Investigation of venting turbidity currents in the Rudbar-Lorestan reservoir in Iran

Azin Amini[1,a], Sara Venuleo[1,b], Sabine Chamoun[1,c], Givanni De Cesare[1,d], Anton Schleiss[1,e], Fakhredin Takhtemina[2,f]

[1]*LCH, EPFL, Lausanne, Switzerland*

[2]*Poyry, Tehran, Iran*

[a]azin.amini@epfl.ch

[b]sara.venuelo@epfl.ch

[c]sabine.chamoune@epfl.ch

[d]giovanni.decesare@epfl.ch

[e]anton.schleiss@epfl.ch

[f]fakhreddin.takhtemina@poyry.com

ABSTRACT

Venting of turbidity currents is known as an efficient measure to prevent reservoir sedimentation and is applied in many reservoirs globally. It has several economic and ecological advantages compared with other evacuation methods. In the literature, numerous researchers mentioned the importance of venting, but mostly qualitatively. Given the complexity of the phenomenon and the presence of many parameters affecting the efficiency of venting, case studies offer good insight into solutions for specific reservoirs where there is a high probability of occurrence of turbidity currents. In the present study, the efficiency of venting turbidity currents is investigated for Lorestan Reservoir in Iran. For that purpose, 3D numerical simulations of turbidity currents over 11 km and venting operation are performed using ANSYS Inc. software. The results of the present research allow to optimize venting operations in the Lorestan Reservoir and reservoirs having similar general characteristics. Recommendations are drawn on outlet opening timing and discharge allowing to vent the greater amount of sediments while minimizing the water release.

1. Introduction

The Rudbar Lorestan project is one of a series of hydropower development projects in the Dez River catchment upstream of the existing Dez Dam in Iran. Rudbar is the furthest upstream scheme planned, in a cascade of dams planned over 220 km. The project site is in Lorestan Province in the high Zagros mountains of west central Iran at approximately 490 41’ 7’’ East, 320 54’ 23’’ North (Figure 1). The scheme impounds the river with a 153 m high Earth Core Rockfill Dam (ECRD) at the Rudbar River to create a reservoir of about 20 km long with an estimated useful storage capacity of 248 hm^3. The catchment area is 2’255 km^2, producing an average annual flow of about 31 m^3/s after upstream abstraction. The dam is equipped with two bottom outlets. Table 1 summarizes the main characteristics of the hydraulic scheme.

Figure 1. Rudbar Lorestan dam site location (www.google.com)

Table 1. Main characteristics of Rudbar Lorestan HPP

Watershed area	2’255 km^2
Annual water yield	759 million m^3
Annual total sediment yield	1.7 million tons
Annual suspended load yield	1.3 million tons
Average discharge	30.2 m^3/s
Dam type	Earth Core Rockfill Dam (ECRD)
Live storage capacity	248 hm^3
Dam height	155 m
Number of bottom outlets	2

Like in many other reservoirs worldwide, sedimentation is a concern in Rudbar Lorestan dam. Sedimentation leads to the reduction of the reservoir’s storage capacity and consequently its lifetime. On the other hand, sedimentation may cause clogging of intakes and bottom outlets which influences their serviceability and efficiency. As such, an efficient and sustainable sediment management will be required to maintain the storage capacity in long-term. Venting the turbidity currents, if well planned, can reduce reservoir sedimentation significantly and enhance the efficiency of hydropower energy production.

The aim of the present study is to assess whether the periodic reservoir turbidity current venting is technically feasible over a variety of reservoir operational conditions and to test turbidity current venting as a measure of sustainable reservoir sediment management in Rudbar Lorestan.

