Delft3D morphological modelling of sediment management in daily peaking run-of-the-river hydropower (PROR) reservoirs in Nepal

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ABSTRACT

Himalayan rivers are known to have very high sediment yield when compared to similar river basins around the world and the same applies to the rivers in Nepal. Therefore, reservoir sedimentation is one of the most serious concerns for all kinds of existing and planned reservoirs in the region. This is particularly important for relatively smaller daily peaking reservoirs as their daily peaking storage volume can be diminished at very high annual rates. But, unlike in the large reservoirs, the operation of gates can have significant impacts on the long term sediment management in peaking run-of-river (PROR) reservoirs. The objective of this study is to explore the performance and application of a state-of-the-art Delft-3D morphological model coupled with Real Time Control (RTC) tool for reservoir gate operation, to address the problems associated with sediment management in PROR reservoirs. The main focus of the research is on following issues: (i) sedimentation in PROR reservoirs in the hilly region of Nepal; (ii) sediment management options in PROR reservoirs; (iii) reservoir sustainability for PROR reservoirs in the himalayan rivers.

1. INTRODUCTION

The application of hydropower dams and storage reservoirs are especially important to Nepal as "Nepal is one of the most water-abundant countries in the world, with 6,000 rivers, total mean annual runoff of 224 km^3 and per capita water availability of 9,000m^3 (Suhardhiman et al. 2015). The total hydropower potential of all the rivers as run-of-river (ROR) schemes in Nepal is 53,836 MW (Jha 2010) out of which the country has currently constructed the total installed capacity 802.37 MW (NEA 2016). Most of the constructed hydropower projects in Nepal are ROR hydropower projects. There is only one hydropower project with storage, namely Kulekhani–A HPP. There are three other hydropower plants in Nepal (Kali Gandaki-A HPP, Middle Marshyangdi HPP and Lower Marshyangdi HPP), which store water in daily basis for peaking energy demand during the dry period. During monsoon, they produce energy as run-of-river plants (NEA 2016). These projects are normally termed as peaking Run-of-the-River (PROR).

Himalayan/hilly rivers of Nepal carry a lot of sediments, particularly during high flow period. Construction of reservoirs in Himalayan Rivers causes problems like sedimentation at the reservoir leading to storage loss (important for peaking ROR HPP). On the other hand, sedimentation in front of the spillway causes transport of large sediments over the spillway leading to abrasion of the crest and glacis. Furthermore, such morphological changes at the headworks may lead to unfavorable flow pattern at intakes. In addition to they cause abrasion, damages, and malfunctioning of turbines and other apparatuses (e.g. gates, trash racks etc). The sediment management aspects are valuable if considered during prefeasibility phase (e.g. the selection of reservoir site). This can be crucial in regions with high sediment loads like in young Himalayan region of Nepal and India. For example, the reservoir planform of Middle Marsyangdi (Nepal) appears to be rather unfavorable if we consider sediment management aspects. Due to complex planform with strong bends, the location does not appear to be favorable from a morphological point of view. This has led to a large deposition at the inner bend in front of the intake, and toe erosion at outer bend upstream of the dam during flow release through the spillway (e.g. for flushing/sluicing) threatening the slope instability. (See Figure 1).

Figure 1. Google earth image of dry Middle Marsyangdi reservoir in Nepal with pictures of inner bend deposition near the intake and toe erosion at outer bend protection near the spillway

There are very limited research works being done related to modeling of reservoir sedimentation and sediment management considering proper gate operation of the dam. The use of 2D numerical modeling to simulate reservoir flushing has been done by Boeriu et al.(2011). Numerical models were also used to simulate the scenarios conducted in the physical model in the prototype scale by Haun and Olsen (2012) & Olsen (2010). Multiple studies have also been done to model the reservoir flushing with a comparison from the field measured data of reservoir sedimentation by Esmaeili et al. (2012 & 2015). In all of the above-mentioned studies, the flushing processes were achieved by controlling the discharge out of downstream boundaries of the model. Though, this method can work relatively well for flushing process but for real time gates operation and better dam representation a new approach of coupling a 2D numerical model with real-time control (RTC) toolbox is and. This study aims at applying by this new approach to investigate sediment management effect in a peaking Run-of-the-River (PROR) hydropower project.

2. STUDY AREA AND OBJECTIVES

Kabeli River is located in the eastern part of Nepal and is one of the major tributaries of Tamor River. The river in the project area can be classified as the mountainous river as the catchment area of the river (862.3 Km^2 at the proposed dam site) has the elevation ranging from 560 masl to 5600 masl as shown in Figure 2. A peaking Run-of-the-River project with an installed capacity 38 MW has been proposed in the river. The project will operate as a daily peaking reservoir providing 6 hours of peak energy during the dry season, whereas the project will operate as a Run-of-the-River hydropower project during the wet season. The power plant has been designed for the power discharge of 37.8 m^3/s, whereas the design discharge for the dam, spillways, and energy dissipation structure is 1860 m^3/s (100 year return period flow).

The proposed dam consists of 4 low-level gates of each dimension 10 m X 10 m (W X H). For the purpose of the research, the gates are named as Gate 4, Gate 3, Gate 2 and Gate 1 are gates numbered in reverse order counted from the left bank of a river or from the intake (Hydro-Consult 2011).

