Morphological modelling of sediment-induced problems at a cascade system of hydropower projects in hilly region of Nepal

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ABSTRACT: In this paper, we have presented morphological study of a cascade system of hydropower dams, namely Middle Marsyangdi (MMHEP) and Marsyangdi (MHEP) in Nepal. These two plants provide more than 20% of the total energy. However, the upstream reservoir (MMHEP) has been suffering from significant sedimentation problem since its commissioning as it has lost more than half of its storage capacity just within 4 years of exploitation. Current study is mainly focused on modelling and analysis of sedimentation problems, particularly at MMHEP, that can be attributed to the consequences of ignoring the river planform and sediment inflow while selecting the reservoir site. Morphological process at MMHEP as well as downstream river reach and MHEP has been modelled using Delft3D model with Feedback Control Tool to simulate synchronized operation of two reservoirs in a cascade system. Effects of flushing operation as well as sensitivity of different sediment transport formulae on simulation results have been revealed and analyzed. The results show consistent model behavior and trends despite the complexity involved in morphological modelling with synchronized operation of two reservoirs in a cascade as well as data scarcity. Recommendation has been made for further improvement of the models based on proper data and information in future.

RÉSUMÉ : Dans cet article, nous avons présenté une étude morphologique d'un système en cascade de barrages hydroélectriques, à savoir le Marsyangdi moyen (MMHEP) et le Marsyangdi (MHEP) au Népal. Ces deux centrales fournissent plus de 20% de l'énergie totale. Cependant, le réservoir en amont (MMHEP) souffre d'un important problème de sédimentation depuis sa mise en service car il a perdu plus de la moitié de sa capacité de stockage en l'espace de quatre ans d'exploitation. L'étude actuelle porte principalement sur la modélisation et l'analyse des problèmes de sédimentation, en particulier à MMHEP, qui peuvent être attribués aux conséquences de l'ignorance de la forme de la rivière et de l'afflux de sédiments lors de la sélection du site du réservoir. Les processus morphologiques à MMHEP, en aval de la rivière et MHEP ont été modélisés à l'aide du modèle Delft3D avec Feedback Control Tool pour simuler le fonctionnement synchronisé de deux réservoirs dans un système en cascade. Les effets de l'opération de rinçage ainsi que la sensibilité de différentes formules de transport des sédiments sur les résultats de la simulation ont été révélés et analysés. Les résultats montrent un comportement et des tendances de modèle cohérents malgré la complexité de la modélisation morphologique avec le fonctionnement synchronisé de deux réservoirs en cascade ainsi que la rareté des données. Il a été recommandé d'améliorer à l'avenir les modèles fondés sur des données et informations appropriées.

1 INTRODUCTION

Himalayan rivers are very high sediment-laden comparing to similar river basins around the world due to the fact that the Himalayan geology is young and fragile. Consequently, sediment-induced problems in dams and reservoirs are one of the most significant concerns for all kinds of existing and planned projects in the region. This is particularly important for relatively smaller daily peaking reservoirs as their peaking storage volume can be diminished quickly. Reservoir operation can have noticeable impacts on the sediment management in Peaking Run-of-the-River Hydropower Projects (Mool et al., 2017). Moreover, flow and sediment management are more challenging for a cascade system of dams.

Dams are intervention in a natural system that induces adverse impacts as well. Nevertheless, the negative impacts of dams can also be attributed to poor planning, mismanagement, inefficient operation and improper consideration (or negligence) of impact mitigation options and conditions. The importance of dams and reservoirs, their positive and negative impacts shall objectively be weighed vis-a-vis multi-sectorial benefits and any nation's specific priorities and demands (Giri & Narayan, 2018).

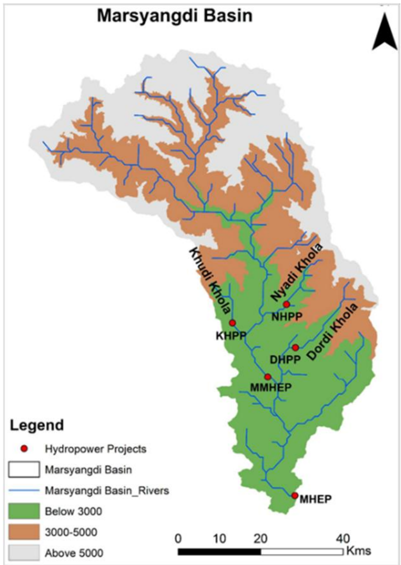

Figure 1. Marsyangdi basin with location of MMHEP and MHEP including other planned dams (WECS, 2017)

In this study, we have selected two peaking reservoirs, namely Middle Marsyangdi Hydropower Project (MMHEP) and Marsyangdi HPP (MHEP), which are located in one cascade system. The two plants provide more than 20% of the total energy share in Nepal. However, the upstream reservoir (MMHEP) has been suffering from significant sedimentation problem since its commissioning as it has lost more than half of its storage capacity just within 4 years of exploitation.