Figure 2. Rudbar Lorestan dam under construction, upstream view (www.iwpc.ir, 2015)

2. Turbidity current venting

During floods, the density of river water usually increases due to a subsequent increase in the concentration of the suspended sediments that the river carries, causing the river to plunge underneath the free surface of the ambient clear water of the reservoir. After plunging, the turbidity current travels along the reservoir's bottom and, in case of high enough concentrations, it can reach the dam. If the bottom outlets are opened at the right moment, the sediment can be vented and respectively evacuated through the outlets before settling in the reservoir. This process is called venting. This method has been already applied in Iran for other reservoirs. An example is the Sefid Rud Reservoir where venting of turbidity currents was applied using power intakes and a bottom outlet. Results showed considerable increase in efficiencies when opening the bottom outlet compared to cases where only power intakes were operating (Morris and Fan 1997). Dez Dam also loses around 0.5% of its storage capacity every year to sediments mainly brought by turbidity currents (Schleiss, De Cesare, & Althaus, 2010).

Venting turbidity currents can be investigated through field measurements which can be very challenging given the flood conditions in which turbidity currents occur and venting is performed (Lee, Lai, Tan, & Sung, 2014; Morris & Fan, 1997; Ren & Ning, 1985). Experimental models can also be used to study venting (Chamoun, De Cesare, & Schleiss, 2017; Lee et al., 2014), allowing the assessment of the effect of some key parameters. Theoretical analytical tools can be employed as well (Fan, 1986, 2008; Yu, Hsu, & Fan, 2004). However, when it comes to case studies such as the case of Lorestan Reservoir, numerical models are the most appropriate tool, avoiding scale effects and providing numerous results enhancing the understanding of the process. Some researchers opted for the numerical modeling in the past (Lee et al., 2014; Sloff, Commandeur, & Yang, 2016) to study venting in reservoirs such as the Tsengwen and the Shihmen in Taiwan. Such models can provide not only improved insight on the operation of venting but also significant information on the turbidity current's dynamics as well as the erosional and depositional characteristics (De Cesare, Schleiss, & Hermann, 2001; Georgoulas, Angelidis, Panagiotidis, & Kotsovinos, 2010).

In this study, we provide recommendations on operational decisions in order to optimize the venting process with the purpose to evacuate a maximum amount of sediments while losing the least water possible at the Lorestan Reservoir.

3. Methodology

To plan an efficient venting process, three-dimensional (3D) numerical simulations are carried out. Turbidity currents and the venting operation are simulated using ANSYS CFX Inc. (v15.0) software.

Once the numerical model is fully set up, the first step is to assess the characteristics of turbidity currents such as velocity, discharge and sediment concentration along the thalweg and particularly in the vicinity of the bottom outlets. The second step is to determine the turbidity current's venting efficiency and water losses based on bottom outlet operational scenarios during flood events.
These steps can be summarized as:

- Simulation of the turbidity current into and along the reservoir down to the dam;
- Simulation of the venting process for different opening scenarios.

4. Input data

The hydrological data have been collected and analyzed by Pöyry company in 2008. Wherever data are missing, assumptions are made. These assumptions are based on the data found in the literature or collected for similar projects in the region, such as Dez reservoir. Sensibility analysis of different parameters allow to cope with uncertainties related to lack of data, particularly on parameters related to sediment characteristics.

1. Flood hydrograph

The flood hydrographs for the 2, 5, 10 and 20-year flood events are considered (Figure 3). The total flood duration is estimated by 120 hours, and the peak discharge occurs after 50 hours.

