Optimization of dam operation to maximize flushing during low flood peaks

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ABSTRACT

The downstream area of hydropower dams suffers from erosion due to lack of sediment passing the dam. We used a calibrated model for investigating the reservoir conditions during the flood season (e.g. sediment inflows, reservoir water level, and reservoir bed level and gate operation modes) as to improve sediment feeding to the downstream of dams.

2D_morphodynamic model of Delft3D4 (open source software) coupled with RTC-toolbox (real time control) is used. Reservoir conditions were varied in order to maximize the sediment releases, especially during the low flood peaks.

This showed that a different set of the gates opening, providing similar dam outflow as the original set, may increase the water depth in some locations within the reservoir. It still provides a similar amount of sediment releases during the flushing period. Changing the quantity of upstream bed load inflow in long reservoirs (> 10 km length) such as Funagira (Japan) may reach the dam after more than two flood seasons. Therefore, the spinned-up simulation was conducted to consider sediment inflow effect. The result, furthermore shows that the lowering of the reservoir water level is useful to increase the sediment releases. Also, the higher the reservoir bed level the larger the sediment.

1. INTRODUCTION

Dammed reservoirs are highly beneficial to the humanity, as they play important roles in the economic growth of countries (WMO, 2011). Contrary, they create a negative impact on the river and reservoir morphology and ecosystem (e.g. storage loss, bank erosion and bed degradation to the downstream of dams). Reservoir sedimentation and sediment releases to the downstream poses quite some challenges to the dam operators (Guertault et al., 2014). Around 53% of global sediment fluxes in regulated basins is potentially trapped in reservoirs. This may influence the downstream morphological behaviour and coastal area that rely on riverine sediment supply (Kondolf et al., 2014). Sediment management measures are needed to control the amount of sediment in and downstream the reservoir and to mitigate undesired impacts.

1.1 Reservoir Sediment management

Many classifications are made for the sediment management practices. Morris (2015) provides a sorting system for sediment management. He categorized all measures and practices to four major types of activities that can be taken to alleviate sedimentation in reservoir: 1) reduce sediment yield from upstream, 2) route sediments (maintain transport, minimize deposition), 3) focus or remove sediment deposits and 4) adaptive strategies (raising dam, reallocate storage, decommissioning infrastructure and modify intake). The flushing process is mainly recognized in the third activity.

Fruchard and Camenen (2012) categorize flushing to “hard flushing” (drawdown the reservoir water level to a minimum) and “environmentally friendly flushing” (a drawdown to the reservoir water level but to a certain extent, based on the water sediment concentration allowed which does not harm the downstream). Baran and Nasielski (2011) mention that the impact of flushing on fish is mainly determined by the suspended sediment concentration and the duration of the flushing process. It is very important to evaluate the flushing economically and environmentally. This would improve the return value of flushing process (Olsen and Haun, 2010).

1.2 Morphological change downstream of the dam

Many types of dams and reservoirs present with a high variety of differences in flow releases policies. Brandt (2000) has classified the morphological changes downstream of dams. The classification is based on increase or decrease of discharge, sediment load and transport capacity before and after the dam. This concept can be used to estimate the expected changes at some location downstream of a dam. Numerical modelling could be used to estimate the sediment releases from the dam. Furthermore, Danelli and Peviani (2012) recommend performing a real-time reservoir operation to measure the sediment release to downstream of the dam.

However, using a fixed flushing operation during flood may not help to release sufficient sediment amount to the downstream reach, especially during low flood seasons. This may lead to high erosion processes downstream. In this study, we are aiming to investigate the possibility of maximizing the sediment releases during the low flood peaks, and see how much that would affect the reservoir storage. This application has been conducted at Funagira Dam, Japan.

1.3 Reservoir operation conditions

In order to make a proper investigation of the flushing process, the reservoir operation conditions have to be investigated. The conditions that appear to have influence on the flushing process are: 1) the magnitude of discharge and sediment inflows, 2) the reservoir water level during flushing (flushing water level, 3) reservoir bed level, 4) the gates (dam) operation, 5) the magnitude of water discharge outflow of the dam, 6) downstream river water level, and 7) the reservoir shape and size. In this study, we focussed on number 1, 2, 3, 4 and 5. The condition number 6 and 7 are not addressed here since only one reservoir is explored.

1.4 Study area

The Funagira Dam is situated in the Tenryuu River in Japan. The dam started operation in 1977. The dam has nine gates with a width of 20 m each, a summit of about 16 m each and bottom crest level of 42.0 masl (metre above Mean Sea Level). It has also three turbines for hydropower generation with a minimum operation water level of 54 masl. The turbines are switched off during the flood season as the flood or flushing water level maintains at 50.6 masl. Recently the gate operation has been modified to an equal opening shape operation in which the opening heights increases equally, following the increasing river discharge.

