The effect of different gate opening patterns on reservoir flushing and morphological changes downstream a dam

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1 Introduction

Hydropower dams provide a great service to society. Their number continues to increase because of growing demands for water and electricity. However, they disturb river morphology and ecology. The reservoirs behind the dams suffer from loss of storage and contamination due to sedimentation. The reduction of storage capacity poses challenges to dam operators. The requirements of minimizing storage losses while caring for the ecosystem downstream leads to investigations into optimum operational rules. Sediment management practices for this purpose, such as sluicing and flushing, may generate undesired morphological changes in the reach downstream of the dam. The gate opening pattern is expected to influence this. We developed a modelling approach to simulate flow regulation through a dam to understand the effect of different gate opening patterns on the morphodynamics. The aim is to seek improvements of the flushing process and to understand how this process affects the morphological changes downstream of the dam. We built a 2D morphodynamic model using Delft3D 4 open-source software, capable of simulating the time- and space-varying hydrodynamics and morphological changes in the reservoir and the river reaches. Delft3D software can be coupled with the real-time control toolbox (RTC) to control different gate openings in time. RTC is open-source software too. We apply the approach to Funagira reservoir, located in the Tenryuu River in central Honshū, Japan. The river downstream of the dam suffers from bank erosion and side bar formation due to the existing pyramid-shape opening pattern of the gates. Equal-shape openings are introduced as a new pattern. We analyze and compare both patterns in terms of flushing efficiency and sediment distribution downstream the dam.

2 Background

For all river basins globally, reservoir capacity declined around 5% compared to the installed capacity (Wisser *et al.*, 2013). A 2009 study for 285 dams by the Italian national Committee for Large Dams (ITCOLD) indicates that the loss of storage in 53% of investigated hydroelectric reservoirs in Italy has an average of 47% due to sedimentation. The storage loss at other dams is less than 5% (Bizzini *et al.*, 2009). Reservoir sedimentation poses environmental challenges, such as deposition of contaminated sediments, deterioration of fish habitats due to fine sediments, bed degradation downstream of the dam, and coarsening of the riverbed downstream to a state no longer suitable for spawning (Spreafico, 2007). Moreover, reservoir sedimentation increases the probability of flooding along the reach upstream of the reservoir due to bed aggradation (Kantoush *et al.*, 2010).

The downstream bed degradation may cause undesired bank erosion and scour. It may also contribute to coastal erosion (Guertault *et al.*, 2014). Around 53% of global sediment fluxes in regulated basins are potentially trapped in reservoirs. This may influence the downstream morphological behaviour and coastal areas that rely on riverine sediment supply (Kondolf *et al.*, 2014). The associated long-term economic losses need to be mitigated (Liu *et al.*, 2004). Improved sediment management and reservoir operation rules are thus of vital importance. Knowledge on ways to increase the passage of sediment to the reach downstream will help in increasing the life time of a reservoir as well as in mitigating downstream erosion of riverbanks and coastlines.

Additional measures to pass sediment are sluicing, dredging and flushing (Fruchard and Camenen, 2012). Flushing could be called “dredging for free”. The cost of flushing 1000 ton of sediment is negligible compared to the cost of dredging of the same amount. There are two types of flushing: hard flushing by maximum drawdown of the reservoir water level and environmentally friendly flushing by a limited drawdown to mitigate or avoid adverse impacts on the downstream ecosystem (Baran and Nasielski, 2011). However, flushing sometimes affects the hydropower plant revenue. Danelli and Peviani (2012) recommend real-time reservoir operation to obtain a better understanding of the sediment transport through the dam. Here we follow this recommendation in a case study. We investigate sediment flushing for the Funagira Dam using two different gate opening patterns, viz. the pyramid-shape pattern (Pyr) and the equal-shape pattern (Equ).

The left bank suffers from erosion within the first 1.5 km downstream of the dam. Further downstream, side bars developed as shown in Fig. 1. This erosion and sedimentation pattern is likely caused by cross-stream variations in bed shear stress and the formation of an eddy when the gates are open during floods. In the original operation, the central gates were opened first and the other gates were opened next at higher discharges, following a pyramid shape pattern. This has been modified into an equal-shape opening pattern by which opening heights are increased equally. The nine spillway gates are 20 m wide and 16 m high, with a crest level of 42.0 m MSL (Above Mean Sea Level). The turbines operate between water levels of 54.8 m and 57.0 m MSL.