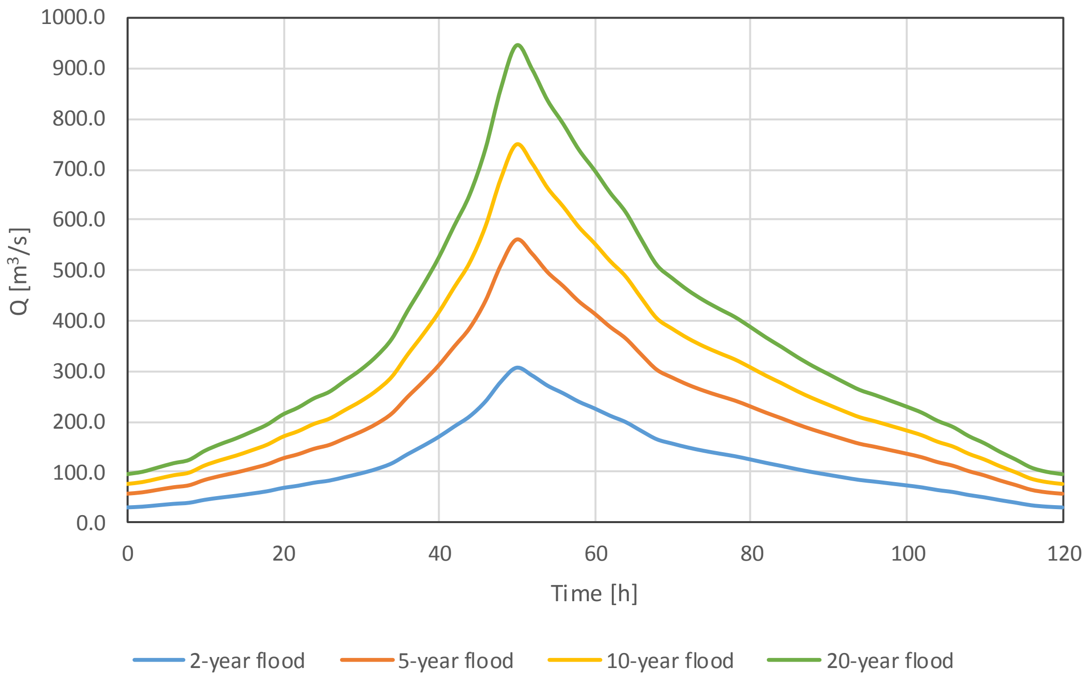

Figure 3. Hydrographs of flood events (Pöyry report, 2008)

2. Solidograph

Concentration of the suspended sediment in a river is usually measured by turbidimeters. The instruments installed in gauging stations upstream of the reservoir can provide useful and pertinent data on sediment concentrations. Since no measurement on sediment concentrations is available for the present project, the suspended sediment discharge (Q_s) is linked to the water discharge (Q_w) by:

$$Q_s = AQ_w^b \qquad (1)$$

where *A* and *b* are coefficients defined based on the existing data on monthly inflow as well as annual suspended load yield. *b* is set to 0.5 based on recommendations of Mulder and Syvitski (1995) for monthly discharge values, while *A* has to be defined for each reservoir. This value depends on the hydrological and geological characteristics of the catchment area. The only data available on suspended load is its total annual mass which is 1.3 million tons (Table 1). On the other hand, the monthly averaged water discharges are available. Therefore, the monthly averaged sediment discharge, Q_s, is calculated using Equation 1 by varying "*A*" coefficient to obtain a total annual sediment mass of 1.3 million tons. As such, the value of 0.0224 is obtained for *A* and Equation 1 can be expressed as:

$$Q_s = 0.0224 Q_w^{0.5} \qquad (2)$$

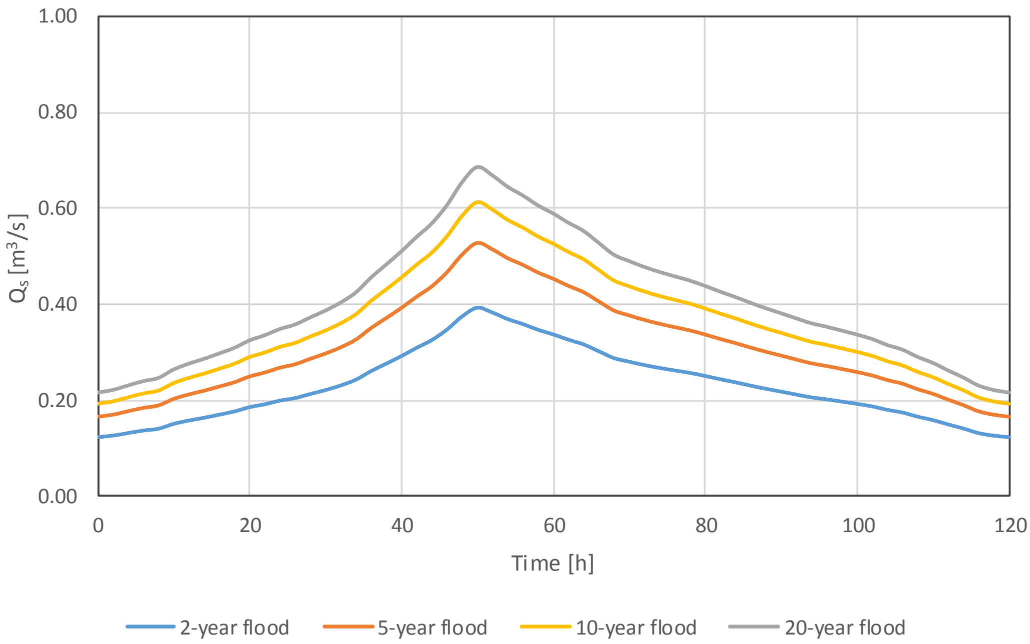

Figure 4. Simulated solidographs of flood events

Solidographs for floods of different return periods are presented in Figure 4. These graphs are obtained by applying Equation 2 on flood hydrographs presented in Figure 3. The arrival time of sediment discharge peak is 50 hours as for the water inflow discharge.

3. Sediment properties

The grain size distribution of suspended sediments at Rudbar Lorestan dam site in unknown. However, samples taken in Dez River can be representative for the present study due to the proximity of the two reservoirs. From the existing sediment samples taken, the grain size distribution of the fine deposits in Dez River has a mean diameter of some 50 µm (KWPA, 2005).

5. Numerical modeling and scenarios

In order to evaluate the venting efficiency at different operational conditions, two geometry models are created considering the initial water elevation at the model:

- Initial water level corresponding to the normal water level (n.w.l.);
- Initial water level corresponding to the minimum water level (m.w.l.).

For each of these initial conditions, four flood events are simulated respectively having 2, 5, 10 and 20 years return period. As a first step, all simulation scenarios are run keeping the bottom outlets closed. Different opening configurations are then tested depending on the considered flood event and on the initial water level.

It is decided to consider three bottom outlet opening configurations: 100% and 50% as well as 25% opening of both bottom outlets. Additionally, a configuration with the main bottom outlet closed and the second one completely opened (100%) is considered.

The sediment inflow is introduced into the numerical model as a volume fraction uniformly distributed at the model's inlet. In the model, the turbidity current forms as a result of density difference at the plunge point and flows along the reservoir's bottom (Figure 5).

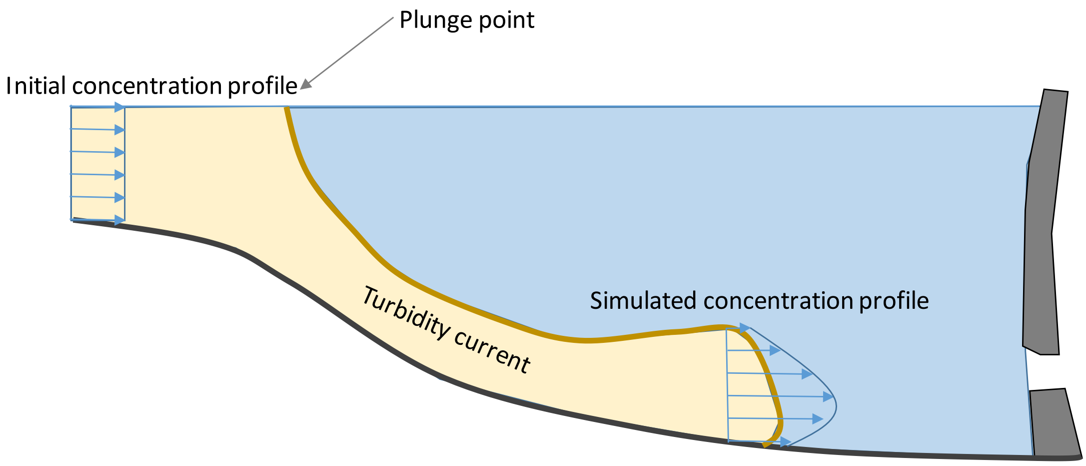

Figure 5: Schematic view of turbidity current and initial condition; the sediment is set uniformly as a volume fraction at inlet; the turbidity current will form later in the model.