Figure 1. The erosion downstream of Funagira Dam (Source: Google-Earth).

From the operation practice, it is proved that if the flood peak high or equal to 5000 m^3/s, the existing flushing process is able to convey sediment to the downstream. However, the low flood peaks (< Q5000) are not able to carry enough sediment to the downstream using the current flushing operation rules. Consequently, the reach downstream of the dam suffers from erosion, especially due to low sediment transport (flushing capacity) during low flood seasons (see Figure 1) Moreover, the flood peak of Q5000 occurs every 5 years and Q8000 every 7 years. Therefore, it is vital to improving the flushing rule to convey more sediment to the downstream during more frequent low floods.

1.5 Modelling Approach

Delft3D and real-time control (RTC) toolbox are used. Delft3D4 is open source software package (http:// oss.deltares.nl), developed by Delft Hydraulics/Deltares. It is a model system (2D and 3D) that consists of integrated modules for the simulation of hydrodynamics, transport of water-borne constituents (e.g. heat and salinity), sediment transport and morphological change (Mulatu, 2007). The RTC toolbox is used to control hydraulic structures like weirs, pumps, and hydropower and water intakes.

Delft3D model is developed to be able to run and interact, in parallel, with RTC. The developed FLOW2D3D version 6.02.07.6118 of Delft3D4 software is capable of retrieving gate opening information which is calculated by the RTC toolbox based on the input water level or feedback received from Delft3D every time step. Quasi 3D-morphodynamic model is used. The model is calibrated in a previous study. The gate operation is simulated by using the Barrier Function of Delft3D. The barrier is a combination of a movable gate and a quadratic friction term which is added to the momentum equation. The depth-averaged flow rate through the barrier is calculated using the following weir equation:

$$Q = \mu A\sqrt{2g(H1 - H2)} \tag{1}$$

where: Q is the discharge in m^3/s, μ is the barrier contraction coefficient ($0 < \mu \leq 1$), A is the area of the barrier (the width of the gate times the gate opening) in meter, g is the gravitational acceleration in m/s^2 , H1 is the reservoir water level in m and H_2 is the downstream water level or in some cases the dam overflow crest level, in meter.

In order to let the model calculate the gate opening to maintain the user-defined reservoir water level, the PID controller (Proportional Integrating Differentiating) in RTC toolbox module is utilized to control the reservoir water level. RTC provides Delft3D_Flow module with the corresponding gate opening (or the barrier bottom elevation) in every time step. The PID controller operates the gates automatically every time step, such that the prescribed reservoir level is maintained in the computation. The value of the control parameter, i.e. the gate height, can be computed as follows:

$$h_i = h_0 + k_p\, e(t) + k_i \int_0^t e(t)\, dt + K_d \frac{de(t)}{dt} \tag{2}$$

Where: k_p is the proportional gain factor (determine the reaction time of the controller), k_i is the integral gain factor (reduces the standard deviation introduced by k_p), K_d is Differential gain factor (provide damping in the controller), e is the deviation of actual water level to the desired water level (error), , t is the time, h_0 is the initial value of the gate height and h_i is new value of the gate height which will be transmitted to the Delft3D-Flow.

The gain factors are calibrated to achieve optimal performance of the controller. The RTC provides Delft3D-flow with a new gate height to maintain the user-defined reservoir water level.

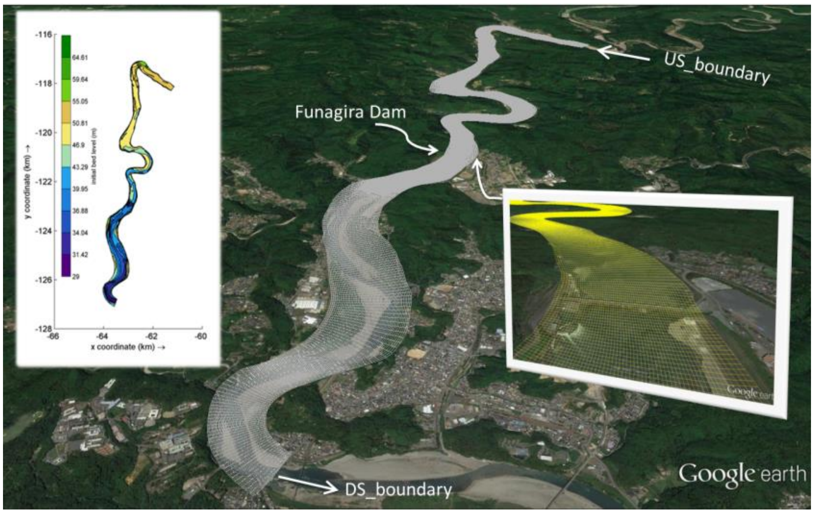

Figure 2. Computational grid, location of boundaries and bed topography

2. MODEL BACKGROUND

The computation grid and bed topography were generated using QuickIn tool of Delft3D4 (See Figure 2). The grid covers Funagira reservoir and the river downstream. The total length of the grid is approximately 15 km (10 km upstream the dam and 5 km downstream the dam). The upstream boundary condition of the model is a discharge (s) inflow. The downstream boundary condition is represented by the discharge rating curve of the river cross-section under the bridge located 4.85 km downstream the dam.