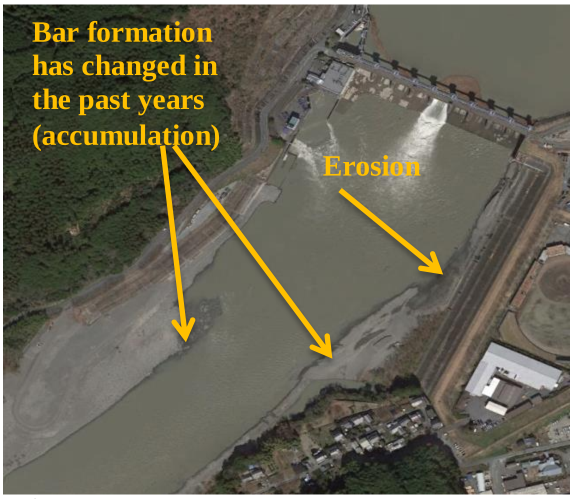

Fig. 1. The area downstream of Funagira Dam where bank lines and bar patterns have changed over the past years (Source: GoogleEarth).

While releasing the flood peak and flushing the sediment, the dam operator maintains the water level at 50.6 m MSL. We focus on the period of the flood peak when the turbines are off and the gates are operated.

3 Modelling approach

The high flow velocities generate high bed shear stresses and let the water carry a high amount of sediment to the downstream reach of the dam. We simulate this behaviour by 2D modelling approach using Delft3D software, coupled to the RTC real-time control module to operate the gates. Previous studies on the Tenryuu River demonstrated that the Delft3D modelling system is capable of reproducing these processes (Becker, 2015 ; Sloff, 2009; Sloff, 2001; Yossef, 2010). We used three peak discharges to analyze and to calibrate the hydrodynamic behaviour and the bedload transport. We employed two different bed topographies in the reservoir because this may have an influence on the downstream morphological changes. Flushing in one year may result in a lower reservoir bed topography in the subsequent year. In view of inevitable model uncertainties, we interpreted the results in a qualitative way and compared the results to data from a physical scale model.

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 equation:

$$Q = \mu A\sqrt{2g\left(H_1 - H_2\right)} \qquad (1)$$

where Q is the discharge, μ is the barrier contraction coefficient ($0 < \mu \leq 1$), A is the area of the gate opening, g is the acceleration due to gravity, H_1 is the reservoir water level and H_2 is the downstream water level or, sometimes, the dam overflow crest level. The contraction coefficient is used to acquire the equivalent energy loss coefficient (C_{loss}) in both velocity directions (U and V) at the barrier. A depth-averaged analysis shows this coefficient to be related to the barrier contraction coefficient by

$$C_{loss} = 1/\left(2\mu^2\right) \qquad (2)$$

The energy loss coefficient can be used as a calibration coefficient to ensure that the barrier discharges the correct amount of water through the corresponding gate opening (Deltares, 2016).

4 Hydrodynamic model set-up and calibration

The computation grid and the model topography, as shown in Fig. 2, were generated using the QuickIn tool of Delft3D 4. The 15 km long grid covers the Funagira reservoir and the river downstream. The upstream boundary condition of the model is a discharge inflow. The boundary is located in the upstream reservoir, about 9.8 km from the Funagira Dam. Three stepwise hydrographs of flood waves were used as an upstream boundary (see Fig. 3). These hydrographs had flood peaks of 5000 m^3/s (medium), 8500 m^3/s (high) and 11130 m^3/s (design). They are similar to the inflows in the physical model. A discharge rating curve was specified at the downstream boundary, under the bridge located 4.85 km downstream the dam (See *Fig. 4*). Based on the data received, *Fig. 4* gives an example of the pyramid-shape operation data for a 5000 m^3/s peak flood hydrograph.