6. Results

Arrival time

In the following, the expression "arrival time" is meant as the time of the appearance of the turbidity current at the reference section, 300 m upstream of the dam. Different scenarios are evaluated based on:

- Velocity and concentration profiles at the reference section;
- Sediment volume fraction evolution at the reference points;
- Sediment flow evolution at the reference section.

Generally, the arrival time can be easily identified due to the abrupt change of the sediment volume fraction and sediment flow values. The analysis of the velocity and sediment concentration profiles is used as a further tool to confirm the obtained results.

The arrival time of the current at the dam site is fundamental as it is directly related to the best timing for the opening of bottom outlets. If the bottom outlets are opened at the arrival time of the current, the velocity field of the current decelerates when arriving at the dam. Thus, the current continues to exit out of the reservoir during the entire venting period allowing continuous sediment evacuation.

Table 2 compares the arrival time for different scenarios with normal water level. Flood scenarios with higher discharge peak, and consequently higher sediment amount, arrive faster than those with lower discharge. The average velocity of the turbidity current is calculated by dividing the arrival time by the distance from the model inlet to the reference section.

Table 2: Arrival time of the turbidity current at the dam site for 2-,5-,10- and 20-year floods respectively with n.w.l.

Flood return period (years)	**Flood peak (m^3/s)**	**Arrival time at the dam site (hours)**	**Average velocity of the turbidity current (m/s)**
2	307	30.5	0.10
5	560	29.0	0.11
10	748	28.0	0.11
20	944	25.5	0.12

Venting efficiency

Venting is an operation which should reduce the amount of sediment deposition in the reservoir and thus avoid sedimentation problems in the vicinity of the dam (e.g., bottom outlets clogging). For this reason, the venting efficiency is evaluated with respect to both the global (with respect to entire reservoir) and local (with respect to the area close to the dam) scale. Thus two definitions of venting efficiency are applied (Chamoun et al., 2017):

- *Global venting efficiency*
- *Local venting efficiency*

The first is computed as the ratio between the amount of sediment that passed through the outlets during the venting and the amount of sediments entering the reservoir over the entire simulation:

$$\varepsilon_{global} = \frac{\sum_{time} Q_{sediment\ out}}{\sum_{time} Q_{sediment\ in}(inlet)}$$

The second is computed as the ratio between the amount of sediment passed through the outlets during the venting and the amount of sediment passed through the "reference section" during the entire simulation:

$$\varepsilon_{local} = \frac{\sum_{time} Q_{sediment\ out}}{\sum_{time} Q_{sediment\ in}(reference\ section)}$$

This last definition allows to compute the amount of vented sediments that travelled through the "reference section" and thus reached the area close to the dam.

The venting efficiency for this return period flood event is evaluated for four different bottom outlet openings: 25%, 50%, 100% opening of the main and the second bottom outlet at the same time as well as when the second bottom outlet alone is open at 100%.

Figure 6 shows the time-evolution of the sediment and water inflows and outflows for the four venting scenarios for a 2-year flood event. In Figure 7 the obtained values of venting efficiency are compared for different outlet openings. It is found that the local efficiency for the case with 25% opening of bottom outlets is half of the case with 100% opening. While the local efficiency value reduces only 10% for the case with 50% opening comparing to the case with 100% opening. The obtained results with 100% opening of the second bottom outlet alone are similar and slightly better (regarding the venting efficiency) compared to the results obtained with 50% opening of both outlets.