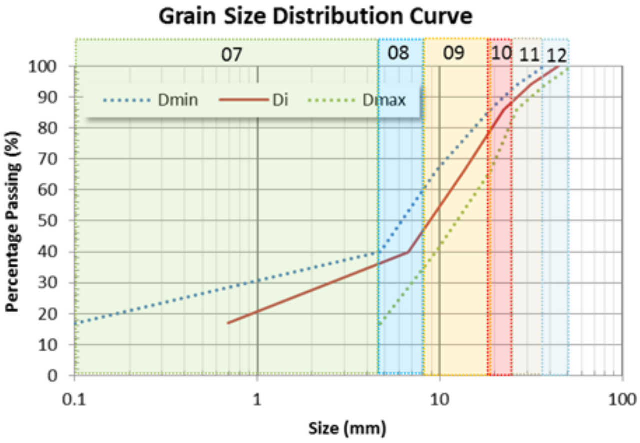

Figure 3. Grain size distribution of sediment. 6 fractions were used (Sediment07 ~Sediment12)

2.1 Morphological setup

Six sediment fractions, as shown in Figure 3, are used in the model. Initially, the grain sizes are evenly spread over the river bottom. In reality, sorting takes place. To arrive at a proper initial sediment distribution, a spin-up run has been carried out. The initial sediment layer thickness is 5 m (8000 kg/m^2) upstream the dam and 2 m (3200 kg/m^2) downstream the dam. The banks and the dam area are considered fixed (non-erodible) and therefore modelled with 0 m layer thickness. The initial bed composition was spun up by running the model with bed level updating turned off in order to let the bed assume an appropriate composition.

The fractional 2D version of the Ashida-Michiue (1972) formula is used to calculate the sediment transport, assuming the bed material to be transported primarily as bed load:

$$S_{bc} = \propto 17\sqrt{\Delta g D_i^3}\ \ \theta^m \left(1 - \xi\frac{\theta_c}{\theta}\right)^p \left(1 - \sqrt{\xi\,\frac{\theta_c}{\theta}}\right)^n \quad \text{and } \theta = \left(\frac{q}{C}\right)^2 \frac{1}{(\Delta\, D_i)} \tag{3}$$

Where: S_{bc} is bed load transport rate (m^2/s), α is multiplication factor (-), Δ is the relative sediment density ($\rho s - \rho w$)/ρw , with density of water ρw (~ 1000 kg/m^3) and density of sediment ρs (~ 2650 kg/m^3), g is the gravitational acceleration (m/s^2), D_i is the mean grain size of the size fraction (m), ξ is the hiding and exposure factor for the sediment fraction considered (-), θ_c is the critical Shields parameter (-), C is the Chézy value (m$^{1/2}$/s), q is the magnitude of flow velocity (m/s) and m,p and n are calibration parameters, with default values of 2,1 and 1, respectively. Suitable values for α and θ_c are selected to be 0.6 and 0.035 respectively, following morphological calibration.

Many other parameters have to be specified, such as mixing layer thickness, and the effect of spiral flow on sediment transport. The Koch & Flokstra (1980) formula for the effect of bed slopes on transport capacity was used. The coefficients in this model (Ashd and Bshd) were tuned to obtain realistic bed topography between the inner and outer bends within the river corridor. The model has ten under layers and the thickness of the transport layer is 0.5 m.

2.2 Hydrodynamic results

In order to lower the reservoir water level in the flood season or what we called “flushing level”, hydrodynamic simulations have to be conducted to recognize the free flow water level corresponding to different discharges. The results show that with discharge less than 2000 m^3/s, the flow shall be within the reservoir channel. Table 1 illustrates the free water level correspond to different discharges, showing that the flushing level of 50.6 m is closer to the free flow of Q8000. This explains, in the current operation rules, why gates have to be fully opened if the inflow discharge is larger than 8000 m^3/s.

Table 1. The free flow reservoir water level correspond to various discharges

Discharge inflow (M^3/s)	Free flow reservoir water level (masl)
900	44.95
1000	45.03
2000	46.10
3000	46.91
5000	48.33
8000	50.2

The effect of using the free flow is mainly noticeable within the first 5 km upstream of the dam. Hence, lowering of reservoir water level may increase the erosion of the reservoir channel within the first 5 km as shown in Figure 4 and Figure 5. In these figures, the longitudinal profile shows a situation with reservoir water level of 50.6 m compared to a free flow level of different discharges.