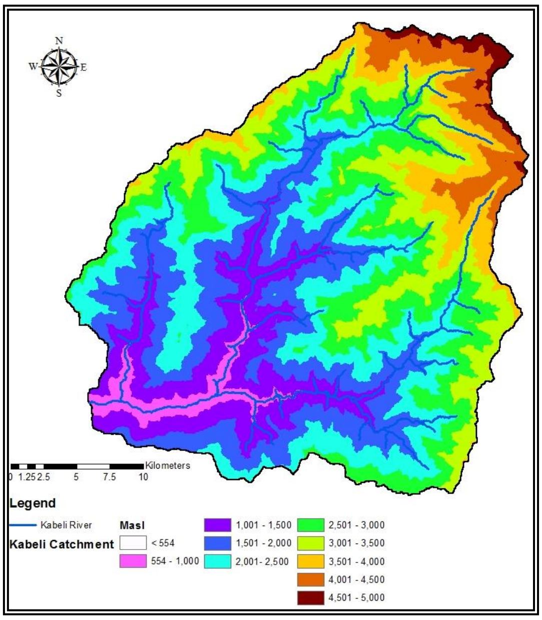


Figure 2. Catchment area of Kabeli River at proposed dam location

The main objective of this study is to explore the possibilities of morphological model coupled with Real-Time Control (RTC) tool, to replicate morphological development of the reach within storage area (reservoir) under various conditions of spillway gates operation. In this way, the attempt has been made to establish the background for using the numerical model as a supplementary to the physical model in some cases, while for a number of cases it can be an alternative to the physical model. Activities that have been performed to achieve the objective can be outlined as follows: (i) development of a morphological model of the reach with graded sediment and couple it with RTC , (ii) exploring effect of alternative options of long term gate operation (other than recommended in the project) on reservoir morphology.

3. FIELD AND LABORATORY INVESTIGATIONS

3.1 Field observation and survey

Field observation for water levels, river discharges, sediment concentration, sediment deposit in the river bed and topographical survey were performed during updated feasibility study conducted from 2010 to 2012.

3.1.1 Reservoir bathymetry survey

Topographical survey of the area was conducted in 2010 for the update feasibility study. The cross-sectional survey has also performed for the reservoir area and the downstream reaches. This cross-sectional data was used to perform physical model study for the proposed dam and reservoir. The topographical survey data of the reservoir and the river is imposed to Quickin software (available in the Delft3D package) to generate the model topography.

3.1.2 Hydrological study

Long-term discharge data for the proposed dam location from 1965 to 2008 was generated by using Catchment area co-relation (CAR) method with the adjoining catchment of Tamor River which is a common method used in Nepal to predict the discharge in ungagged catchments. The river discharge from 1998 to 2008 was considered for the simulation of 10 year period. This discharge has been used as the upstream boundary condition for the Delft3D model. The gauging of the catchment was started from 2010 when the river gauging station was established about 500 meters downstream of proposed dam axis. Due to the ideal location, the gauging station has to be used as the downstream boundary for the numerical model. The equation of the rating curve used is shown below.

$Q = 42.23 \times (G + 0.05)^{1.477}$ Where, Q = Discharge at gauging station (m^3/s), G = Gauge level (m)

3.1.3 Sediment study

Suspended sediment has been measured in the river in the year 2010 for an entire year. From this data, the estimated total annual suspended sediment is 0.64 million tons/year (0.24 Mm^3/year) (Hydro-Consult 2011). There was no real correlation found between measured sediment concentrations and measured discharge. The highest correlation was found to be 0.34 when discharge was lagged by 3 days. With low correlation and a small number of measured data, it is really hard to establish the relationship between measured discharge and suspended sediment concentrations.

Test pit studies were done on the deposited bed material also shows the very high gradation in the deposited bed load of the in the river bed. A test pit was dug near the proposed dam axis of dimension 3m X 3m X 3m and the excavated material was subjected to in-situ sieve analysis. The grain size distribution of test pit has been used for the estimation of bed sediment load in the river for the study. Pratt-Sitaula et al. (2007), conclude that to calculate total sediment load in Himalayan Rivers an additional 50% needs to be added to the suspended sediment measurements. The paper estimates the bed load to be about 35% of the sediment flux. The research was done in Upper Marshyangdi River in Nepal which lies in the mid-western region of the country. Accordingly, a reasonable estimate of annual bedload transport for Kabeli River can be 0.12 Mm^3/year.

The representation of highly graded sediment as can be seen in Figure 3 with the considerable high percentage of sand, gravels, and cobbles present, cannot be justified by a single representative diameter (D_{50}). Therefore, three different grades of sediment have been used. The sediment grades used are (i) Sand – (d <2 mm), (ii) Gravel – (2mm< d <64 mm), & (iii) Cobbles – (64 mm< d <256 mm). The particle size distribution for river bed deposit is shown in Figure 3. The figure also shows the fraction of each grade of sediment by mass volume which has been used to define the thickness of each sediment layer in Delft3D model.

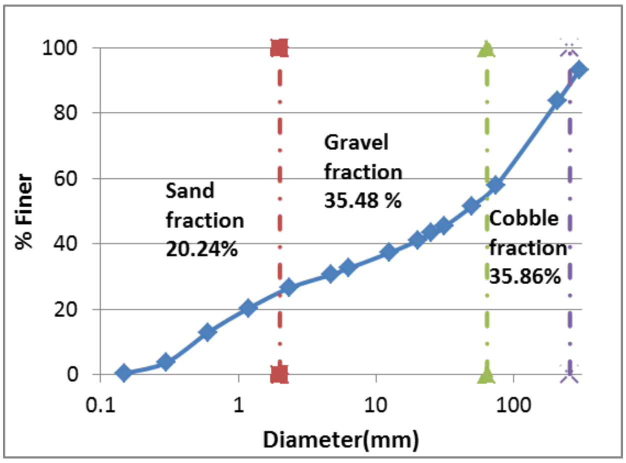


Figure 3: Particle size distribution of river bed deposits

3.2 Physical experiment

Physical model study for the proposed dam and reservoir was performed in 2012 at Hydro Lab, Nepal at a scale of 1:50. The model was constructed to satisfy following conditions: (i) Geometric similitude, (ii) kinematic similitude and (iii) dynamic similitude. The main objectives of the physical modeling were to study (i) hydraulics of power intake, (ii) flow pattern in a settling basin, (iii) energy dissipaters and (iv) reservoir sediment management.