Considering the global venting efficiency, the 100% opening leads to an efficiency almost five times higher than the 25% opening and 2 times higher than the 50% opening.

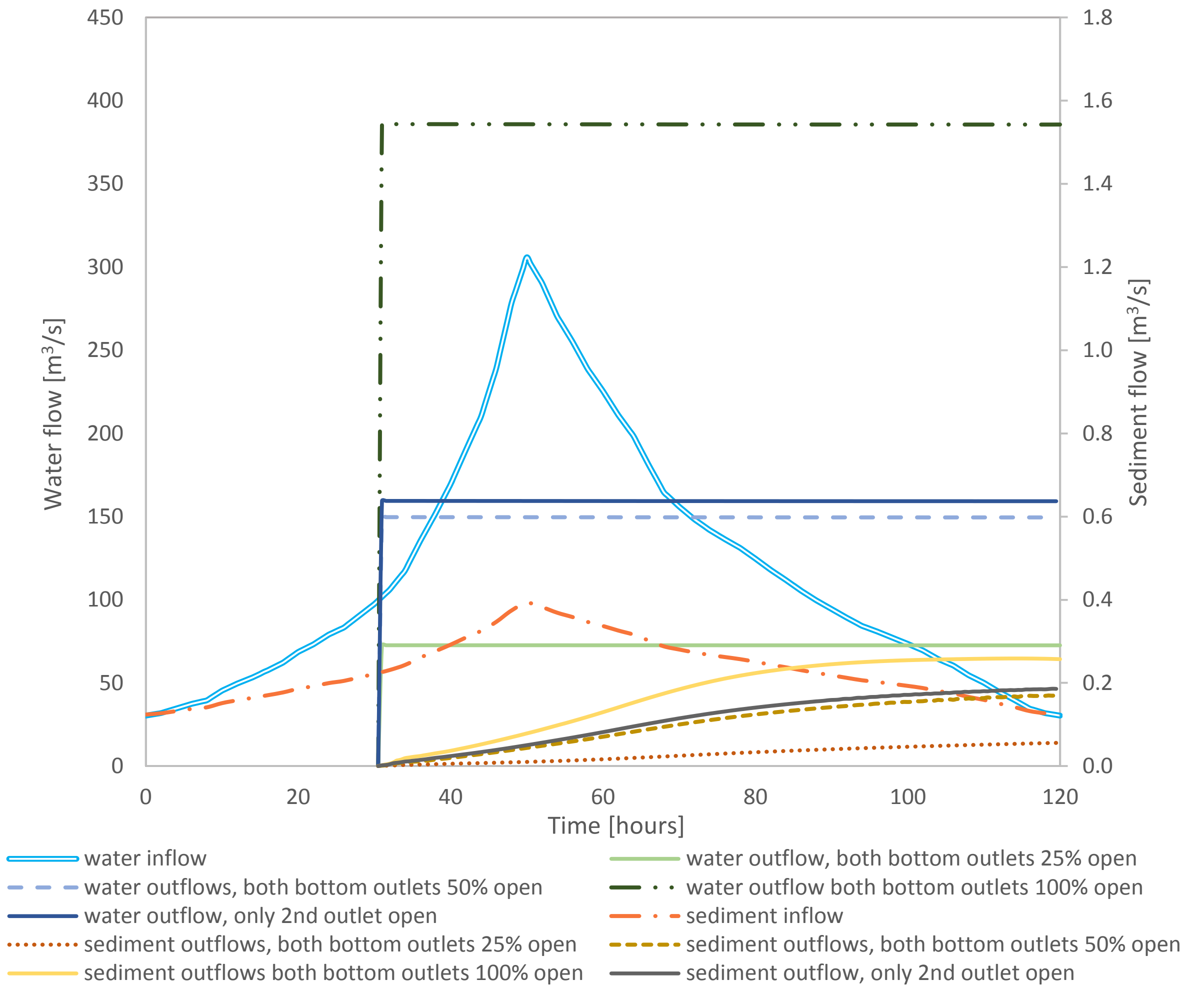

Figure 6: Sediment and water inflows and outflows for a 2-year flood event with 100%, 50% and 25% opening of both bottom outlets and when the second outlet is 100% open and the main one is closed.