1.1 *Objective and scope*

The main objective of this case study is to investigate the performance of hydrodynamic and morphological modelling of the synchronized operation of two reservoirs in a cascade system. The model incorporates two reservoirs including spillway and the gates as well as the river reach between them. Owing to the lack of enough data, this first study has been simplified and some synthetic scenarios have been simulated and compared.

The scope of this study is outlined as follows:

- Review and analysis of existing practices of reservoir sediment management and impact assessment pertaining to cascade system of dams
- Development of a morphological model of cascade system of two dams
- Coupling feedback control tool for gate operation of both dams in a cascade system to simulate synchronized operation including sediment transport and morphology
- Replicating sedimentation of upstream reservoir
- First assessment of the effects of sediment flushing on the downstream reservoir including the effect of synchronized dam operation

1.2 *Salient features of HEPs*

Salient features of both hydropower projects are presented in Table 1.

Table 1. Salient feature of MMHEP and MHEP

Description	MMHEP	MHEP
Type	PROR (5 hrs peaking)	PROR
Installed capacity (MW)	70	69 MW
Catchment area (km^2)	2729	3850 km^2
Average annual flow (m^3/s)	99.5 m^3/s	210 m^3/s

Spillway capacity (m^3/s)	4270 (at RL = 626 masl)	Not available
Spillway crest level (masl)	629 and 630	323 and 324
Spillway gates	3 radial gates (12 m W x 19.54 m H)	3 gates (16 m W x 13.8 m H at 324.0 masl) and 2 gates near intake (16 m W x 14.8 m H at 323.0 masl)
Maximum gross/net head (m)	110 / 98	90.5 m
Design live storage volume (m^3)	1.65 million	1.5 million
Dam type/ crest length (m)	Combined concrete gravity and rock fill dam/ 95	Concrete/ 102
Year commissioned	2007	1989

2 REVIEWING SEDIMENT-INDUCED PROBLEMS

2.1 *Middle Marsyangdi (MMHEP)*

MMHEP is located about 40 km upstream of the MHEP. This dam has been suffering from severe sedimentation problems right after its commissioning as well as toe erosion at outer banks as shown in Figure 2 and Figure 3. There could be few reasons for this problem among which the most visible one is ignorance of large and meso-scale morphological feature of the river while considering the site. The reservoir planform does not appear to be appropriate from the morphological point of view. This demonstrates how important it is to consider morphological aspects while selecting the reservoir location.

Another reason for this problem (reported by dam authority as well) appears to be operational aspect. It appears that there were mistakes in operation of the reservoir during (first after the commissioning) monsoon (June-July) of 2009. It seems that no sluicing was carried out

Figure 2. Sediment-induced problem at MMHEP (sedimentation at the inner bend and erosion at the toe of the outer bend) – The Google Earth image shows the reservoir condition of April 2008 (during construction), while the pictures were taken during drawdown for dredging and maintenance.

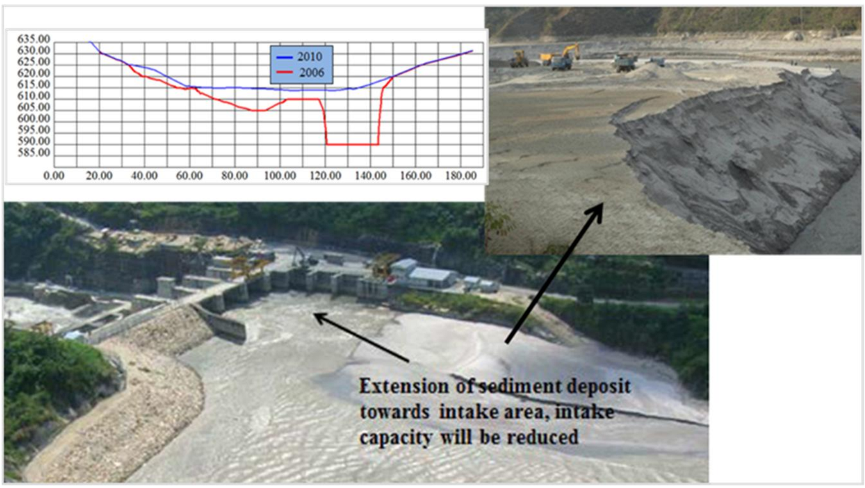

Figure 3. Sediment deposition near the intake area, observed during October 2009 (lower picture, Kayastha, 2010), deposition seen during drawdown for the dredging work in 2010 (upper right), and upper graph shows change in cross-section, located about 70 m upstream of the dam (Shrestha, 2012)

and the reservoir was operated at Full Reservoir Level (FRL), which resulted in significant sedimentation in the reservoir (Kayastha, 2010). This has been revealed by a measurement that was conducted in 2010 (Shrestha, 2012).