We calibrated the model by comparing water levels in the reservoir and downstream of the dam with the physical scale model results. This was carried out only for the equal-shape opening pattern, as no scale model data were suitable for the pyramid shape pattern. The reservoir water levels were tuned to be within the range of the scale model. Reservoir water levels were tuned by adjusting the energy loss coefficient of the barrier and the roughness of the bed downstream of the dam.

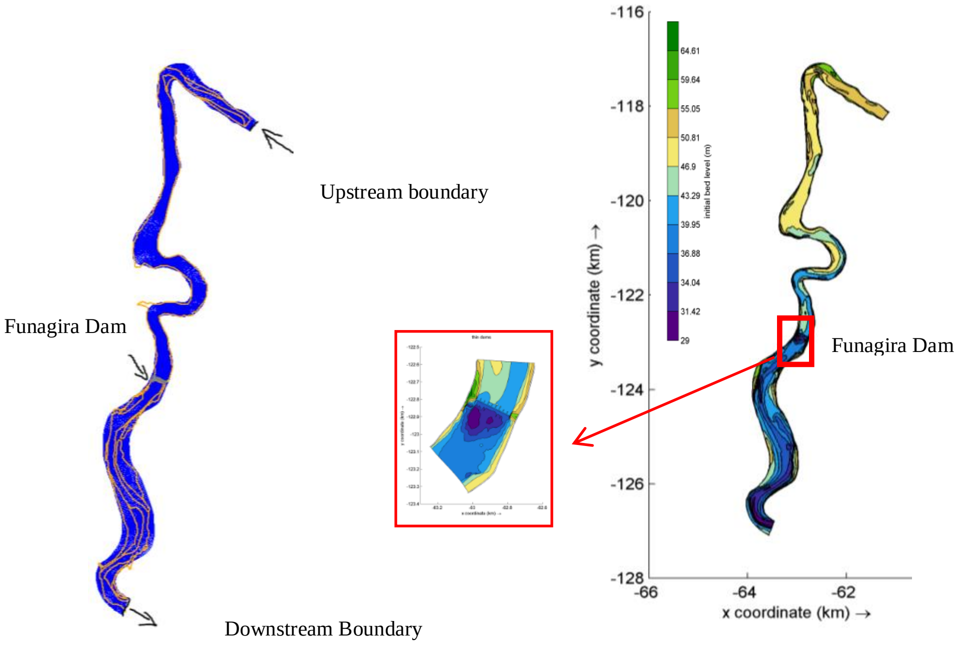

Fig. 2 Computational grid and location of boundaries (left) and the initial bed topography (right)

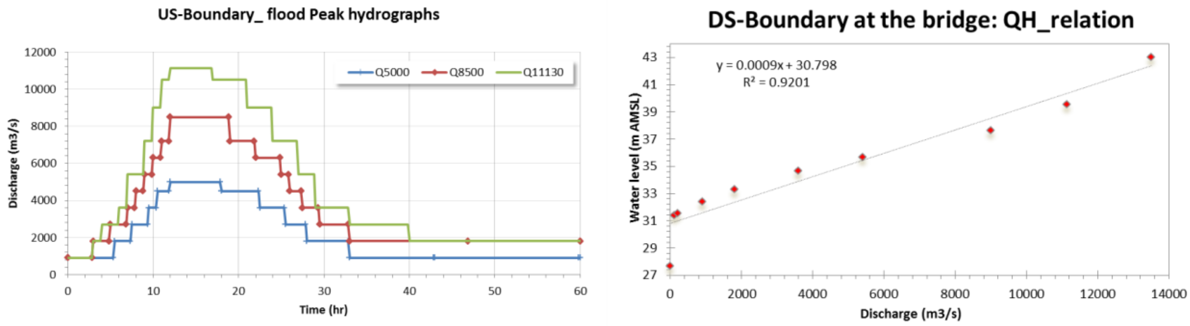

Fig. 3 Flood hydrographs used as upstream boundary conditions of the model on the left. Discharge and water level data obtained from the client at the bridge downstream the dam on the right