Physical model data and results have been used to calibrate and validate the discharge coefficient of the proposed gates and other hydrodynamic components of the numerical model. Physical model gates operation recommended has also been used as reference to the scenarios executed in this study. The recommended gates operation for various floods is given in Table 1.

Table 1. Gate operation recommended for reservoir operation in floods (Hydro Lab 2012)

Return period	Discharge (m^3/s)	Recommended gate opening (m)			
		Gate 4	**Gate 3**	**Gate 2**	**Gate 1**
Upto 1 year return period	277	<= 1.6	closed	closed	closed
Upto 2 year return period	710	<= 1.5	<= 1.5	<= 1.5	<= 1.5
Upto 5 year return period	1004	<= 2.4	<= 2.4	<= 2.4	<= 2.4
Upto 10 year return period	1210	<= 3.0	<= 3.0	<= 3.0	<= 3.0

According to the scale model, the turbines are recommended to be shut down if the river discharge reaches above 10 year return period flow or the sediment concentration is higher than 10,000 ppm in the river.

4. NUMERICAL MODEL

A depth-averaged version of the Delft3D morphological model, is open source software, with graded sediment transport has been used. The model solves two-dimensional Navier-Stokes equations coupled with sediment continuity equation. Besides, the model incorporates other useful aspects, such as domain decomposition, consideration of floodplains and dry areas including wet and dry processes, sediment transport over non-erodible layers and functionality for sediment management to assess dredging and dumping etc. (Yossef et al. 2008, Giri et al, 2016). The model is capable of replicating complex time-dependent multi-dimensional phenomena, such as curvature-induced sand bars and pool patterns in bends. The 2D-morphological model is coupled with RTC toolbox to operate the gates. RTC toolbox software includes feedback PID controller as well.

4.1 Model set-up

The grid of the model was generated using RFGRID tool of Delft3D software package. This tool is able to generate and check the quality of the generated grid . The most important grid quality criteria's are (i) orthogonality (less than 0.4) (ii) smoothness (less than 1.1 in both directions) (iii) Aspect ratio (0.5 to 2). Subsequently, the bathymetry of the generated grid was created by triangulating the survey points using QUICKIN tool. The grid and bathymetry of the model and the setup of the gates and the dam are shown in Figure 4.

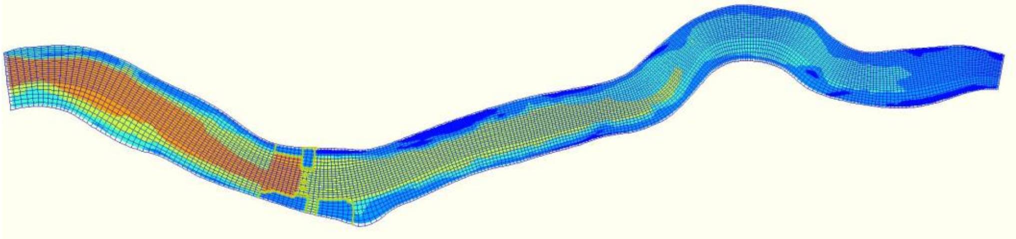


Figure 4. Delft3D model grid with bathymetry

Piers, and walls in the model has been represented using thin dams. As per Delft3D Flow user manual (Deltares 2016), thin dams are infinitely thin objects which prohibit flow exchange between the two adjacent computational cells without total wet surface and volume of the model.

The gates are 10 meters wide each and have been modeled using two cells. All the concrete structures in the proposed dam have been defined as the non-erodible cells. The cell at each gate has been defined as the non-erodible cells as the initial level provided acts as gate crest level.

The effect of hydraulic structures like Hydraulic gates in the Delft3D model has been achieved by adding a quadratic friction term in the momentum equation of Navier-strokes equation. The additional quadratic friction term can be calculated by using following formula (Deltares 2016).

$$M_\xi = -\frac{C_{loss} - u}{\Delta x} \times u \times \sqrt{u^2 + v^2}$$

$$M_\eta = -\frac{C_{loss} - v}{\Delta y} \times v \times \sqrt{u^2 + v^2}$$

Where,
M_ξ & M_η = Quadratic friction terms in both directions
C_{loss} = energy loss coefficient = $\frac{1}{2 \times C_d^2}$
C_d = Coefficient of discharge for hydraulic structure
u & v = flow velocities in two x& y directions
Δx & Δy = grid spacing in both x&y directions

4.2 Bed roughness

A constant Manning's friction coefficient value has been adopted for the entire model, as there is no reliable data to estimate the variation in the friction coefficient in the river. Regardless that Manning's coefficient has been provided in the model for bed roughness, the sediment transport formulas in Delf3D has been formulated in terms of Chezy's friction coefficient. So, the model calculates the Chezy's coefficient for given Manning's value using water depth, providing the roughness field varying (weakly) with flow depth. Manning's friction coefficient values has been calibrated using field measurements of water levels in the proposed reservoir area and measured discharge at that time. The calibrated value of Manning's friction coefficient is 0.0725.