There is also erosion problem at the toe of the left bank near the spillway (note that it is outer bend of the river), which appears to be occurring during high flow release (for sluicing and flushing) as depicted in Figure 2. Besides, the sediment-induced problems are related to abrasion of spillway surface and turbine erosion.

To handle the problem of sedimentation (at least partly), a bedload excluder has been placed in front of the intake to exclude the bedload during high flows. The reservoir is flushed 3-4 times during monsoon when the sediment load is high. It takes around 6 hours to fully drawdown the reservoir. During this time the power plant is shut down. The deposited sediment in the reservoir was removed by dredging as well (Figure 3).

2.2 *Marsyangdi (MHEP)*

The MHEP is located downstream of the MMHEP. It appears that this reservoir does not have significant sedimentation problem comparing to the MMHEP (note that average inflow to MMHEP is higher than MMHEP due to presence of tributaries). This can be attributed to a favourable location from morphological point of view (more or less straight and narrow river). However, the alignment of the intake is not very favourable and there is sedimentation problem at the pondage area near the headworks that requires regular sediment removal. This shows that how the morphological feature is important to avoid the sedimentation and intake approach flow problems. Some of the reported problems and current approaches are as follows (WECS 2017):

- Turbine erosion was found while carrying out maintenance work (every 3 years), but not much severe than MMHEP.
- The bathymetry near the intake and settling basin is regularly measured by using echo sounder in monsoon using boat. The flushing operation is planned based on the condition when the bed level increases more than 3 m. The powerplant is shut down during flushing operation.
- It takes about 4-5 hours to flush the sediment from the settling basin.
- During high flows, the gate no. 5 (located near the intake) is open first up to 0.4 m (the water level is maintained at 333 m). If the water level further increases, then the gate no. 1 (farther most from the intake) is open up to 0.2 m. If this is not enough then again gate no. 5 is open to 0.8 m to 1 m and again gate no. 1 up to 0.4 - 0.5 m. If water level increases more (usually flood condition), then only gate no. 4, 2 and 3 is used subsequently to control the water level
- There is a landslide prone area upstream of the headworks at the left bank (outer bend), which should be carefully taken care of and monitored during flushing operation, since it triggers the erosion of the toe.

3 DATA COLLECTION AND ANALYSIS

3.1 *Hydraulic data*

A study of MMHEP was carried out by DHI-India and partners for Nepal Electricity Authority (NEA) and KfW (2016). The report contains some data and information (collected and measured). Some information and observed hydraulic data during 2013 have been used in this study. The measurements were carried out during higher flow period as well. The measurement shows the maximum flow of about 700 m^3/s, while the minimum low flow is about 60 m^3/s.

There are not many information and data available for the lower reservoir (MHEP), so we have only considered some hypothetical scenarios at this stage. It will be improved further once data are available.

3.2 *Sediment data*

Suspended sediment concentration data at upstream area (where MMHEP is located) are available for 2013 and 1997 for two different locations (NEA, KfW, 2016) as depicted in Figure 4. Besides, particle distribution curves of suspended sediment for different time and location are depicted in Figure 5. The observation has revealed that there is a time-lag between maximum sediment concentration and the peak flow discharge. This is a logical observation given the fact that the sediment peak normally occurs before the discharge peak. There is a trend of refinement of particles near the intake area.

A preliminary analysis, done in a previous study (NEA, KfW, 2016), suggests that the sediment yield could be around 1.79 mm/km^2/year (this has to be checked in future study).

