Proceedings of the 37th IAHR World Congress
August 13 – 18, 2017, Kuala Lumpur, Malaysia

INVESTIGATION OF TURBIDITY CURRENT VENTING FOR TWO DIFFERENT RESERVOIR BED SLOPES

SABINE CHAMOUN(1), GIOVANNI DE CESARE(2) & ANTON J. SCHLEISS(3)

(1,2,3) Laboratory of Hydraulic Constructions (LCH), Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland,
sabine.chamoun@epfl.ch

ABSTRACT

Reservoirs represent an important source of energy that should be preserved and sustained. However, the lifetime of reservoirs is being reduced due to natural processes such as sedimentation. To face this problem, different sediment mitigation techniques are employed in numerous reservoirs. These techniques sometimes require the complete emptying of reservoirs. In the particular case where sedimentation is due to the presence of turbidity currents, the most adequate technique for the evacuation of sediments is by venting these currents through bottom or low-level outlets. Venting is investigated in the present work using an experimental model where turbidity currents are generated and vented under different conditions through a bottom outlet. Several measuring instruments are used to monitor the turbidity currents and two bed slopes are tested. The effect of the slope variation on the release efficiency of venting is studied. Additionally, venting is shown to induce no retrogressive erosion. Results from this research can provide useful input for reservoir operators where sedimentation occurs.

Keywords: Reservoir sediment management; turbidity currents; venting; bottom outlets; slopes.

1 INTRODUCTION

In the last decades, thousands of reservoirs were built around the world due to their multifunctional use. Some reservoirs have a long lifetime and serve efficiently for decades or centuries. However, the efficiency of other reservoirs is endangered by processes hindering their sustainability such as sedimentation. The latter is by definition the transport and deposition of sediments from watersheds into reservoirs during flood events. In the long term, sedimentation reduces the storage capacity of the reservoir, blocks and erodes hydraulic machinery and causes the impoverishment of the downstream river in essential sediments for fish habitats (Kantoush and Sumi, 2010). To reduce the impact of sedimentation, many techniques are being tested and applied worldwide. Some methods consists on managing sediments in the watershed such as reforestation, bypassing etc. Other techniques are applied in the reservoir by drawing down the water level causing retrogressive erosion (i.e., pressurized or free-flow flushing) or by mechanically dredging sediments from the reservoir into the downstream river (Brandt, 2000).

However, in some cases, the transported sediments form sediment-laden currents called turbidity currents. The latter are a type of density current, advancing because of density differences with the clear water of the reservoir (Fan and Morris, 1992). Due to their high sediment concentration, turbidity currents plunge below the clear water surface of the reservoir and can advance along the thalweg until reaching the dam structure. In order to evacuate the sediments introduced by turbidity currents into reservoirs, low-level outlets or intakes should be used to vent the currents once they reach the dam. If no outlet structures are present/operated, the turbidity current hits the dam and forms a muddy lake before settling and filling up the reservoir in the vicinity of the dam. The sediments reaching the dam are generally very fine (i.e., silt and clay). They can solidify and block outlets if they are left to deposit. Therefore, the turbidity current should be ideally transited downstream while it is reaching the dam and not after the deposition of the sediments.

Venting of turbidity currents, if performed under controlled and optimal conditions, can be very beneficial both economically and ecologically. It allows the restoration of the downstream river conditions by providing the required fine sediments while using relatively small release discharges, leading to low water losses. However, venting of turbidity currents requires good knowledge of both operational conditions and turbidity currents' dynamics. Despite the fact that venting is applied in reservoirs around the world (Chamoun et al., 2016a), dam operators are still lacking considerable information that allows them to optimize the release efficiency during venting operations. Several researchers discussed venting turbidity currents but very few investigated this technique quantitatively (Fan, 1986; Lu, 1992; Lee et al., 2014; Chamoun et al., 2017;). The most influential parameters are nevertheless known due to field investigation (Morris and Fan, 1997). In this paper, venting of turbidity currents is investigated using an experimental model. Two bed slopes are tested. The generated turbidity currents are firstly described and characterized. Then, the effect of the slope variation on the efficiency of venting is evaluated.

The experimental model is first described, followed by the test procedure and measuring instruments. Then, the results are discussed: velocity profiles, deposition and venting efficiencies are analyzed. Finally, conclusions and recommendations are provided.

2 EXPERIMENTAL MODEL

The experimental tests are performed in a long and narrow flume of 8.55 m length, 0.27 m width and 0.9 m height. It can be tilted from 0% to a 5% slope. In the present paper, the 2.4% and 5% slopes are discussed. As shown in Figure 1, there are three main compartments in the flume: the head tank, the main flume, and a downstream compartment. The head tank receives the sediment-water mixture from the mixing tank placed below the flume. The main flume represents the reservoir where the turbidity current advances. Finally, the downstream compartment receives the residual water that overflows the wall in order to keep the clear water level constant during the tests. A sliding gate separates the head tank from the main flume. The inlet is placed at the bottom of the sliding gate, and links the head tank to the main flume once the gate is opened. At 6.7 m from the inlet, a wall of 80 cm (for the 2.4% slope) and 92 cm (for the 5% slope) is placed and simulates the dam. It has an opening at the bottom simulating the outlet. The latter is centered on the width of the flume and has a rectangular shape (12 cm x 9 cm).