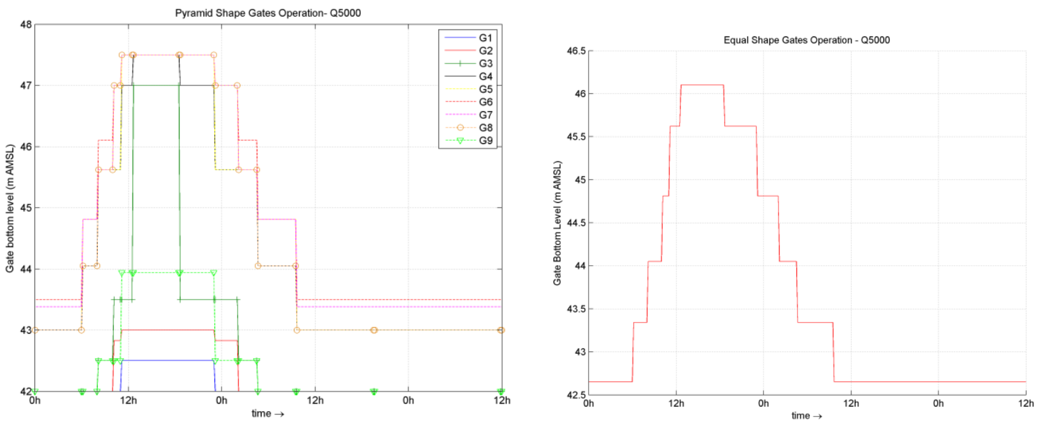

Fig. 4 Example of pyramid-shape gate opening pattern (left plot) and equal-shape gate opening pattern (all gates having the same bottom level time series) (right plot), both for the hydrograph with a peak of 5000 m3/s.

For a proper timing of opening the gates, the travel time of the flood peak from the upstream boundary to the dam was estimated to amount to 40 minutes, based on the model runs. The theoretical reservoir water level is 50.6 m AMS, but the data from the physical scale model show that this water level fluctuates within a certain range for every flood hydrograph. Table 1 displays the range of dynamic fluctuation of the water levels in the reservoir for the flood hydrographs explained in Fig. 5(a).

Table 1 Ranges of fluctuation of reservoir water level corresponding to different flood peak discharges (source: physical model results)

Flood Discharge	Reservoir water level (m MSL)	
	Min	Max
Q5000	49.8	52
Q8500	48	53
Q11130	48.5	54

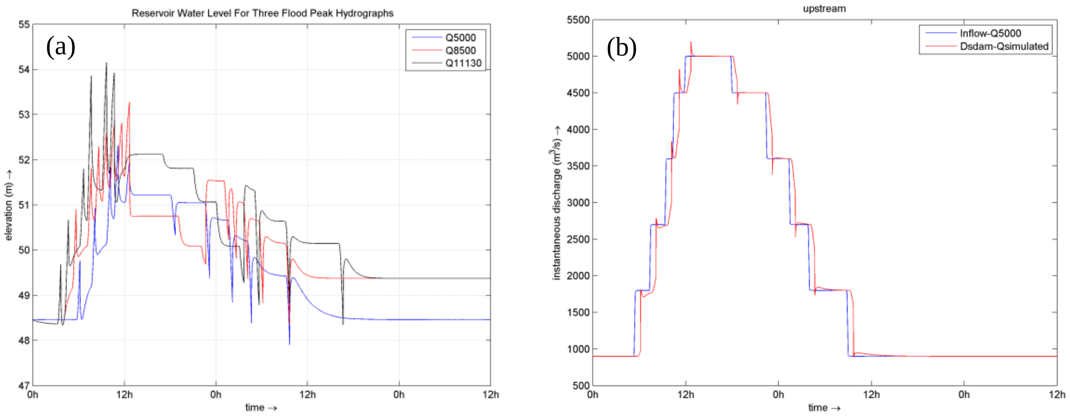

Fig. 5 Simulated reservoir water levels corresponding to three flood discharge hydrographs (plot (a)). Q5000 inflow discharges compared to discharges simulated by the model 100 m downstream the dam (plot (b))

Fig. 5(a) shows results of the simulated water levels for the equal-shape opening pattern. By comparing those results with the water levels in Table 1, we conclude that reservoir water level fluctuations are mostly within the range of the data. However, the initial conditions are less than 50 m MSL, namely 48.5 m MSL and 49.5 m MSL for the equal-shape pattern and the pyramid-shape pattern, respectively, and a discharge of 900 m^3/s. This discrepancy between the data and the results might result from the interpolation of bed topography. Discharges through the gates are considered too in the calibration. Fig. 5(b) shows the simulated discharges of inflow, and the discharges recorded downstream of the dam.

