeated four times to simulate four consecutive monsoon seasons (see left plot of Figure 4). This is meant to simulate the sedimentation process at MMHPP that occurred during 4 years of its exploitation (2006-2010). We note that there is no hydraulic data for other years to carry out a hydraulic analysis, e.g. to identify flood peaks based on data of several years; this has to be improved if more data become available. At the downstream, a stage-discharge relation is used as boundary condition (see right plot of Figure 4).

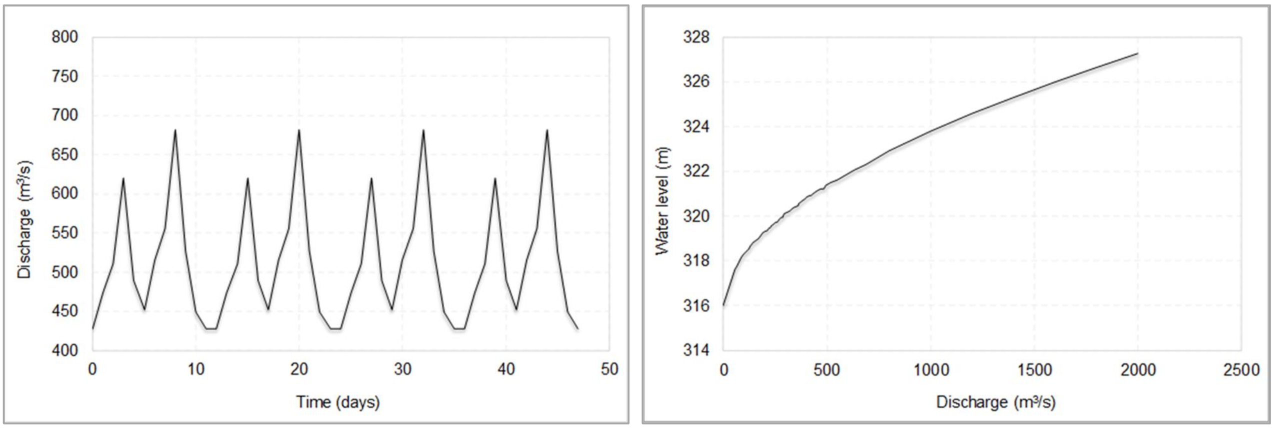

Figure 4. Upstream discharge boundary (left) and downstream stage-discharge relation (right)

3.2.2 Real-Time Control tool for reservoir operation

Real-Time Control (RTC) tool is an open source, modular toolbox dedicated to the simulation of real-time control and decision support of hydraulic structures. It can be used (i) standalone or in combination with hydraulic models for general modelling studies, (ii) as a decision support component in operational forecasting and decision-support systems for example for drought management, water allocation, reservoir operation (e.g. for flood control, irrigation, hydropower etc.) and its optimization, (iii) as a real-time control component in SCADA systems (supervisory control and data acquisition systems) in which RTC-Tools implements feedback control and advanced Model Predictive Control (MPC) for implementing state-of-the-art control strategies aiming at a safe, energy and cost aware, integral management of water resources systems. See the technical manual for more information (Schwanenberg and Becker, 2019).

This tool is coupled with Delft3D-FM morphological model as well that can be used for operation of dams and weirs. There are two ways to replicate the reservoir operation, first is to fix the reservoir operation and the model computes the gate operation (usually PID control is used in this case). In case, the reservoir water level is varying under certain inflow condition, then time-series of reservoir level can be assigned in combination with gate operation rule. Both ways can be combined as well under varying flow condition.

3.2.3 Reservoir operation scenarios

One reference case and two cases with different reservoir operation strategies were considered in this study. These are the same cases as we used in our earlier study that was carried out using Delft3D model (Giri et al., 2019). The simulated cases are as follows:

(a) Reference case: A constant reservoir level were maintained at 626 m and 336 m for upstream (MMHEP) and downstream (MHEP) reservoirs respectively.

(b) Case 1 (left plot of Figure 5): the operation rules for the reservoirs, in which the water level in the reservoirs and the gate opening is adjusted using the RTC Tool to maintain the desired water level, and the operation of both reservoirs is synchronized without any time lag.

(c) Case 2 (left plot of Figure 5): In this case the gate of the downstream reservoir is opened earlier and maintained at the low operation level, compared to Case 1. The upstream reservoir level is drawn-down to the minimum operation level and maintained for a day. Subsequently, the gates of the upstream reservoir are gradually closed until the maximum operation level is reached and closed within one day. After that, the downstream reservoir starts filling up. The basic idea is to simulate a synthetic case, in which the lower reservoir is flushed first and then allow sediment transport from upstream. Moreover, the sluicing of the downstream reservoir continues after the closure of the upstream reservoir in order to get rid of any remaining sediments, transported from the upstream reservoir. We note that there is no data and information about how the operation of these two reservoirs are synchronized.