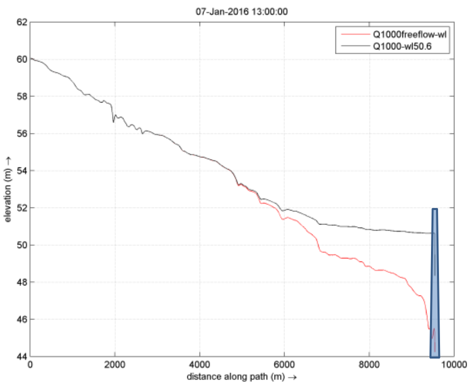

Figure 4. Q1000 water level profile

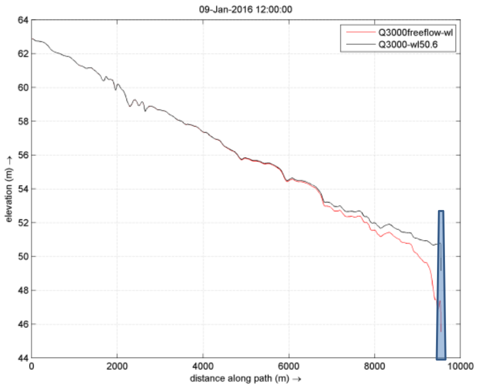

Figure 5. Q3000 water level profile

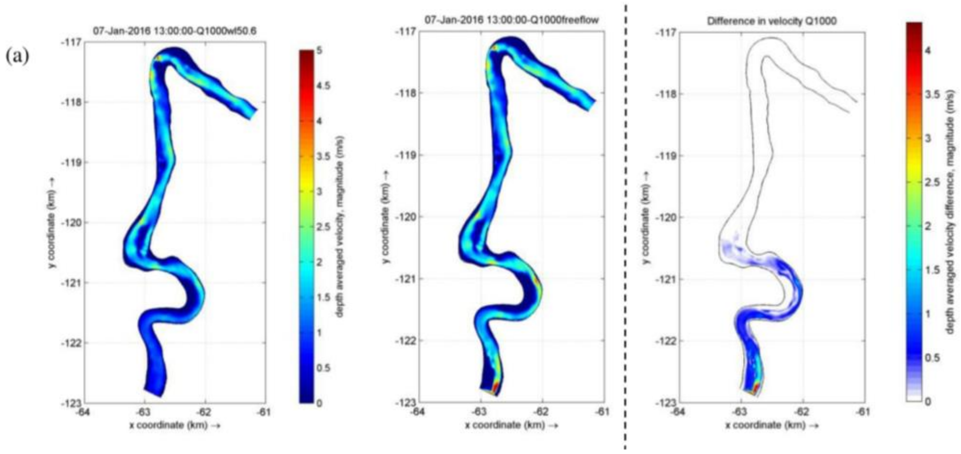

Figure 6. The difference in velocity with respect to current flushing level and free flow of Q1000

Lowering of the flushing level may increase the velocity within the reservoir as shown in Figure 6. As an example, Figure 6 illustrates the velocity distribution within the reservoir for different steady state discharges of 1000 m^3/s, using different maintained flushing levels (50.6 m and the relevant free flow related to discharge as shown Table 1). The velocity maps comparing the velocity distribution and difference in velocity are also shown in the figure. Figure 6 shows that depth average velocity increases between 0.5 to 6 m/s depending on the discharge inflow used. Furthermore, the lowering effect of reservoir water level is concentrated within the first 4 km upstream the dam.

Table 2. Current flushing level and proposed new flushing levels

#	Governing discharge (Q)	Reservoir Maintained water level (WL)	remark
1	8000	50.6	Currently used
2	5000	48.5	Option(1)
3	3000	47.0	Option(2)

The governing operation rules of Funagira reservoir during the flood are:

- If river discharge < a certain discharge (Q) (in m^3/s), reservoir water level will be maintained to WL (in masl), and
- Discharges > Q (in m^3/s), all the gates are fully open (free flow condition).

Based on the above, two extra options of flushing levels have been considered to adapt the operation rules of the dam (flushing level).

Accordingly, option (1) and (2) are considered to study the possibility of enhancing the sediment passing through the dam during the low flood peaks. These two alternatives of flushing level are used in the sediment scenarios and the results are compared to the base case “currently used flushing level”.