4.3 Sediment transport and morphology

The transport formulae of Meyer-Peter-Muller (MPM) and Ashida-Michue have been used to compute the sediment load for the model. Now, the transport formula for both Meyer-Peter-Muller and Ashida-Michue is shown below (Deltares 2016).

- **Meyer-Peter-Muller formula**

$$S = 8 \times \alpha \times D_{50} \times \sqrt{\Delta \times g \times D_{50}} \times \left(\mu \times \theta - \xi \times \theta_{cr}\right)^{\frac{3}{2}}$$

Where,

S = sediment transport rate

α = Calibration parameter for MPM formula (Recommended value 1)

D_{50} = representative diameter for sediment fraction

Θ_{cr} = Critical mobility parameter(0.047)

ξ = Hiding and exposure factor

- **Ashida-Michue formula**

$$S_{bc} = \alpha \sqrt{\Delta \times g \times D_{50}^{3}} \times \theta^{m} \times \left(1 - \xi \times \frac{\theta_c}{\theta}\right)^{p} \times \left(1 - \sqrt{\xi \times \frac{\theta_c}{\theta}}\right)^{q}$$

Where,

S_{bc} = Sediment transport rate

α = Calibration parameter for Ashida Michue formula (Recommended value 17)

D_{50} = representative diameter for sediment fraction

Θ_c = Critical mobility parameter(0.047)

ξ = Hiding and exposure factor

m, p & q = calibration parameter (recommended values 1, 1.5 & 1)

Θ = Shield's mobility parameter

$$\theta = \left(\frac{q}{C}\right)^{2} \times \frac{1}{D_{50}}$$

Where,

q = flow velocity

C = Chezy's friction coefficient

μ = Ripple factor

$$\mu = \min\left[\left(\frac{C}{C_{g,90}}\right)^{1.5}, 1.0\right]$$

Where,

$C_{g,90}$ = Chezy's coefficient related to grains

$$C_{g,90} = 18 \times \log_{10}\left(\frac{12 \times h}{D_{90}}\right)$$

Where, h = water depth

Both of the above-mentioned formulae are suitable for gravel bed and mountainous rivers. Both of the formulae have been used while the other calibration parameters kept at default recommended values as specified in the Delft3D manual. The interaction between multiple sediment types (the hiding and exposure effect) has been considered as well. Ashida & Michiue hiding-exposure coefficient is used. Due to the low correlation between the measured suspended sediment concentrations and discharge, the suspended sediment is considered within the total sediment not separately. Moreover, the long-term morphological changes in the reservoir will be predominantly affected by bed load due to the fact that the reservoir will operate in sluicing mode during monsoon season. A 2D-depth-averaged model used capable to calculate sediment transport at bends and bed slope by incorporating these effects in parameterized way (Flokstra and Koch 1980).

For long-term morphological assessment of a reservoir, the computation time required might be so long. So, to shorten the computation morphological acceleration factor (MORFAC) has been used as it is function available in Delft3D (Deltares 2016). MORFAC of 10 has been used. This means, for instance, a simulation of one year hydrodynamic computation time will provide a morphological bed updates of ten years (morphological time).

4.4 Real-Time Control (RTC) module

The main challenge in the long-term modeling of the reservoir is to maintain stable reservoir levels for long time series hydrographs. This was possible in Delft3D because of the implementation of RTC with feedback PID controller.

$$w(t) = w(t-1) + K_p \times e(t) + K_i \times \sum_{t=0}^{t} e(t) + K_d \times (e(t) - e(t-1))$$

Where, w(t) w(t-1) = New gate level & Gate level of previous time step

Kp, Ki & Kd = Proportionality, integral and differential constants for PID controller

e(t) & e(t-1) = error in reservoir level from set-point in current and previous time step

The application of this module allows the Delft3D model to maintain the stable water level at desired set point for a long time series hydrograph is shown in Figure 5.