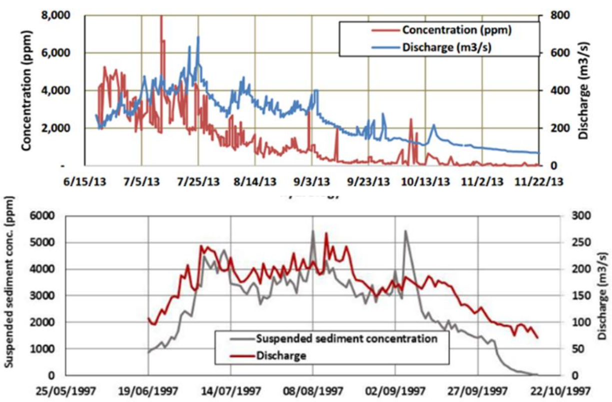

Figure 4. Sediment concentration data of 2103 at Bhakunde Besi site, upstream of MMHEP (upper plot) and at Phalia Sangu (at MMHEP dam site), measured in 1997 (lower plot) (NEA, KfW, 2016)

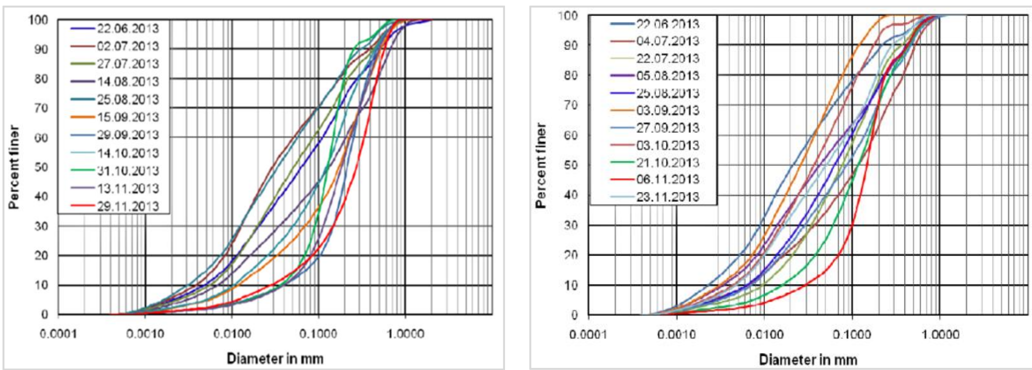

Figure 5. Particle size distribution of SS at two different locations, namely Bhakunde Besi at upstream (left) and at Phalia Sangu at MMHEP dam site (right) (NEA, KfW, 2016)

4 MORPHOLOGICAL MODELLING

This study includes modelling of cascading system of dams using two-dimensional morphological model (Delft3D) coupled with feedback control tool. The model simulates synchronized reservoir operation of two peaking Run-of-River (ROR) hydropower weirs to assess hydrodynamic and morphological effects.

In this study, the main purpose is to assess the model capability to simulate morphological evolution due to the synchronized operation of the two reservoirs. Such study is rather new, and to our knowledge, there is no such published work, in which a morphological model and feedback control tool are coupled and applied in a cascade system of reservoirs with synchronized operation (recently some morphological modelling studies considering operation of single dam and barrage were carried out by Giri et al., 2019 and Mool, 2017). This study is only the initial phase and can be improved further and verify when more data and information are available.

4.1 *Model set-up and schematization*

All The model set-up process and the assumptions made are outlined as follows:

- The two reservoirs are included in a single model domain
- The grid has been constructed for both reservoirs that are connected by the river reach as depicted in Figure 6.
- The measured bathymetry of the pre-construction period has been used for simulation of sedimentation at the MMHEP that occurred after commissioning.
- For the simulation of effect of gate operation, initial bed level of MMHEP has been used based on measurement data of 2010.
- There is no bathymetry data for the river reach and lower reservoir. Therefore, a flatbed condition is considered with the slope based on available reservoir level data and valley slope. This shall be improved in future once data are available. The bed levels, which are used in the current study, for both reservoirs are depicted in Figure 7.
- The weirs for the MMHEP are schematized as per collected information, while the weirs for the MHEP has been assumed with one opening due to absence of the data. This will be improved in future in case more data and information were available. Bathymetry and schematization of weirs for both reservoirs are depicted Figure 7.

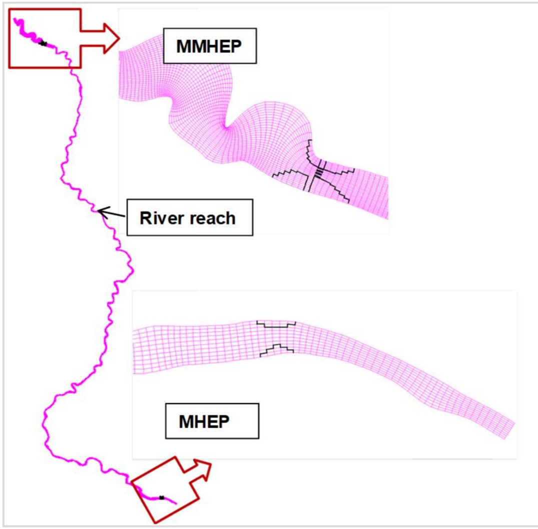

Figure 6. Model grid of the reach including both reservoirs, showing the details of the two reservoirs and weir schematization