The downstream water level was tuned to the observed water level by making sure that the river bed thalweg is well interpolated and that the river channel is smoothly linked in the model topography. Three sets of water levels were provided at 300 m downstream of the dam. Set1 is called “local assumption of 2012”, Set2 is the water level observed in the physical model tests and Set3 is another set of data from the physical model called “new local”, apparently based on an update of the local assumption, called.

Fig. 6 shows the result of simulated water levels downstream the dam for the Q11130 flood hydrograph. The simulated water levels are higher than the local assumption (Set1), but it is within the upper range of the physical model results and almost similar to Set3, especially at high discharges. Nevertheless, at discharges below 6000 m3/s, the model overestimates the downstream water level.

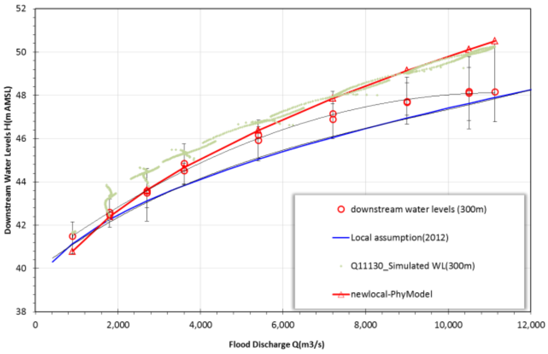

Fig. 6 Comparison between simulated water levels downstream the dam and similar data.

5 Morphodynamic model set-up and calibration

We used 6 sediment grain size fractions as shown in Table 2, based on data provided for previous studies. 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 was carried out.

Table 2 Sediment grain sizes used in model bed composition

no.	Diameter (mm)		Initial sediment percentage in bed composition
	min.	max.	
07	0.10	4.75	17
08	4.75	9.50	12
09	9.50	19.00	30.5
10	19.00	26.50	25
11	26.50	37.50	17.5
12	37.50	53.00	8

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 non-erodible and therefore modelled with 0 m layer thickness. We used the Ashida-Michiue sediment transport formula with overall calibration factor 0.6, critical incipient-motion Shields parameter 0.035 and otherwise default values. We employed the Koch-Flokstra formula for the effect of bed slopes on sediment transport direction, tuning its parameters to obtain realistic bed topography between the inner and outer bends in the river corridor. We used the active-layer modelling approach with 10 under layers and an active-layer thickness of 0.5 m.

We compared the results of the simulations to the data from the physical scale model. Fig. 7 compares the bed level changes between the physical scale model and the numerical model, for a cross-section 150 m downstream of the dam. In the scale model, sedimentation of 0 to 8 m was observed. The same order of magnitude was observed in the numerical model, including the highest deposition in the right part of the channel.