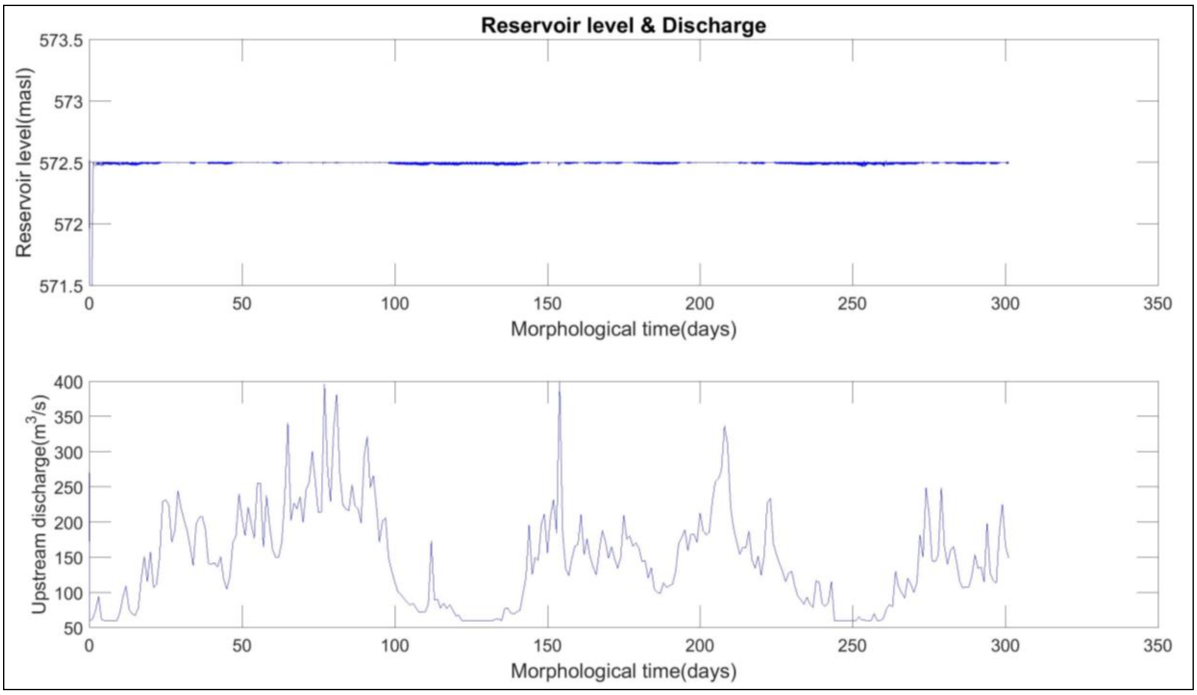


Figure 5. Reservoir level using RTC with PID controller to control reservoir level of model at 572.5 masl.

5. RESULTS AND ANALYSIS

5.1 Hydrodynamic calibration and verification

5.1.1 Observed water level

The hydrodynamic part of the river model has been calibrated by using the field measurement data of water levels at four different locations within the proposed reservoir area for two different discharges (i) 87.81 m^3/s and (ii) 78.67 m^3/s. Using this measured water level and discharge, Manning's friction coefficient (constant over the model domain) was used as a calibration parameter. The value of Manning's friction coefficient obtained is 0.0725. The calibration values are shown in Table 2.

Table 2. Calibration of friction coefficient (Hydro Lab 2012)

Gauge	Measured Discharge = 87.81 m^3/s			Measured Discharge = 78.67 m^3/s		
	Measure level (masl)	Model result (masl)	Error (m)	Measure level (masl)	Model result (masl)	Error (m)
CG-1	567.61	567.505	0.105	567.46	567.424	0.036
CG-2	564.63	564.649	-0.019	564.59	564.649	-0.059
CG-3	559.51	559.517	-0.007	559.42	559.434	-0.014
CG-4	554.52	554.503	0.017	554.44	554.404	0.036

5.1.2 Spillway operation and reservoir levels

The reservoir operation levels of this dam have been fixed during the detailed design phase of the project and at 577.3 masl (Maximum reservoir level) and 572.5 masl (Minimum reservoir level and monsoon operation level). In the numerical model, the reservoir was only operated for 4 months of monsoon flows at level 572.5 masl. in order to simulate gates operation, a good estimation of the discharge coefficient of the gates is required. This was obtained from the result of various experiments done during physical model study. The average value of gate discharge coefficient gained is 0.89.

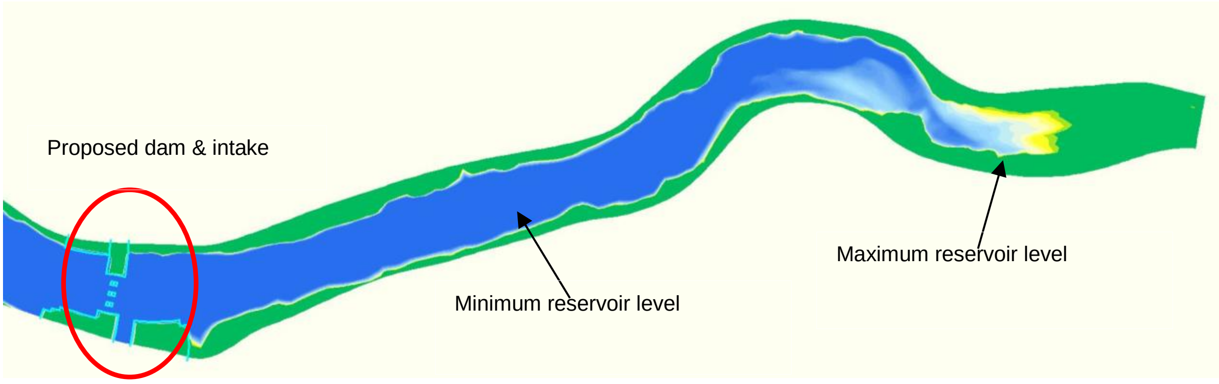


Figure 6. Reservoir extents in Delf3D model

In Figure 6, the extents of the reservoir in Delft3D model can be seen. In the figure, all the area under dark blue is lower reservoir area whereas maximum reservoir extent is up to the lines bordered by dark green color.