3. MORPHODYNAMIC RESULTS

3.1 Sediment inflow effect

A spin-up morphological run is prepared using stepwise inflow hydrograph with a peak of 8000 m^3/s. This is mainly to recognize the effect of sediment inflow into the reservoir on the amount of sediment passing the dam during sediment-management operations. The sediment passing the dam is recorded to be used as sediment input fluxes to the model because the actual sediment inflow is unknown. This amount of sediment fluxes is multiplied by 2 and divided by 2 to check the sensitivity of the reservoir sedimentation and sediment passing the dam to these highly uncertain sediment inflow fluxes. These runs also show the time sediment takes to pass the dam. Three similar morphological scenarios are prepared for six subsequent flood peaks of 8000 m^3/s. The only difference between them is the amount of sediment inflow which is illustrated as follows:

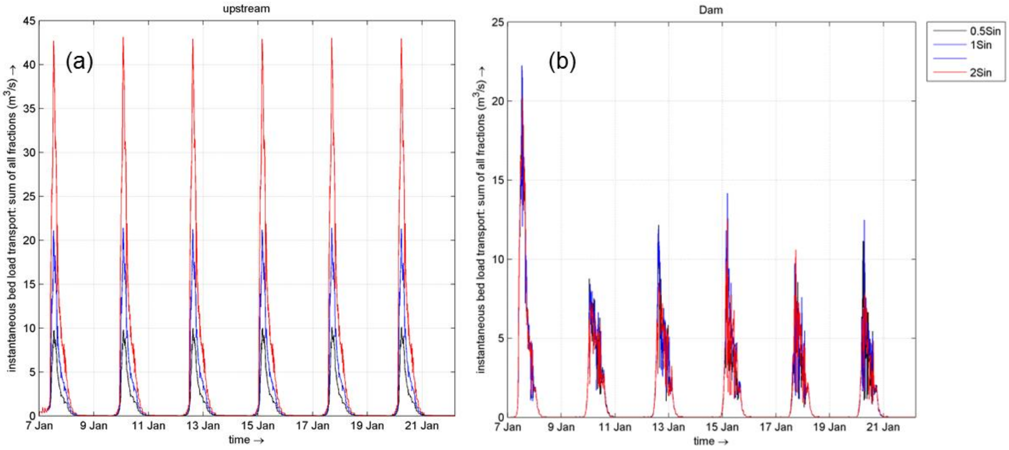

Figure 7. plot (a) sediment inflow fluxes. Plot (b) sediment dam outflow fluxes

- Use the same sediment fluxes as shown in Figure 7 (1S$_{in}$)
- Divide the recorded amount by 2 and use it as inflow fluxes (0.5S$_{in}$)
- Multiply the recorded amount by 2 and use it as inflow fluxes (2S$_{in}$)

The result of the three scenarios shows that after the first year the sediment outflow from the dam becomes more stable. If we compare Figure 7(a) (the sediment inflow to the model) and Figure 7(b) (sediment passing the dam), it can be seen that although all the sediment inflow is variable for the three scenarios, the outflow from the dam is more or less the same. This means that the operation of the dam is the main trigger to control the amount of sediment passing, and the reservoir more or less intercepts any surplus of sediment.

According to Figure 8, the sediment inflow would start to reach the dam on 13th of January. This time falls within the third flood period as shown in Figure 7. Therefore, to consider the inflow sediment effect, the bed composition of 1S$_{in}$ scenario after the third flood peak is used to initiate the other morphological scenarios to examine other reservoir conditions.

3.2 Bed level simulation

Three scenarios were formulated in order to investigate the sensitivity of sediment management operations to the reservoir bed level, representing conditions with little or much accumulation of sediments in the lake. The scenarios are built up using the flood peak of 8,000 m^3/s and flushing level of 50.6 m. The original reservoir bed level is used as reference scenario (S_{ref}). This bed level is lowered by 1 m (S_{low}) and raised by 1m (S_{high}). This 1 m is equivalent to 2.5 million m^3.

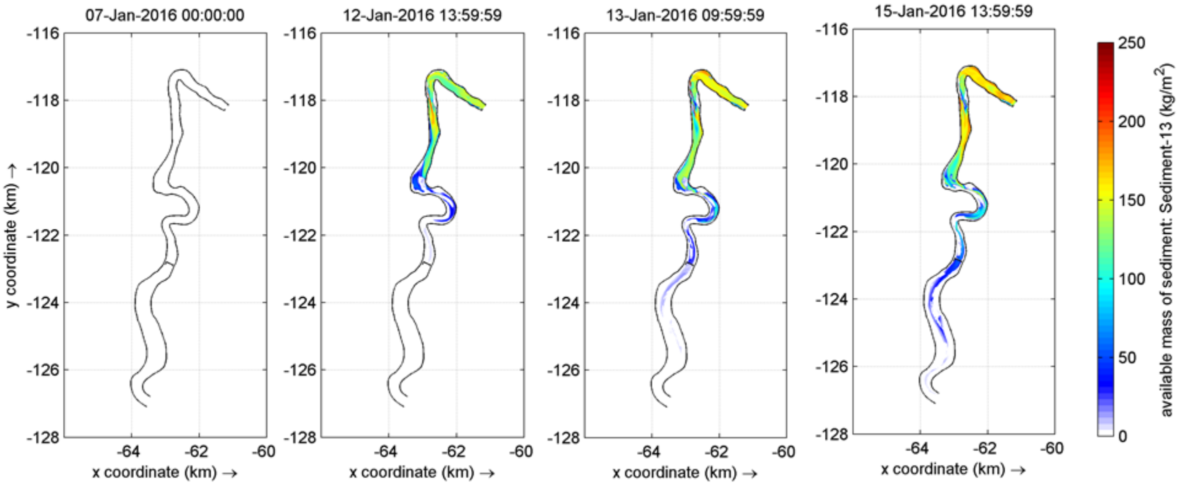

Figure 8. The expected time for sediment inflow to reach the dam

The result displays that increasing of the bed level, increases the amount of sediment passing the dam and vice versa. The table below illustrates the cumulative deposition and erosion and the total of both for every scenario.