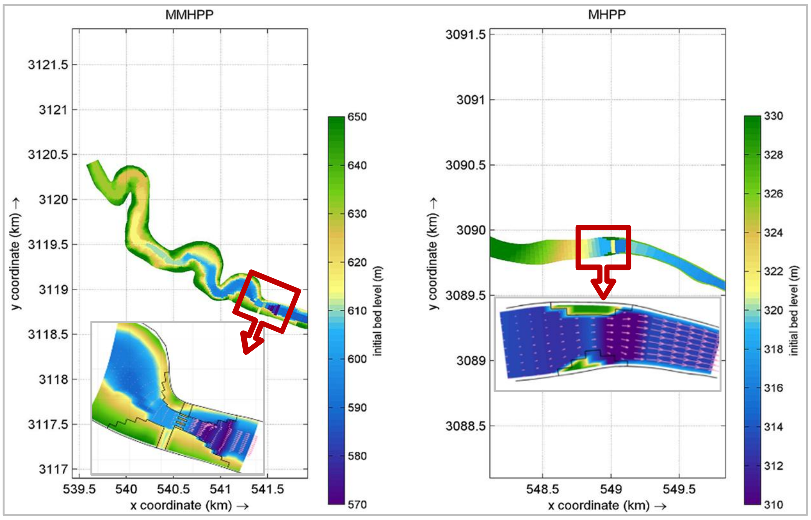

Figure 7. Model bathymetry for both reservoirs (with details of weir schematization)

4.2 *Modelling conditions, formulations and scenarios*

4.2.1 *Flow boundary condition*

Since the flushing scenarios are considered in current simulations, five days of high flow period (representing one short flood season when the river is morphologically active) has been used as upstream boundary condition. For this, a part of the discharge hydrograph (flood period) has been considered as upstream boundary for the model as shown in Figure 8 (left plot) assuming that most of the sediment transport and deposition takes place during this period. The same flood wave has been repeated for longer computations. This period may still be small to replicate the sedimentation process during monsoon period and will be considered in future study. A rating curve is used as downstream boundary condition as depicted in Figure 8 (right plot).

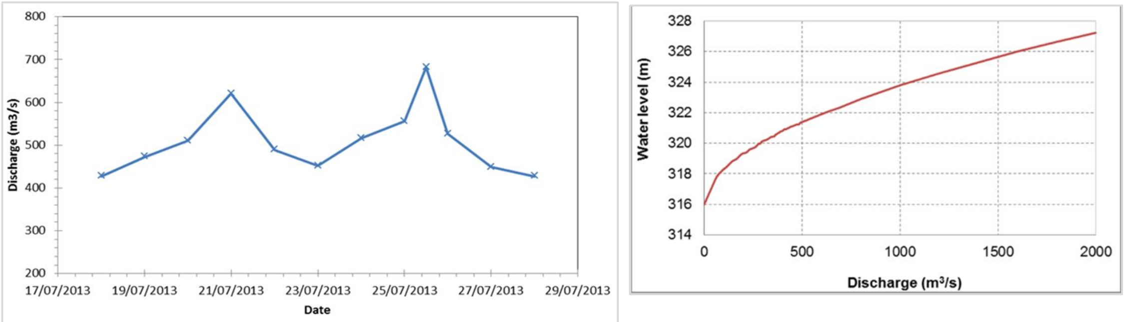

Figure 8. Upstream discharge (left) and downstream Q-H boundary conditions

4.2.2 *Reservoir operation scenarios*

One reference case and two cases with different reservoir operation scenarios are considered in this study. The conditions are as follows:

1) *Reference case*: The reservoir levels are kept constant, namely 626 m and 336 m for upstream (MMHEP) and downstream (MHEP) reservoirs respectively.

2) *Scenario 1*: The operation rules of the reservoirs are designed as depicted in Figure 9 (left plot). The operation in both reservoirs is synchronized without any time lag, i.e. the gates of both reservoirs are open and closed at the same time.