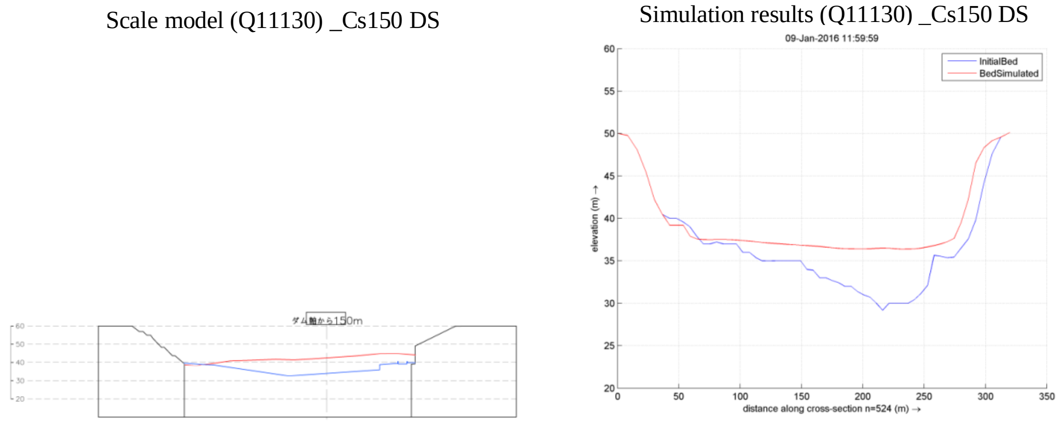

Fig. 7 Comparison between Q11130 model result and scale model result of cross-section 150 m downstream the dam.

The main purpose of the calibration is to tune the parameters in such a way that model results have sufficient quality for simulating and comparing scenarios. Remaining differences may be attributed to limitations of the model, such as complex flow patterns and the influence of suspended sediment. Furthermore, a hydraulic jump occurs in the system for discharges of 1000 m^3/s and higher when downstream water levels are low. The resulting model captured the overall dynamics sufficiently well in a qualitative sense.

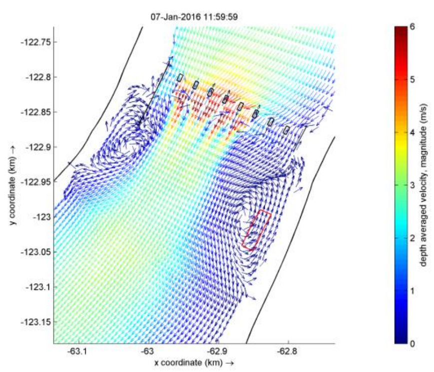

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Fig. 8 Depth-averaged velocity vectors at a discharge of 5000 m3/s and pyramid gates operation pattern. The red rectangular shows the position of the area subject to erosion at the downstream left bank.

After calibration, we simulated 12 scenarios to compare the downstream morphological changes and to understand to which extent the upstream bed level and the gate opening pattern influence river morphology downstream. The 12 scenarios result from combinations of three flood hydrographs, two gate opening patterns and two bed topographies, namely the initial bed level of the calibration, called “BedA”, and a bed topography that is 1 m lower in the reservoir, called “BedB”. The upstream lowering of 1 m represents the average erosion predicted by the scale model.

6 Results

The flow velocity adjacent to the downstream left bank is recorded to check whether its value is sufficiently high to explain the observed erosion. For the pyramid-shape opening pattern, the velocity varies between 0 and 2 m/s at the downstream left bank for the Q5000 hydrograph. The depth-average velocity at this bank is less than 2 m/s as shown in Fig. 8. The eddy does not show a significant influence on the shear stress on the bank. Cumulative erosion and deposition are shown in Fig. 9. More sediment is deposited downstream for BedA, because this bed is eroded more than BedB. All scenarios lead to more or less the same pattern of erosion and deposition downstream. No significant erosion occurs at the downstream left bank and no deposition tendency is visible within the areas bounded by a polygon in Fig. 9. Fig. 9 also gives an overview of the equal-shape pattern for two Q5000 scenarios. Equal shapes lead to more widely distributed deposition than the pyramid shape. Again, BedA produces more deposition than BedB.