Table 3. Sedimentation comparison of three different reservoir bed levels

Scenario (steady)	Sedimentation in the reservoir (10^3 m^3)			Morph_ downstream the dam (10^3 m^3)		
	Deposition	Erosion	total	Deposition	Erosion	total
S_{ref}	1,700	-2,080	-380	920	-1,080	-170
S_{low}	1,690	-2,200	-520	1,010	-1,060	-50
S_{high}	1,750	-2,020	-270	840	-1,120	-280

The results explain that deposition or erosion of around 2.5 Mm^3, using the current operation, would increase or decrease the sediment passing the dam by approximately ± 40 % (e.g. $P = ((S_{low} - S_{ref})/S_{low})$). However, in term of quantities, this ± 40% only represents ± 5% (P/2.5 Mm3) of the deposited/eroded material to/from the bed using the current operation (RES-wl = 50.6 masl and flood peak of 8,000 m^3/s).

3.3 Reservoir water level

Two alternative reservoir flushing levels were investigated in addition to the current reservoir water level as shown in section 2.2. The main approach of the scenarios would be to change the flushing level during flood season to 48.5 m and 47 m. These new two operation concepts have to correspond to the flood magnitude. Therefore, eleven steady state simulations have been executed to explore different reservoir water level and different peak discharges and erosion, and the deposition results are compared. The scenarios have similar settings except for the discharge inflow and reservoir water level as shown in Figure 9.

According to the simulations for the lower the flushing level, a higher sediment amount passes the dam. The discharge of 1,000~2,000 m^3/s is expected to erode the reach downstream of the dam if we are using the current operation. Flood-peak discharge of 3,000 m^3/s, using the current operation, may turn the total cumulative deposition and erosion to a positive amount. This means the reach downstream of the dam is subjected to deposition. Furthermore, lowering the reservoir water level to 48.5 m or 47 m will increase the sediment supply to downstream reach even more.