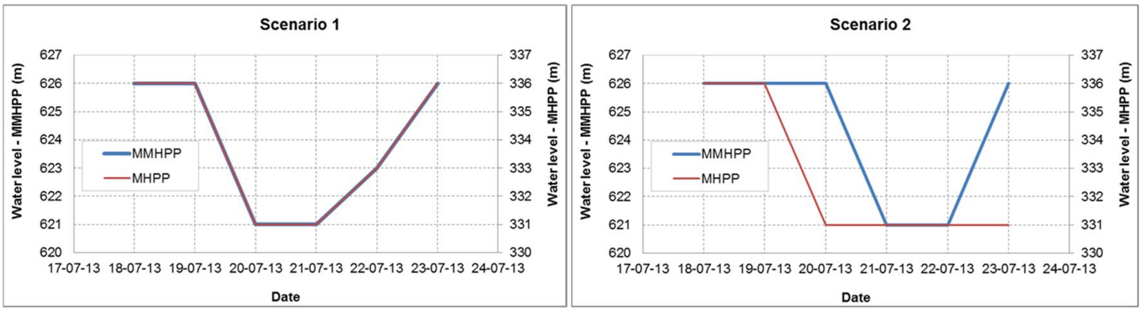

Figure 9. Scenarios of synchronized flushing operation (gate operations, reflected on water level variation in both reservoirs)

3) *Scenario 2*: The operation rules of the reservoirs are designed as depicted in Figure 9 (right plot). The operation is designed in such a way that the gate of the downstream reservoir is open earlier and maintained at the low operation level. Then the upstream reservoir water level draws down to minimum operation level and maintained for around a day. Later the gates of the upstream reservoir is gradually closed after three days until the maximum operation level is reached (it is closed within one day). After that, the downstream reservoir starts filling up. The basic idea is to simulate a synthetic scenario, 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 remaining sediments, transported from the upstream reservoir.

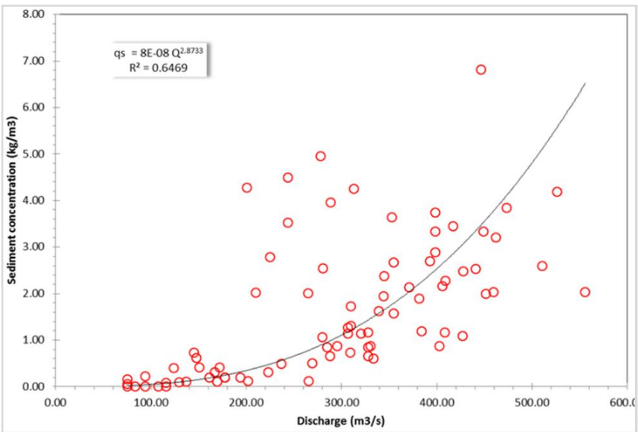

Figure 10. Q-SS relation based on sediment concentration measured at Bhakunde-Besi (upstream of MMHEP)

4.2.3 *Morphological and sediment conditions*

The morphological conditions, used sediment transport formulations and model parameters are presented in Table 2. Two types of bed material fractions are considered, namely sand and mud. The transport formulae of Ashida- Michue (1974) and Partheniades-Krone (1965) are used to compute the sediment transport of the sand and mud (silt) respectively. For the simulation of sedimentation and flushing of the upstream reservoir, we have used Engelund-Hansen formula given the fact that the deposition materials are fine sediment with high mobility and the formula considers total transport. This also demonstrates the sensitivity of the model to sediment transport formulation.

It is to be noted that the connected river reach has been kept non-erodible to assess whether the flushed sediment from the upstream reservoir reaches the downstream reservoir or not. This is also the case the steep hilly and mountainous rivers in Nepal is usually armored and in dynamic equilibrium condition.

Based on the data, shown in Figure 4, a Q-SS relation has been generated and used as inflow sediment concentration flux to the model.

Table 2. Morphological and sediment conditions, parameters and formulae

Conditions/formulations/parameters	
Upstream sediment boundary	For bedload: Equilibrium bed level For suspended load: time series inflow fluxes
Sediment size	0.200 mm for sand, 0.017 mm for mud (fall velocity = 0.25 mm/s)
Sediment transport formula (sand, mud)	Sand: Ashida-Mechiue and Engelund-Hansen Mud: Partheniades-Krone
Secondary flow effect (E_{spir})	0.5
Bed slope effect (A_{shld}/B_{shld})	1.5/0.5

4.3 *Simulation results and analysis*

4.3.1 *Sedimentation at MMHEP*

The upstream reservoir (MMHEP) has suffered from high sedimentation between 2006 and 2010. In order to replicate that, some simulations have been carried out using different transport formula. Engelund-Hansen (1967) sediment transport formula has been used instead of Ashida-Michiue (1974). The model replicates propagation of sedimentation front with time. The more realistic result looks for the simulation with EH formula (Figure 11). Although the model seems to have underestimated the sedimentation (particularly near the dam) and its propagation. However, there could be various reason for that such as proper flood and sediment transport conditions (particularly less flood period in the model), initial bed level and available bed materials in the reservoir bed. It is to be noted that some erosion pattern, seen in the bathymetry data, does not appear to be consistent and also measurement in some areas are missing. This has to be explored further in our future study. What we can say now is that the model is capable to replicate the sedimentation process.