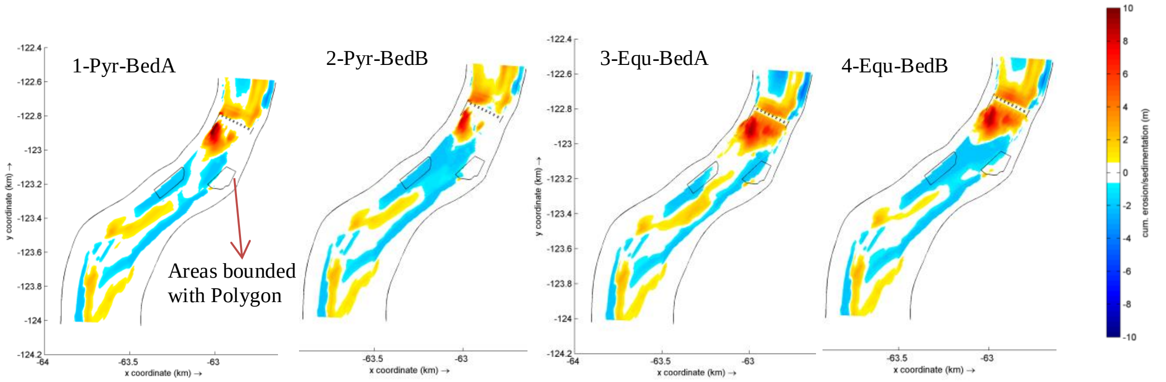

Fig. 9 Total cumulative deposition and erosion downstream the dam. Comparison between S1, S4, S7 and S10 of Q5000, Pyramid-shape gate opening and two different upstream bed topographies (BedB < BedA by 1 m).

For the more quantitative results, we recorded the cumulative bed load transport at the dam and at a cross-section almost 1 km upstream the dam (at 30.75 km) as shown in Fig. 10(a). The cumulative bed load transport is recorded without porosity. In Table 3 , the results of Fig. 10(b) are analyzed and interpreted. The cumulative bed load transport obtained from the two figures is multiplied by 1.65 to account for porosity.

From Table 3, the amount of sediment released to the downstream river by the equal-shape opening pattern is almost 1.5 times the sediment released by the pyramid-shape opening pattern. Furthermore, the higher the upstream bed the more sediment can be flushed from the reservoir. The sediment bed load transported through cross-section 30.75, using the equal-shape opening pattern, is 1.1 to 1.2 more than the sediment amount passed using the pyramid gates opening. On the other hand, the sediment eroded from the reservoir (within 1 km upstream the dam) using the equal-shape pattern is approximately twice the sediment volume flushed using the pyramid-shape pattern. We followed a similar approach for flood hydrographs Q8500 and Q11130.

The equal-shape pattern is always effective in terms of the amount of sediment eroded from the reservoir as shown in Fig. 11. However, during high flood peaks the lower bed further upstream gives a lower sediment transport to the reservoir. This may allow more sediment to be picked up within the reservoir as depicted in the Q11130 scenarios in Fig. 11. The BedB scenario erodes more sediment from the reservoir than the bed type A scenario of Q11130 in the case of the equal-shape opening pattern.

7 Conclusions

We draw the following conclusions:

- The equal-shape opening pattern flushes more effectively than the pyramid-shape opening pattern. (in this study 1.5 times more sediment can be flushed).
- The pyramid-shape opening pattern produces an eddy at the left bank, but this eddy is not strong enough to create high shear stresses on the bank to move the concrete tetra blocks used there for bank protection.
- The area downstream of the dam is subject to high flow velocities due to supercritical flow and a hydraulic jump. Eddies would occur there due to asymmetrical gate opening. This area has to be well protected to avoid damage due to erosion or scouring of bed and banks.
- Effective flushing (i.e. removing deposits through erosive forces) is only possible if we draw down quickly and to a very low level. The quicker the draw down, the higher the eroded volume, but also the higher the downstream flood peak and sediment concentration. However, this is not possible to be used

RTC toolbox is very successful in operating the dam gates and it is highly recommended to be coupled with Delft3D to represent a dam or hydraulic structures within the model domain.

The equal gates operation minimizes the forming of eddies downstream of the dam, and decreases the erosion of the bed and banks, if they are not well protected. It is also more efficient in term of sediment flushing than the pyramid gates operation. However, pyramids operation could also help to get different erosion pattern upstream of the dam, if that is required.