5.2 Reservoir morphology

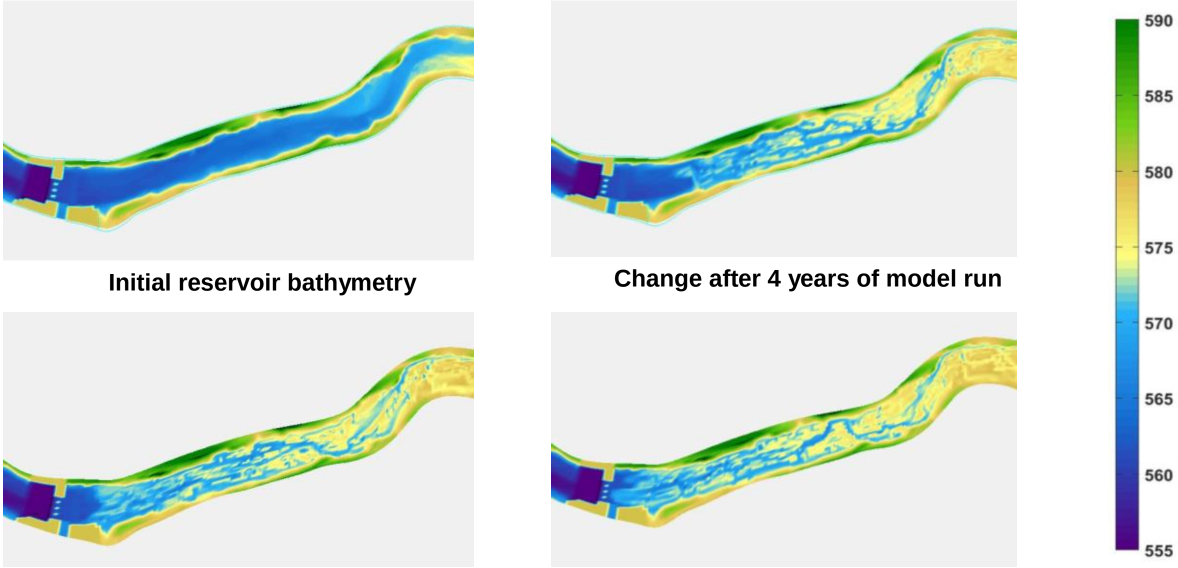
5.2.1 Reference scenario

The reference scenario has generated by running the model with four months of daily monsoon discharge (June – September) from the year 1998 to 2008. Both Meyer-Peter and Muller (1948) & Ashida and Michue (1973) formulation has been applied in the model with and without hiding exposure. In both formulae, all the calibration parameters has been used as recommended in the Delft3D user manual (Deltares 2016) except the calibration parameter α for Ashida-Michue formula, for which value of 1 has been used instead of recommended value of 17. The reservoir operation in the numerical model has been imposed as the recommended in the physical model study for monsoon flows with reservoir level at low reservoir level as shown in Table 1.

Table 3. Reservoir sedimentation using different formulas

Transport formula	**Hiding-exposure**	**Reservoir sedimentation (Mm^3/year)**			
		Year 1	**Year 2**	**Year 3**	**Year 4**
Meyer-Peter-Muller (1948)	Not used	0.415	0.18	-	
	Used	0.161	0.084	0.088	0.055
Ashida-Michue (1974)	Not used	0.544	0.0915	-	-
	Used	0.365	0.152		

In this scenario, only Gate 4 is used with PID controller to control the water level of the reservoir, whereas other gates have been controlled by a fixed rule according to the discharge in the river. From Table 3, Meyer-Peter-Muller formula with hiding and exposure has the closest annual bedload transport to the estimated bed load transport 0.12 Mm^3/year. This model has been taken as the reference scenario. From the reference scenario, the simulated reservoir bed level changes after 4, 6 & 8 years is shown in Figure 7.



Initial reservoir bathymetry

Change after 4 years of model run

Change after 6 years of model run

after 8 years of model run

Figure 7: Change in reservoir bed level over time in reference scenario

As it can be seen in figure 7, reservoir delta reaches the intake after 6 years operation. One of the objectives of operating gate 4 (the closest gate to intake) is to prevent deposition in front of the intake. But this method of operation actually attracts bed sediment delta towards the intake. As we can see in Figure 7, the delta is now in front of intake which may lead the intake to draw large sediment particles due to bed aggradation. The change in the reservoir storage is also shown below in Figure 8. As can be seen in figure 8, the rate of change of storage volume per year in first 4 years of simulation was found to be 9.2% per annum and for 8 years of simulation was found to be 6.8% per annum. These rates turned to be reasonable when compared to the reservoir volume loss of the other two PROR reservoirs currently are being operated in Nepal.

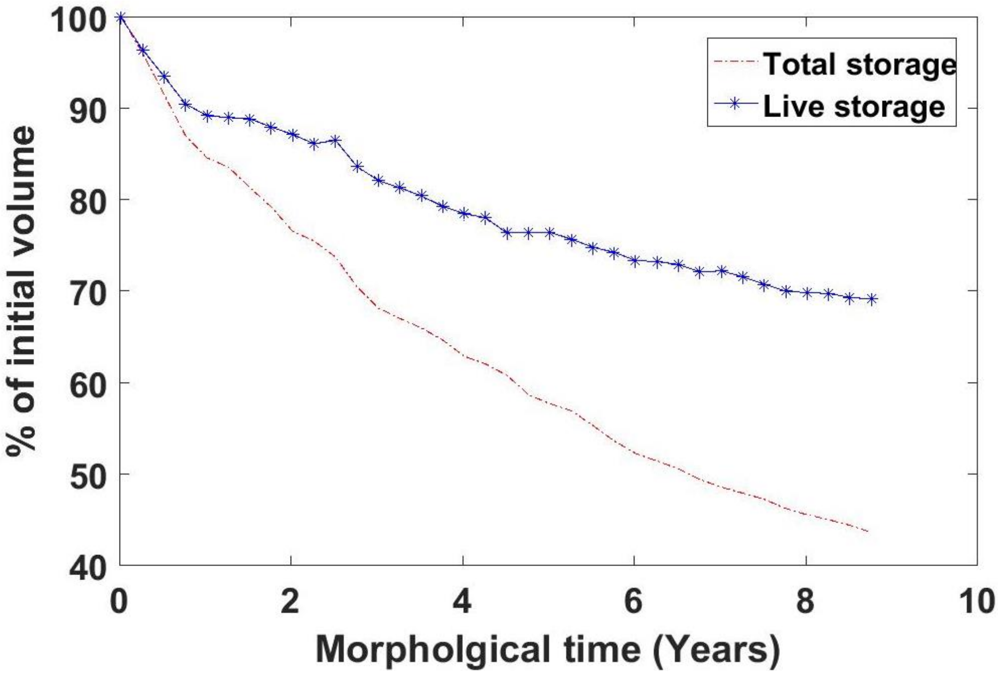


Figure 8. Change in reservoir storage and live storage volume

In Figure 8, for the scenario of power generation the live storage volume is the only important volume in these kinds of reservoirs. It is seen that live storage volume of the reservoir was reduced by 30% after 8 years of simulation. This loss of volume can directly be linked to the loss in the generation of peak energy of the reservoir.