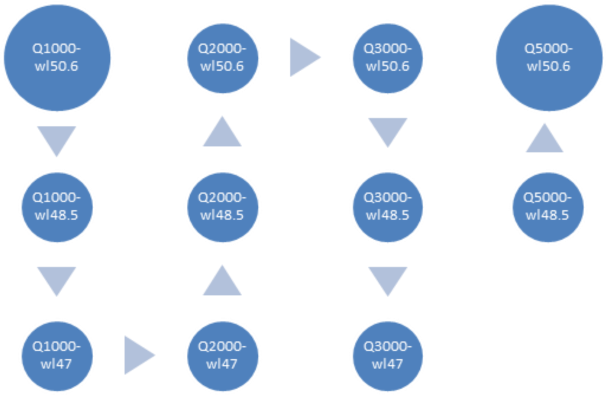

Figure 9. Reservoir water level scenarios varies in discharge and flushing level

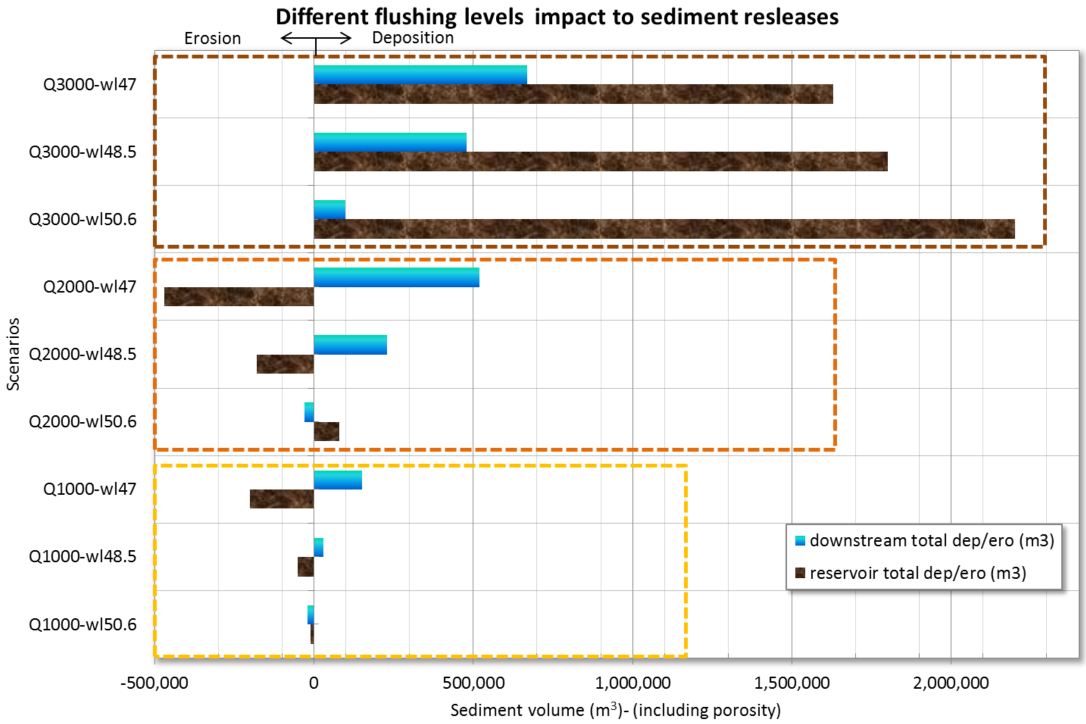

Figure 10. The total cumulative deposition and erosion of (Q1000~Q3000).

Figure 10 illustrates the results of using 48.5 m and 47.0 m as flushing level compared to the current flushing level of 50.6 m. It can be seen that the downstream reach is subjected to erosion if the discharge peak is less than 2000 m^3/s, but turns to deposition for higher discharges. Furthermore, the deposited amount of sediment can be 4 or 6 times more if we lower the flushing level to 48.5 m or 47.0 m, respectively.

3.4 Gate operation mode

The gate operation can be manipulated to divert the flow toward the right side which may increase the bed shear stresses locally in the reservoir. Therefore, adjusted gates operation mode is introduced by closing gate 1,2 and 3 and verified during the falling limb of wet years.

Two scenarios were conducted using three consecutive flood peaks of 8,000 m^3/s and similar reservoir water level (50.6 m). In the reference scenario, all the nine gates are equally. In the adjusted gates operation scenario, gate 6, 7, 8 and 9 have a similar operation, while gate 1,2,3,4 and 5 are operated differently as shown in Figure 11b. This is to ensure that those gates are closed earlier during the falling limb of the flood hydrographs.

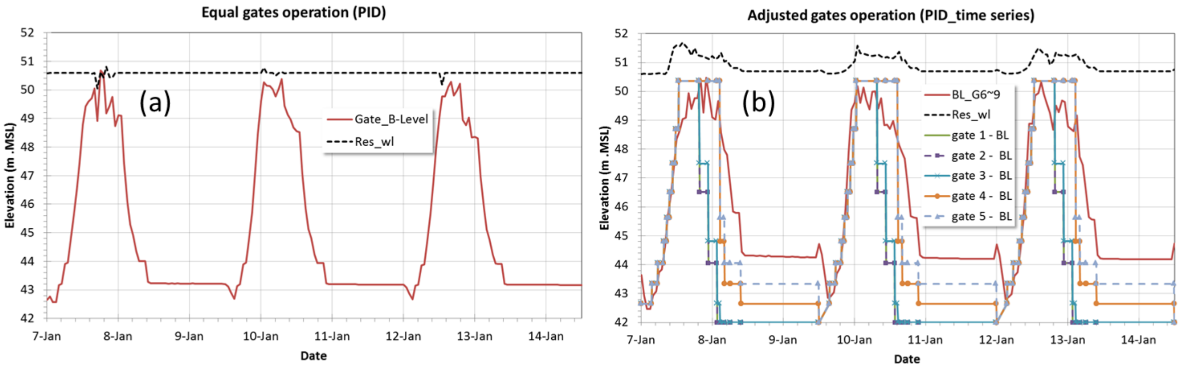

Figure 11. Plot (a) equal gates operation, plot (b) adjusted gates operation.

For recreation and due to the bending shape of the reservoir, some locations (especially the gravel bar upstream right) may require having more water depth. Therefore, during the rising limb of the flood it is possible to use the equal gate operation, and during the falling limb to start closing left gates first. This may divert the current to the right and increase the bed shear stress on top of that formation. Figure 12 depicts the difference in cumulative deposition and erosion between equal gate operation and adjusted gate operation. It shows that the adjusted operation increases the erosion upstream and downstream of the dam. However, the total amount of sediment passing the dam is almost similar. This might indicate that using the adjusted operation may increase the bed shear stress in part of the reservoir area, but at the same time reduces bed shear stress on other parts in the reservoir.