It is to be noted that modelling of mentioned cases of dam operation is not fully included in this paper (as the study is still in progress).

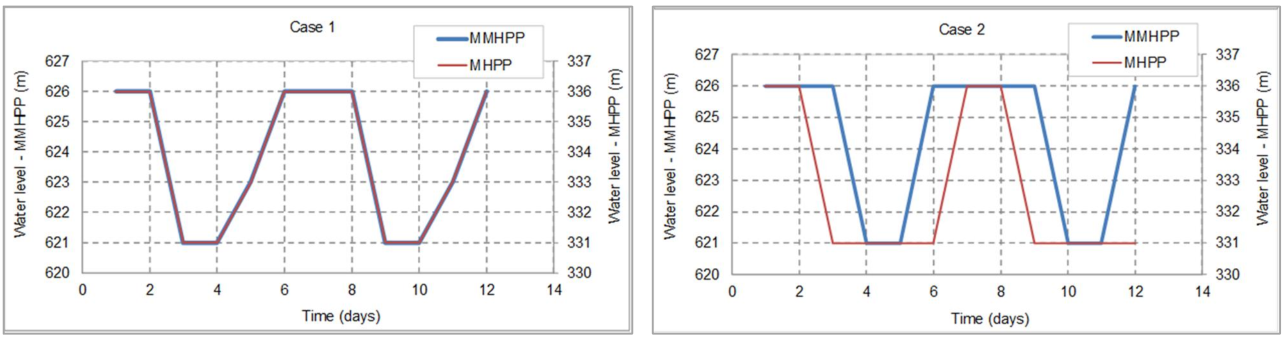

Figure 5. Synthetic scenarios of gate operation of two reservoirs

3.3 Sediment transport and morphology

In this study, we used the formula of Engelund-Hansen (EH) for the total sediment transport. EH formula seems to be appropriate given that there is a large amount of fine sediment transport during monsoon with high mobility, which led to the storage loss of the upstream reservoir (MMHPP) in a very short period. For a sensitivity test, we used Ashida- Michiue (AM) formula. These simulations with different sediment transport formulae also demonstrate the sensitivity of the model to sediment transport formulation.

We used a sediment size of 0.2 mm in order to simulate the sedimentation at MMHPP; this is the size of deposited fine material. The river reach between the two reservoirs is kept non-erodible to assess whether the flushed sediment from the upstream reservoir reaches the downstream reservoir or not. Also, the tributaries are not considered in this study due to lack of data and information. This will be improved in future study.

4. RESULT AND ANALYSIS

4.1 Reservoir sedimentation at MMHPP

The upstream reservoir (MMHPP) had mostly suffered from high sedimentation between 2006 and 2010. In order to replicate that, simulations were carried out using Delft-FM with different sediment transport formula as mentioned above. The result shows that Delft3D-FM model captures the sedimentation process at MMHPP (as depicted in Figure 6). It is interesting to note that the propagation of the sedimentation front towards the dam was simulated better than the previous study with Delft3D (Giri et al., 2019). Despite that the result is better than Delft3D, the simulated sedimentation amount was overestimated by the model. This can further be improved by carrying out proper calibration of the sediment transport formula. It is to be noted that some erosion pattern at MMHPP, seen in the bathymetry data (right plot of Figure 6), does not appear to be consistent (or they include dredging of the reservoir which is not reported anywhere). Also, measurement in some areas is missing as indicated. We have no data and information to explore this further. It is also not clear why the performance of Delft3D-FM is better. Maybe this is related to numerical scheme and parameters that will be explored in future study.

4.2 Sensitivity to sediment transport formula

The simulation results show sensitivity to the sediment transport formulation. A typical example is depicted in Figure 7, showing the sensitivity of sediment transport formulation and parameter. Overall, simulations with EH formula show more sedimentation than with AM formula that is closer to the observed trend. Despite the fact that the reservoir is in a hilly region with graded sediment, the deposited material gives an impression that majorly fine sediment was transported and deposited in the reservoir during the monsoon (this can also be seen from the picture, depicted in Figure 2 above). Therefore, the use of EH formulation can be regarded as justifiable given the fine sediment dynamics and high mobility during high flow period, which we considered in our computations. We will explore this further in our future study.