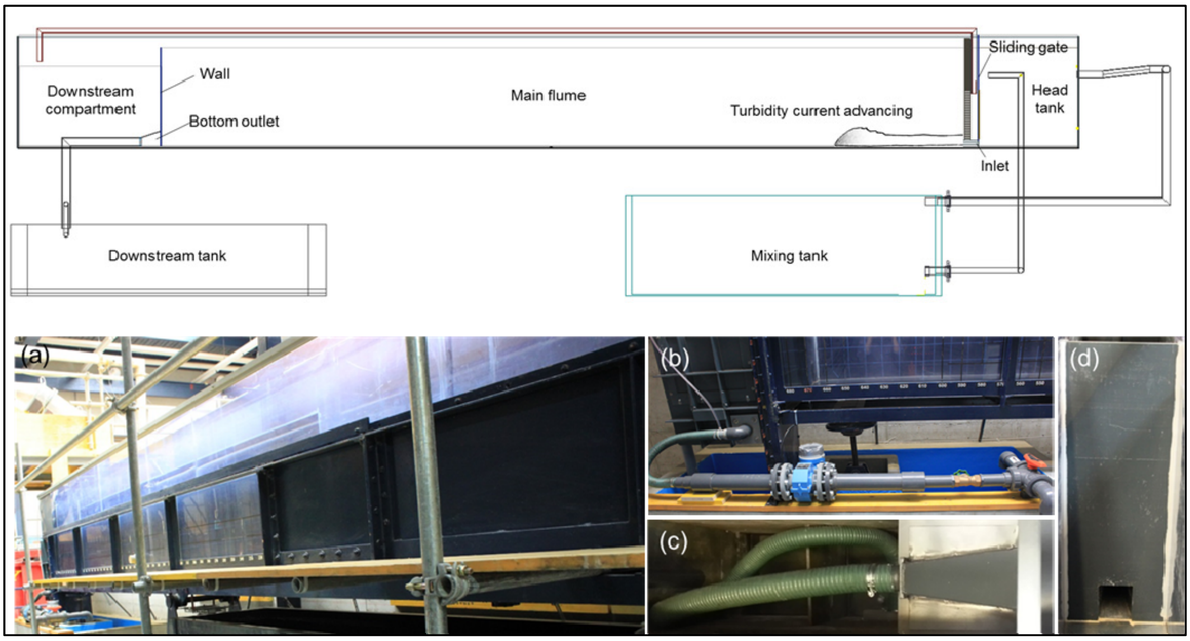

Figure 1. Annotated scheme of the experimental set-up and photos of (a) the main flume, (b) the downstream installation, (c) top view and (d) front view of the bottom outlet.

2.1 Test procedure and measurements

First of all, a water-sediment mixture is prepared in the mixing tank by adding a specific mass of sediments resulting in the required initial concentration of the current. This mixture is continuously mixed using a recirculating pump placed inside the tank. It ensures the suspension of the sediments in the water and thus keeps the concentration constant.

When the mixture is ready, it is pumped into the head tank and is recirculated between both tanks until it reaches the tested concentration in the head tank. Once this condition is fulfilled, the recirculation between the mixing tank and the head tank is stopped and the sliding gate is opened. The mixture is then directly pumped into the main flume. Due to the density difference, a turbidity current is formed and advances on the bed of the flume. The turbidity currents are continuously-fed throughout the duration of the test. Once the current reaches the bottom outlet, venting starts and the current is evacuated with a specified outflow discharge. The released mixture then reaches the downstream basin.

The sediments contained in the turbidity currents are represented by a powdery material (thermoplastic polyurethane). The particle density of the material is ρ_s = 1160 kg/m^3, the characterizing diameters are d_{10} = 66.5 µm, d_{50} = 140 µm, and d_{90} = 214 µm; d_x being the diameter for which x% of the sediments have smaller diameters. Based on the d_{50}, the settling velocity v_s was estimated by 1.5 mm (Stokes' Law and Cheng, 1997).