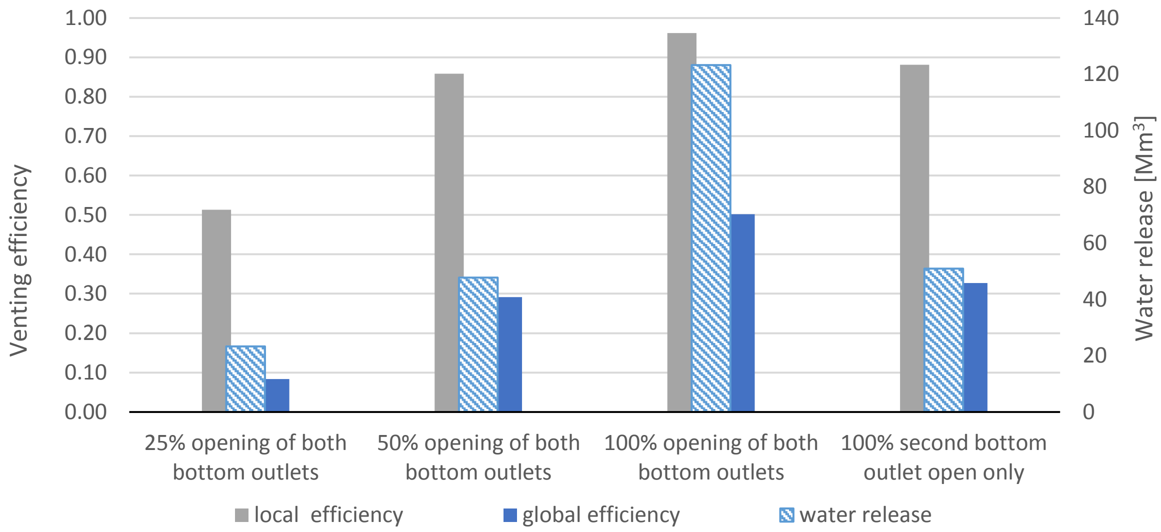

Figure 7: Global and local venting efficiency and water release comparison for different bottom outlet openings (for a 2-year flood)

Table 3 allows comparing the obtained venting efficiencies and water release values for a 2-year flood and scenarios with normal water level (n.w.l.) and minimum water level (m.w.l.). The water level in the reservoir influences the amount of water released. Considering the same opening of the bottom outlets, the higher the reservoir water level the higher the amount of released water.

Moreover, the global venting efficiency is slightly higher when the initial reservoir water level is lower. However, there is almost no difference in terms of local efficiency when comparing normal and minimum water level simulations for the 50% and 100% opening results. The difference is more significant for simulations with 25% opening of outlets.

Table 3 : Comparison between the obtained venting efficiency values (for a 2-year flood)

Parameter	Scenario	Efficiency for n.w.l.	Efficiency for m.w.l.	Difference
Local efficiency	both bottom outlets 25% open	51%	76%	25%
	both bottom outlets 50% open	86%	88%	2%
	both bottom outlets 100% open	96%	97%	1%
Global efficiency	both bottom outlets 25% open	8%	19%	11%
	both bottom outlets 50% open	29%	33%	4%
	both bottom outlets 100% open	50%	59%	9%
Water release (Mm^3)	both bottom outlets 25% open	23.3	20.8	2.5
	both bottom outlets 50% open	47.8	41.7	6.1
	both bottom outlets 100% open	123.0	103.0	20.0

7. Conclusion

The obtained results are promising and show efficient sediment evacuation through bottom outlets during the venting operation for different scenarios. The study provides general recommendations to enhance the efficiency of venting operations, which are listed below:

- In order not to let the turbidity current slowdown and deposit in the area close to the dam body, it is recommended to open the bottom outlets when the current arrivs at the control section 300m upstream of the dam.
- An opening of only 25% of the bottom outlets is not recommended. It leads to relatively high water losses and low sediment release.
- Opening only the second bottom outlet at 100% while the main bottom outlet is closed leads to similar results as the scenario with both bottom outlets open at 50%.
- The volume of released water during venting is very significant when both bottom outlets are opened at 100%, even for the minimum initial reservoir level, while the venting efficiency does not increase significantly. Thus, this opening configuration is not recommended specially for flood events with a return period less than 10 years.