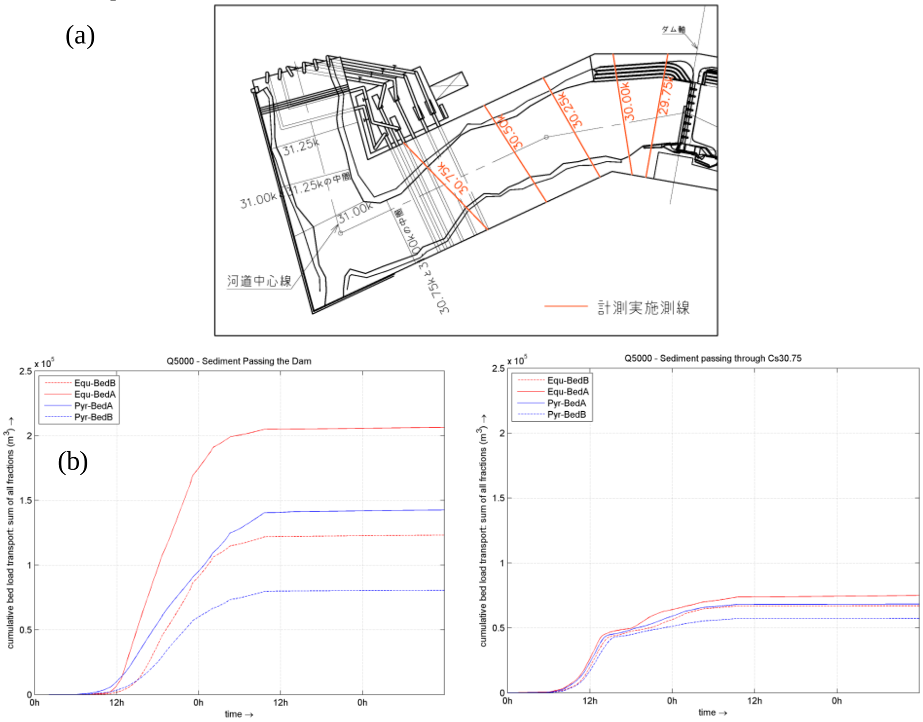

Fig. 10 Plot (a) plan view to the locations of the dam and cross-section 30.75 upstream the dam. The red lines show the cross-sections upstream the dam. Plot (b) cumulative bed load transport through the dam to the downstream reach (on the left) and through cross-section 30.75(on the right) (Without porosity)

Table 3 Q5000 scenario results including the total sediment eroded within 1 km upstream the dam (including porosity)

Q5000 Bed type / Total sediment		BedA ($\times 10^5$ m^3)	BedB ($\times 10^5$ m^3)	Diff ($\times 10^5$ m^3)	% Diff
A- Passing through the Dam	Pyr	2.34	1.33	1.02	43
	Equ	3.40	2.03	1.37	40
	%	145	153		
B- Passing through Cs30.75 (1 km us the dam)	Pyr	1.13	0.94	0.19	17
	Equ	1.24	1.11	0.13	11
	%	110	118		
Eroded Sediment _Us dam (A-B)	Pyr	1.21	0.39	0.83	68
	Equ	2.16	0.92	1.24	57
	%	178	239		

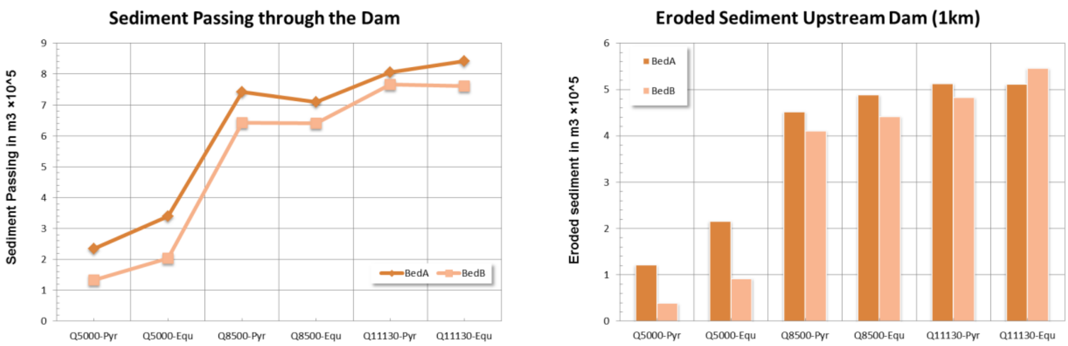

Fig. 11 Sediment passing the dam recorded in all scenarios (left plot), and total sediment eroded from the reservoir (within 1 km from the dam, including porosity). (right plot).

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