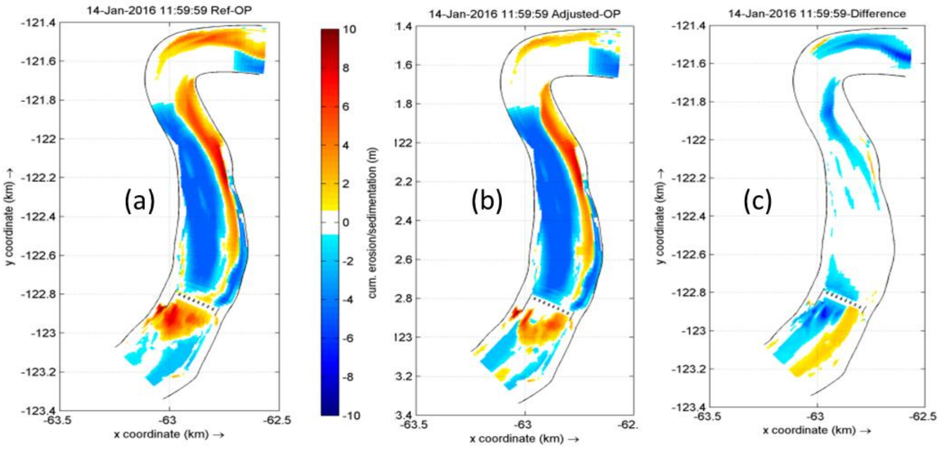

Figure 12. Total cumulative deposition and erosion map. Map (a) equal operation pattern, map (b) the adjusted operation pattern and map (c) is the difference between both maps.

4. CONCLUSION AND RECOMMENDATIONS

This study shows how flushing efficiency and its impacts to the downstream are affected by the conditions in the reservoir and the way the gates are operated. A 2D/3D-morphological model coupled with RTC is found to be a very useful tool to optimize the operation of the gates and improve the flushing efficiency of a reservoir.

The reservoir bed level change, due to sediment accumulation, has a direct effect on the amount of dam outflow sediment. Allowing the sediment in the reservoir to build up, would increase sediment releases, but also creates a high storage loss. It is possible to artificially move deposited reservoir sediment to the reach closer than 5 km from the dam, such that it is easier eroded during the drawdown flushing operation.

The results of the scenarios illustrate that lowering the flushing level would be highly beneficial since more sediment releases through the dam are expected. Flood peak less than 2000 m^3/s may set the overall downstream reach subjected to erosion using the current flushing level. Therefore, using the new proposed flushing levels (48.5 and 47.0 m) may turn over the situation at the downstream reach to be subjected to deposition. Therefore, one of those flushing levels might be considered permanently (for all years) or temporally (only dry years). The selected flushing level is recommended to be investigated against the minimum sediment amount needed, the allowable velocity within the reservoir, the minimum reservoir water level which may trigger bank erosion problem upstream the dam and the allowable velocity and sediment concentration downstream of the dam.

The equal gates operation mode is quite effective during flood peaks. However, due to reservoir shape, a large point bar formation is going on at the right bank. Using adjusted gates operation would increase the water depth there. The adjusted gates operation mode compare to equal mode does not give much more sediment releases from the dam (only 8% extra). However, it is useful to deepen certain or shallow locations within the reservoir.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Baran E. & Nasielski J.(2011). *Reservoir sediment flushing and fish resources*, Report submitted by World Fish Center, Phnom Penh, Cambodia to Natural Heritage Institute, San Francisco, CA.

Brandt, SA (2000). *Classification of geomorphological effects downstream of dams*.

Danelli A & Peviani M (2012). *D6.9 Application of A Morphological Model to Evaluate Downstream Effect of Reservoir Flushing Operation*: Transnational Cooperation Program - South East Europe and the European Union.

Fruchard, F. and Camenen, B (2012). *Reservoir sedimentation: different type of flushing - friendly flushing example of genissiat dam flushing*, Kyoto, Japan: ICOLD International Symposium on Dams for a changing.

Guertault L, Camenen B, Peteuil C, & Paquier, A (2014). *Long-term evolution of a dam reservoir subjected to regular flushing events,* Advances in Geosciences, 39, 89-94.

Kondolf G, Gao Y, Annandale G, Morris G,Jiang E, Zhang J, Cao Y, Carling P, Fu K, & Guo, Q (2014). *Sustainable sediment management in reservoirs and regulated rivers: Experiences from five continents,* Earth's Future, 2, 256-280.

Morris, GL (2015). *Management Alternatives to Combat Reservoir Sedimentation*, International workshop on Sediment Bypass Tunnels Zurich, Switzerland: ETH Zurich.

Mulatu, CA (2007). *Analysis of Reservoir Sedimentation Process Using Empirical and Mathematical Method: Case Study - Koga*.

Olsen NRB & Haun S (2010). *Free surface algorithms for 3D numerical modelling of reservoir flushing*, RiverFlow.

WMO (2011). *Reservoir Operations and Managed Flows*: Associated Programme on Flood Management, Water Meteorological Organization.