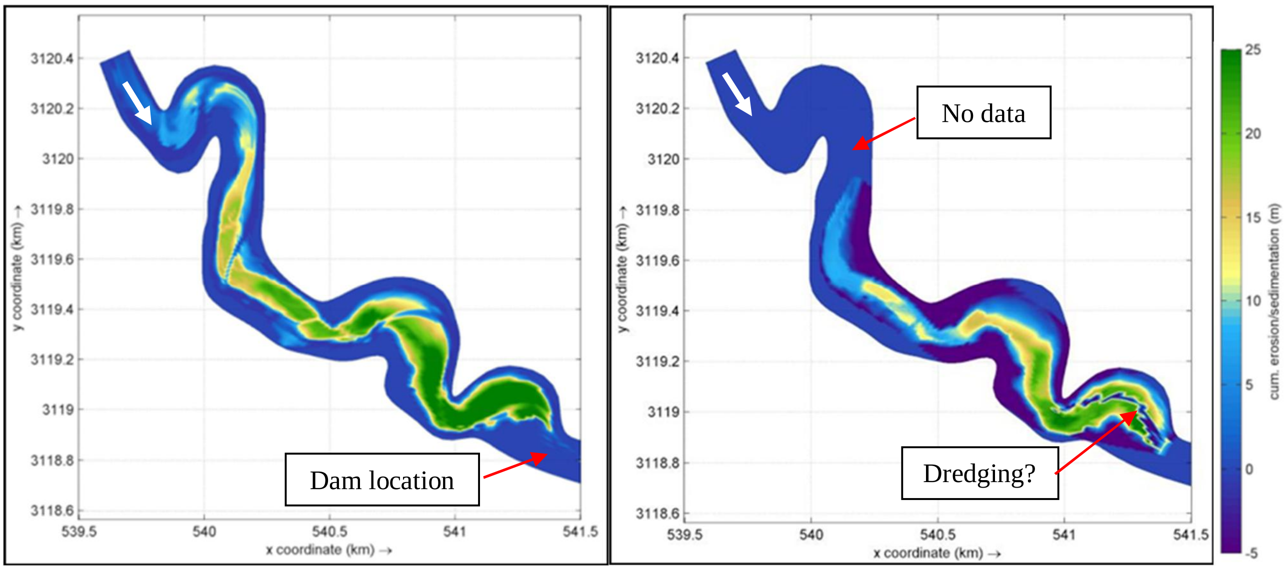

Figure 6. Simulated sedimentation at MMHPP using Delft3D-FM (left) and measurement (right)

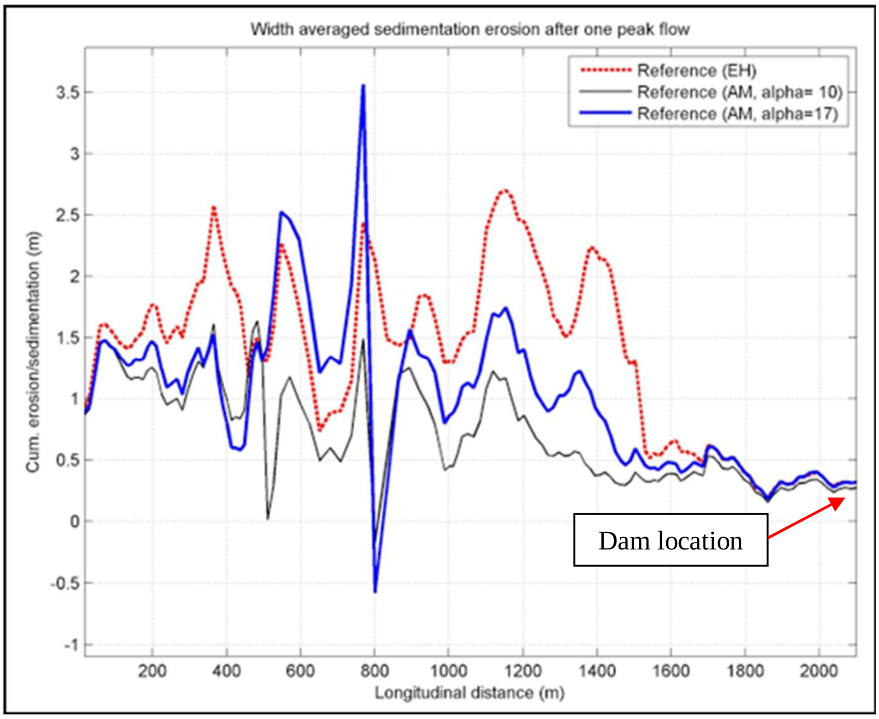

Figure 7. Sensitivity of sediment transport formula and parameters on width-averaged sedimentation-erosion at MMHPP

4.3 Reservoir operation and downstream effect

No noticeable sedimentation problem is reported at the lower reservoir (MHPP). There is also no data and information on the impact of MMHPP on the sedimentation of MHPP. No information of any flushing operation; other than dredging. We qualitatively evaluated the sedimentation at the lower reservoir (MHPP) as a result of the flushing operation of the upstream reservoir (MMHPP). So far, we have simulated and assessed only one case, which shows a large amount of deposition at the lower reservoir as shown in Figure 8. This does not look very realistic. This can be attributed to the overestimation of sedimentation and its propagation at the upper reservoir (MMHPP), which leads to large downstream transport. Further exploration, calibration and more analysis must be carried out.