Simulation results show sensitivity to the sediment transport formulation. Simulations with Enguland-Hansen formula shows more sedimentation in the reservoir, which appears to be more realistic. Despite the fact that the reservoir is in hilly region in which the sediments are graded, the deposited material gives an impression that they are fine sediments. Moreover, they are transported during monsoon. Therefore, the use of EH formulation can be regarded as justifiable given the fine sediment dynamics.

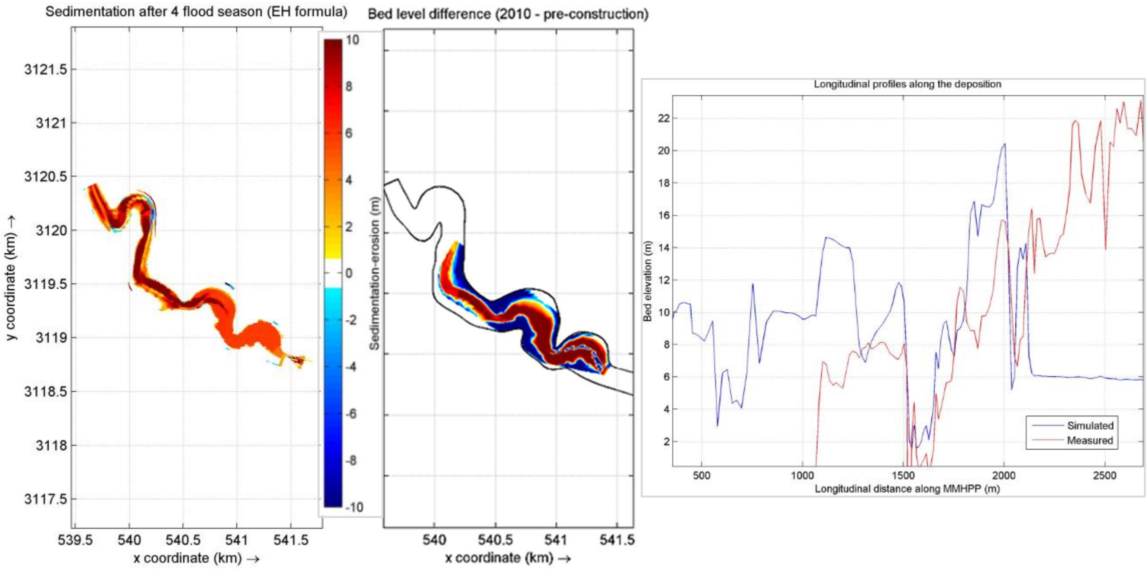

Figure 11. Simulated and measured changes in bed levels after four flood seasons: Spatial plot (left) and longitudinal profiles along the deposition (right)

4.3.2 *Reservoir operation scenarios*

The width-averaged sedimentation pattern along the upstream and downstream reservoirs for all scenarios including the reference case can be assessed from Figure 12. It can be seen that the deposition is less in case of reservoir operation at MMHEP. Also, the deposition at downstream reservoir can be seen as a result of sediment supply due to upstream flushing. The deposition delta in downstream reservoir migrates during operation without noticeable decrease in deposition. The result is only for one short flood period (5 days), so the magnitude is lower, but the trend is clear. Further study will be carried out under the condition of more realistic flood periods and also for other (imporved) reservoir operation scenarios.