5.2.2 Alternative scenarios

In the same reservoir model, four new alternative reservoir operation scenarios have also been tested in which other gate along with Gate 4 has been used to control the reservoir level. Gate operation scenario 1 is the reference case scenario. The details about these scenarios are given in Table 4. The main reasons to test the alternative scenarios are minimize the loss in reservoir volume (both total and live storage) and to find bed formation in favor to the turbines intake. The change in total reservoir storage volume and the live storage volume for different scenarios are shown in Figure 9.

Table 4. Scenarios for reservoir operation

Scenario	**Fraction of discharge to be released from each gate to control reservoir level (%)**			
	Gate4	**Gate3**	**Gate2**	**Gate1**
Scenario 1	100	0	0	0
Scenario 2	50	50	0	0
Scenario 3	75	25	0	0
Scenario 4	25	25	25	25
Scenario 5	40	20	20	20

The change in reservoir storage volume is not significant when tested for different long-term gate operation scenarios. Scenario shows less loss of live storage volume compared to the reference scenario. Now, the sediment deposited in front of the intake from the entire scenario is depicted in Figure 10.

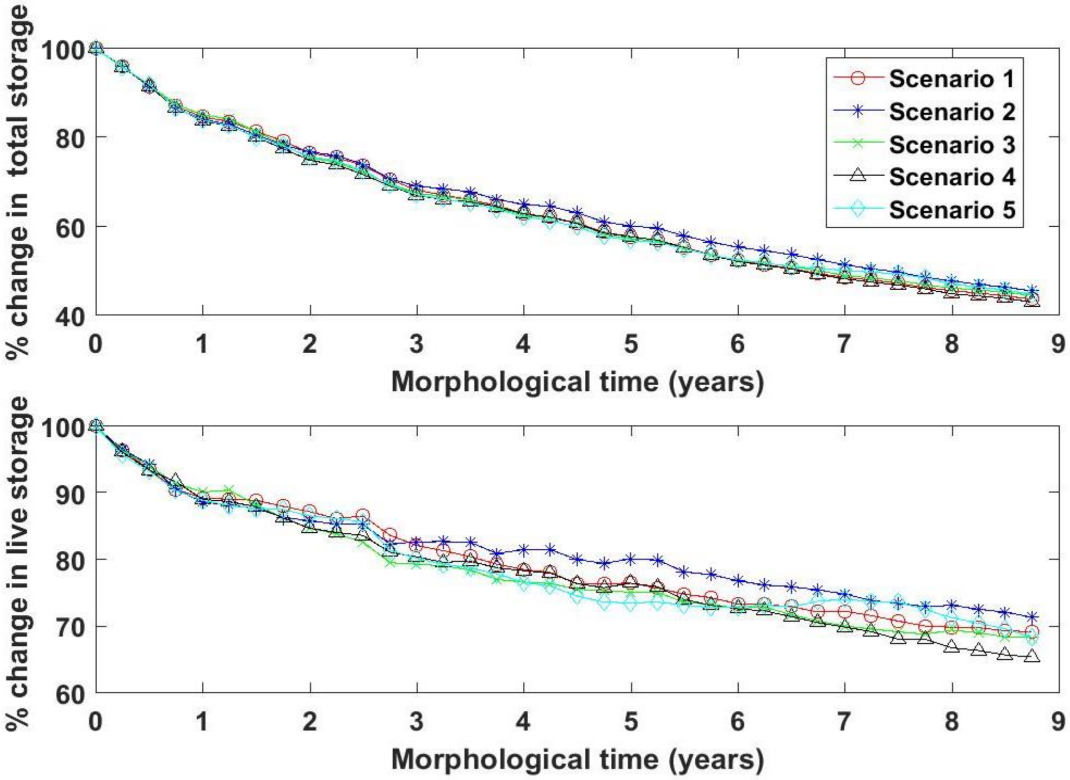
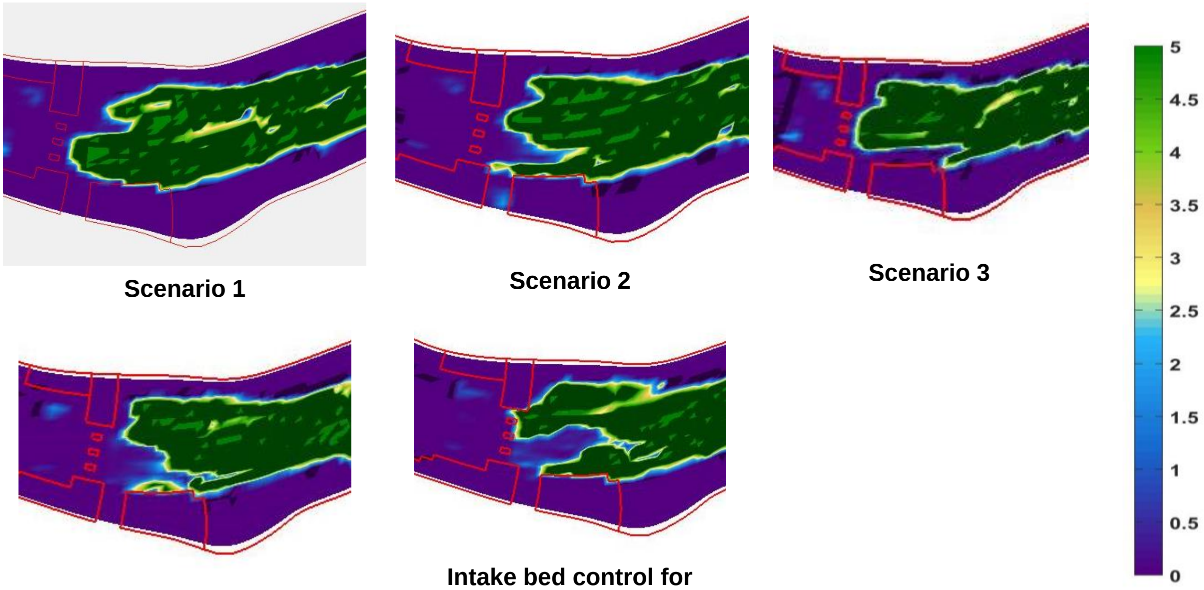