The work is in progress regarding detailed study and impact assessment (hydraulic and morphologic) with a focus on synchronized reservoir operation.

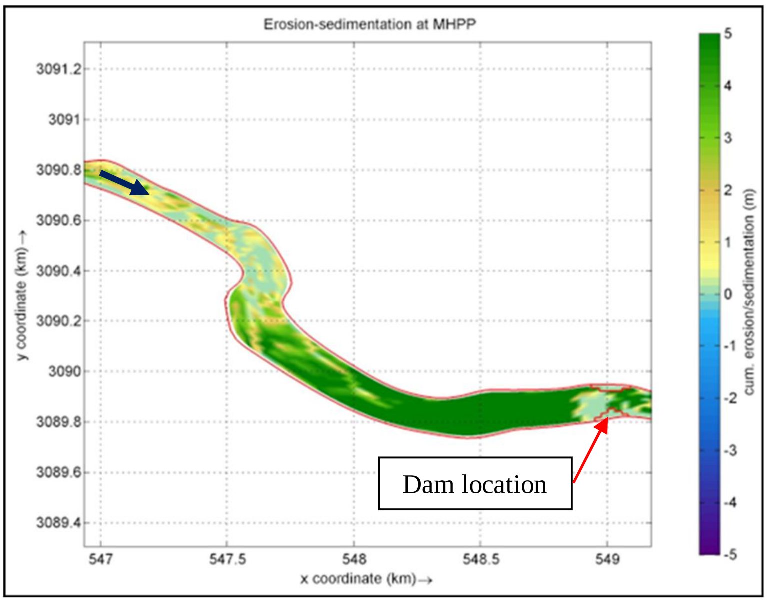

Figure 8. Sedimentation at MHPP due to the transport of sediment released from MMHPP

5. CONCLUSION AND RECOMMENDATIONS

Considering the assessment of modelling exercise of such complexity using D-FM (in which the morphology has only recently been incorporated), the results can be considered as satisfactory. The results show consistent model behaviour and trends despite the complexity involved in morphological modelling including Real-Time Control (RTC) for synchronized operation of two reservoirs. The result concerning the replication of the sedimentation at MMHPP (using D-FM with EH formula) appears to be better than the results of the previous study (using Delft3D with both EH and AM transport formulae as presented in Giri et al., 2019). However, the reasons for the difference between the two models will be explored and analyzed further.

The model is also able to simulate the upstream transport and resulting sedimentation at the downstream reservoir (MHPP) qualitatively good despite that the result does not look very realistic quantitatively. This can be improved in future study. Besides, sensitivity to sediment transport formulae and parameters were assessed. Different transport formula gives different magnitude of sedimentation and sediment delta propagation. For example, the EH formula shows more sedimentation and fast propagation towards the dam (comparable with the observation) than AM formula which shows significant underprediction of the sedimentation volume and delta propagation speed. The use of EH to compute the total sediment load can be justified given the fact that there is predominant fine sediment dynamics that is deposited in the reservoir during the monsoon despite that fact that the river bed sediment is graded.

For future consideration, following recommendations are made:

- Improve the river and reservoir bathymetry as well as weir schematization, particularly for the downstream reservoir (MHPP)

- Carry out more explorative study using D-FM, particularly with a focus on synchronized operation strategies including improved flushing operations (also considering real-world experience if data and information are available)
- Carry out more sensitivity tests on sediment transport formula, also including other approaches for fine sediment transport such as Kitamura (1995) and Partheniades-Krone (1965) formulae (including parameter sensitivity)
- Review flow and sediment conditions properly, particularly for the downstream reservoir, since there are few tributaries, flowing into the river between two reservoirs in case of availability of the data and information
- Assess the morphology of the river reach between two reservoirs (in the current study, the reach between the two dams was considered as non-erodible (armoured), which is usually the case for hilly rivers in Nepal)
- Carry out hydrodynamic calibration and verification to check the gate operation and corresponding reservoir level variation and outflow discharge in case the data and information are available
- Provide possible measures to deal with sediment related problems including impact assessment
- Consider operation optimization in complement with ecological aspect in future study

ACKNOWLEDGMENTS

We highly acknowledge a generous support from Chigasaki Research Institute of J-Power for this study. We also acknowledge Strategic Research Programs (TKI and SO) of Deltares for the support of ongoing study.

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