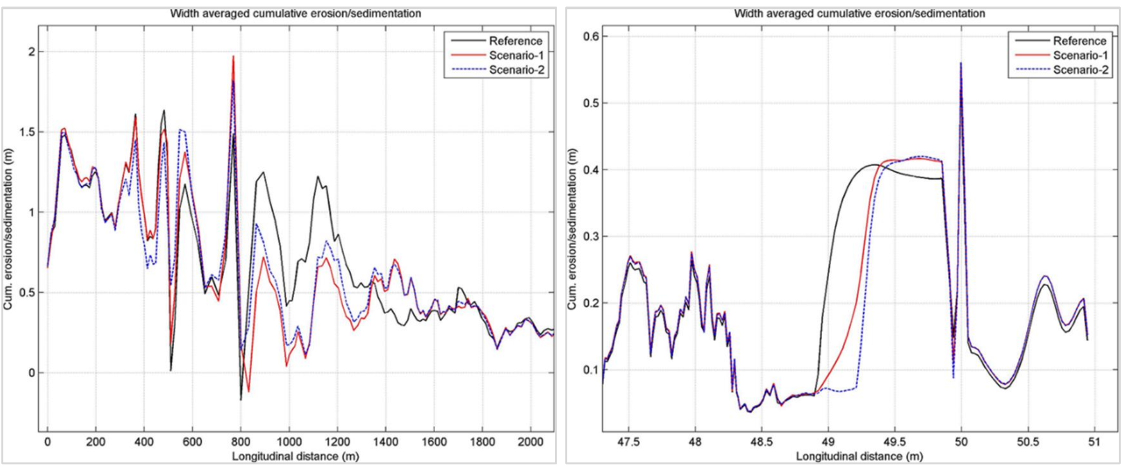

Figure 12. Width averaged longitudinal profiles of cumulative erosion-sedimentation for the reference and reservoir operation scenarios after one flood season at upstream reservoir (MMHEP, left plot) and downstream reservoir (MHEP, right plot)

5 CONCLUSION AND RECOMMENDATION

A review of available data and information has been carried out in this study. Furthermore, two-dimensional morphological models, coupled with feedback control tool for gate operation, have been developed and applied to a cascade system of two dams in a hilly river of Nepal. Firstly, a morphological simulation of sedimentation of upstream reservoir has been carried out. Secondly, simulations for a reference case and two synthetic scenarios of synchronized sediment flushing operations have been carried out to assess their effect on morphological changes. Based on first results, following conclusions and recommendations have been made.

5.1 *Conclusions*

Given the very first assessment of modelling exercise of such complexity, the results can be considered as satisfactory. The results show consistent model behaviour and trends despite the complexity involved in morphological modelling with feedback control for synchronized operation of two reservoirs. Following are the trends and features, simulated by the model:

- Deposition trend at the upstream reservoir
- Less deposition (or it's propagation) in the reservoir in case of flushing in comparison with the normal operation
- Upstream transport and resulting deposition at the downstream reservoir
- Effect of the flushing operation mode at the downstream reservoir
- Magnitude of the changes is small, e.g. the effect of the flushing in both reservoirs, particularly in the downstream reservoir. This can also be attributed to short morphological simulation period.
- Different transport formula replicates different magnitude of sedimentation process. For example, Engelund-Hansen (1967) shows more sedimentation (near to observed) than Ashida-Michiue (1974). The use of EH can be justified given the fact that there is prevalent fine sediment dynamics in the reservoir during floods despite that the dams are located in a hilly river.

5.2 *Recommendations*

The following recommendations can be made for improving the model study:

- Improve the river and reservoir bathymetry schematization
- Update (if data is available) or reproduce bathymetry of the connecting river and the downstream reservoir (MHEP) using morphological model for longer-term simulations
- Improve the dam schematization and operation scenarios
- Update the dam gates schematization for the downstream reservoir
- Update the dam gates operation scenarios as per the real-world experience if information is available
- Improve, test and fine-tuned the flushing scenarios
- Review the flow and sediment condition properly, particularly for the downstream reservoir, since there are few tributaries, flowing into the river between two reservoirs
- Assess the erodibility of the river reach between two reservoirs (in current study, it has been considered as non-erodible (armored), 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.
- Consider the effects of upstream projects (upstream of MMHEP), one of which has already been constructed and some are planned.

REFERENCES

Ashida, K. & Michiue, M. 1973. Studies on bed-load transport rate in open channel flows. *Sediment Transportation*, volume 1.

Engelund F. & Hansen, E. 1967. *A monograph on sediment transport in alluvial streams*. TEKNISK-FORLAG Skelbrekgade 4 Copenhagen V, Denmark.

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

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

Kayastha, G. P. 2010. Sediment study and Management in Middle Marsyangdi Hydropower Plant. *Sediment Workshop 2010*, Kathmandu, Nepal.

Mool, P., Popescu, I., Giri, S., Omer, A., Sloff, K., Kitamura, Y. & Solomatine, D. 2017. Delft3D morphological modelling of sediment management in daily peaking run-of-the-river hydropower (PROR) reservoirs in Nepal. 85^{th} Annual Meeting of ICOLD, July 3-7, Prague, Czech Republic.

NEA, KfW 2016. *Study Numerical Modelling for Middle Marsyangdi Hydroelectric Plant*. Final report, prepared by DHI – India in cooperation with DB Sediment and Cologne University.

Shrestha, H. S. 2012. *Sedimentation and sediment handling in Himalayan reservoirs*. PhD dissertation. Norwegian University of Science and Technology.

WECS 2017. *Study on sediment management in Run-of-River hydropower projects in Nepal*. Final report, prepared by Hydroconsult, Hydro Lab and Recham, Nepal.