Figure 9. Change in total reservoir storage and live storage for different scenarios

The elevation of bed in front of intake is 561.0 masl whereas the sill level of intake is 566.7 masl. Therefore, any deposition in front of the intake can increase the probability of particles like gravel passing through the intake to the turbines blades. As we can see in Figure 10, the reference scenario(Scenario1) is capable to provide deposition formation more in favor to intake performance. When we compare reference scenario to, Scenario 2, 4 and 5, the result is not good enough, whereas Scenario 3 seems to be capable of achieving better deposition formation in front of the intake. Such deposition formation of like the one occurred in scenario 3 may increase the sustainability of other project components like stilling basin.



Scenario 1

Scenario 2

Scenario 3

Scenario 4

Intake bed control for Scenario 5

Figure 10. Deposition in front of intake of the different scenarios

5.3 Model sensitivity and limitations

The morphological model is highly sensitive to the different sediment transport formulae and the calibration coefficients of those transport formulae. Apart from the formulae, the use of hiding exposure also has a significant effect when modeling graded sediment transport. As we can see in Table 3, the use of different formulae and the hiding exposure can significantly change the amount of sediment in the model. Due to lack of data on river and reservoir morphology, the research has to rely on thumb rules based on different catchment in Nepal (Pratt-Sitaula et al. 2007) to select appropriate sediment transport formula and calibration parameters. Apart from the transport formula, use of suspended sediment in the reservoir can also change the results of the model. Currently in the model, the fraction of suspended sediments is considered parametrically in the sediment transport formula (as a total bed material load), and the transport of suspended sediment with advection-diffusion has not been considered. However, for such small PROR reservoir with regular sluicing, the deposition of suspended sediment in the reservoir may not be significant given the time-scale of the phenomenon comparing to bed load, since most part of the suspended load may be transported downstream.

The quadratic friction term in momentum equation of Navier-strokes equation replicates the gates operation of reservoir reasonably well upstream of the gates. The values for discharge through the gates actually matches closely to the values obtained from the physical model at similar gates opening and reservoir level conditions. But the model cannot replicate the flow conditions on the downstream of the gate mainly due to the coarse grid and the limitation of 2D modeling to replicate morphology under supercritical flows and hydraulic jump. Since the research is mainly focused on the morphology inside the reservoir; the limitation in the model has little effect on the research results.

6. CONCLUSIONS AND RECOMMENDATION

6.1 General conclusion

As the study reveals, the coupling of the Delft3D morphological model with the hydrodynamic gates operation with real-time control using feedback PID controller can be used for the morphological development of the reservoir storage area during the planning phase of the reservoir. These kinds of studies can be extremely useful during the planning phase of the reservoir mainly done as supplementary to the physical model. As it can be seen from the study, the model can simulate the long-term reservoir operation to see the morphological development of the reservoir which is very time consuming and expensive in physical models. With additional data regarding river sediments and present morphological changes, the model can make a better prediction about the morphological changes in the reservoir over a long period of operation.

The sedimentation rate of the case study reservoir was found to be very high. The high sedimentation rates were similar to the other PROR reservoir currently being operated in Nepal. The sedimentation of the reservoir also effects the generation of peaking energy during dry season after the first monsoon season, which is the main purpose of the reservoir. From the study it can also be seen that, there were minor differences in among the reservoir operation scenarios tested in terms of the sedimentation of reservoir but bed control in front of the intake can also be improved by changing long term gates operation of reservoir from controlling the water level in the reservoir by only Gate 4 (Reference case) to partially controlling the reservoir level by gate 4 and gate 3 (75% gate 4 & 25% gate 3 – Scenario 3). Further research needs to be done in this case by also using suspended sediments in the numerical model to make concrete recommendations about reservoir gates operation effect into sediment management.

6.2 Recommendations

- As it can be seen form the model results, the reservoir sedimentation in Himalayan Rivers is extremely high. It is recommended that further data collection for the following data needs to be carried out to improve the model predictions for daily peaking reservoirs in Himalayan Rivers
    - Bathymetric survey after major floods to visualize the morphology of the river better and for the better calibration of the morphological model.
    - Long term measurement of sediment concentrations in the river needs to be done to get better idea about the suspended sediment transport in the river
- Despite the tests done for reservoir flushing in the physical models for Himalayan reservoirs, the flushing process also needs to be tested in the numerical model to optimize the efficiency of flushing for reservoirs.
- The operation of reservoirs the extreme hydrological conditions in the Himalayan rivers also needs to be tested in the numerical model.
- The modeling and data collection about reservoir bed level change of the reservoir should be continued even during the operation phase of the reservoir for the better understanding of sedimentation and sediment management of reservoirs.

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