In a general point of view, opening both bottom outlets at 50% during the flood event leads to about 35% evacuation efficiency; i.e., 35% of the total sediment that inflow to the reservoir will be evacuated. Moreover, more than 80% of sediment that arrives to the dam body can be released downstream. These amounts are much lower for a 25% opening of both bottom outlets. As such, opening both bottom outlets at 50% or keeping one closed and the other open at 100% seems to be the best compromise for not losing too much water and at the same time having efficient evacuation.

8. Acknowledgement

This article is provided with the permission of Iran Water and Power Resources Development Company as owner of Rudbar - Lorestan dam and Hydropower project.

9. References

Chamoun, S., De Cesare, G., & Schleiss, A. J. (2016). Managing reservoir sedimentation by venting turbidity currents: a review. *International Journal of Sediment Research*, *31*(3), 195–204.

Chamoun, S., De Cesare, G., & Schleiss, A. J. (2017). Venting of turbidity currents approaching a rectangular opening on a horizontal bed. *Journal of Hydraulic Research*.

De Cesare, G., Schleiss, A. J., & Hermann, F. (2001). Impact of turbidity currents on reservoir sedimentation. *Journal of Hydraulic Engineering*, *127*(1), 6–16.

Fan, J. (1986). Turbid density currents in reservoirs. *Water International*, *11*(3), 107–116.

Fan, J. (2008). Stratified flow through outlets. *Journal of Hydro-Environment Research*, *2*(1), 3–18.

Georgoulas, A. N., Angelidis, P. B., Panagiotidis, T. G., & Kotsovinos, N. E. (2010). 3D numerical modelling of turbidity currents. *Environmental Fluid Mechanics*, *10(6)*(6), 603–635.

KWPA - Khuzestan Water & Power Authority (2005). Dez Dam Rehabilitation Project, Stage 2, Task 1, Reservoir Operation Review and Sediment Study, unpublished project report, ACRES International in association with Dezab Consulting Engineers.

Lee, F. Z., Lai, J. S., Tan, Y. C., & Sung, C. C. (2014). Turbid density current venting through reservoir outlets. *KSCE Journal of Civil Engineering*, *18*(2), 694–705.

Pöyry, Roudbar Lorestan HPP: Update of hydrology. Unpublished report (2008)

Morris, G., & Fan, J. (1997). *Reservoir sedimentation handbook: Design and management of dams, reservoirs, and watersheds for sustainable use*. McGraw-Hill, New York.

Ren, Z., & Ning, Q. (1985). *Lecture notes of the training course on reservoir sedimentation*. Beijing, China: IRTCES.

Schleiss, A., De Cesare, G., & Althaus, J. J. (2010). Verlandung der Stauseen gefährdet die nachhaltige Nutzung der Wasserkraft [Reservoirs silting and their threat on the sustainable use of hydropower]. *Wasser, Energie, Luft [Water, Energy, Air]*, *102*(1), 31–40 (in German).

Sloff, K., Commandeur, A., & Yang, J.-C. (2016). Models for effective sluicing of turbidity-currents in resevoirs. In G. Constantinescu, M. Gracia, & D. Hanes (Eds.), *River Flow Proceedings* (pp. 868–874). CRC Press.

Yu, W.-S., Hsu, S. M., & Fan, K.-L. (2004). Experiments on selective withdrawal of a codirectional two-layer flow through a line sink. *Journal of Hydraulic Engineering*, *130*(12), 1156–1166.