Care was taken to generate turbidity currents having steady and similar initial conditions (i.e., inflow discharge and concentration). Throughout the tests, different measurements were undertaken to characterize the turbidity currents generated and control the operation of venting:

i. The initial and outflow concentrations C_{TC} and C_{VENT} were measured in the head tank and in the downstream basin respectively using calibrated turbidity probes.
ii. The initial and outflow discharges Q_{TC} and Q_{VENT} were measured in the pumping pipe between the head tank and the mixing tank and at the pipe used for venting (Figure 1.b) respectively.
iii. Deposition was measured in space and time using an electrical resistance-based depositometer (De Rooij et al., 1999). It is formed by two electrodes. A reference electrode is suspended 50 cm above the bed of the flume and 62 bottom electrodes are implemented inside the bed of the flume. Bottom electrodes are separated by 10 cm; the first one is placed 10 cm downstream of the inlet and the last one 620 cm from the inlet (50 cm from the outlet). Through a calibration procedure (Chamoun et al., 2016b), the electrical resistance measured between the reference and bottom electrodes was then converted to a mass (or thickness) of sediments. Therefore, deposition was measured during the whole test at 62 different points.
iv. Velocity profiles are measured using UVP (UVP, Metflow, Switzerland, 2014) transducers placed at 6 different locations of the main flume (i.e., 2.8 m, 4.1 m, 5.5 m, 5.8 m, 6.0 m, and 6.2 m from inlet).
v. Water levels in the head tank and in the main flume were measured using ultrasonic level probes.
vi. Temperatures in the head and in the main flume were measured before and after the test, to make sure that density differences are majorly due to the suspended sediments and not due to a temperature difference between the mixture and the clear water.
vii. Videos and photos were recorded throughout the tests using a camera placed in front of the flume.

3 RESULTS

3.1 Tests

The considered tests are shown in Table 1. Two bed slopes were tested: 2.4% and 5.0%. The initial concentration of turbidity currents generated are of 26 g/l on average. Apart from reference tests where no venting was applied, two different venting degrees were tested. The latter represent the ratio between the outflow discharge Q_{VENT} and the turbidity current inflow discharge Q_{TC}. The latter is constant for all the tests and Q_{TC} = 1 l/s. Figure 2 below shows an example of a typical turbidity current while approaching the wall (at 620 cm from the inlet) before venting is applied.

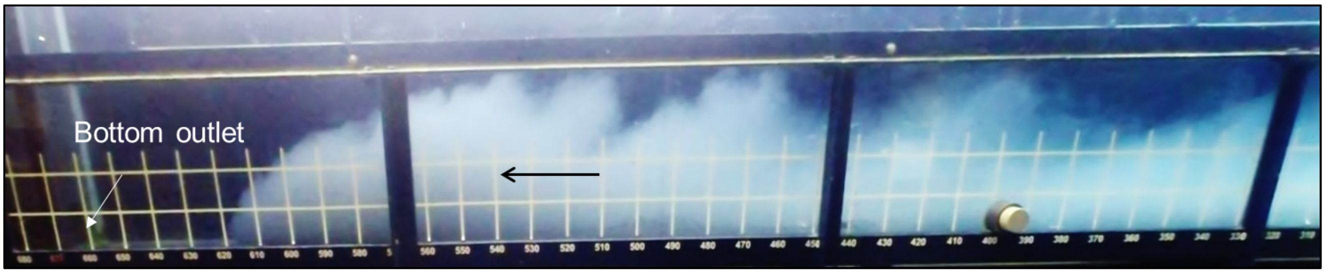

Figure 2. The turbidity current approaching the bottom outlet on the 2.4% slope.

Table 1. Characteristics of the tests.

Slope s (%)	Initial concentration C_{TC} (g/l)	Initial density ρ_{t0} (kg/m^3)	Venting degree Φ (%)
2.4	26.1	1003.3	0
2.4	28.4	1003.6	50
2.4	22.1	1002.7	100
5.0	22.8	1002.8	0
5.0	28.7	1003.6	50
5.0	26.2	1003.3	100

3.2 Velocity

Velocity profiles of turbidity currents provide useful information for their characterization. The profiles taken by the UVP at 4.1 m from the inlet are used to characterize the currents (Figure 3) in terms of velocity U and height h. Turner's equations are used for this goal (Ellison and Turner, 1959):

$$Uh = \int_0^\infty u dz = \int_0^{h_t} u dz \qquad [1]$$

$$U^2 h = \int_0^\infty u^2 dz = \int_0^{h_t} u^2\, dz \qquad [2]$$

where u and z are the local velocity and height, respectively, measured by the UVP profiles and h_t is the height at which u tends to 0.

Based on the velocity and height determination (results are shown in Figure 3), the regime of the currents can be determined through the estimation of Richardson number $Ri = (g'H\cos\alpha)/U^2$ where g' is the estimated reduced gravity at 4.1 m from the inlet (average of the initial reduced gravity g'_0 and the reduced gravity during the approach of the current to the bottom outlet). Additionally, the turbulence rate of the current can be quantified by Reynolds number $Re = UH/v$ where v is the kinematic viscosity of water.

The velocity obtained on the 2.4% slope $U_{2.4} < U_{5.0}$ obtained on the 5.0% slope. Since equal inflow discharges are applied at the inlet for all the tests, the height $h_{2.4} > h_{5.0}$. Reynolds numbers calculated for both slopes are $Re_{2.4} = 6600$ and $Re_{5.0} = 7070$ showing that the currents are fully turbulent (condition applied when Re > 2000 as suggested by Kneller and Buckee (2000)).

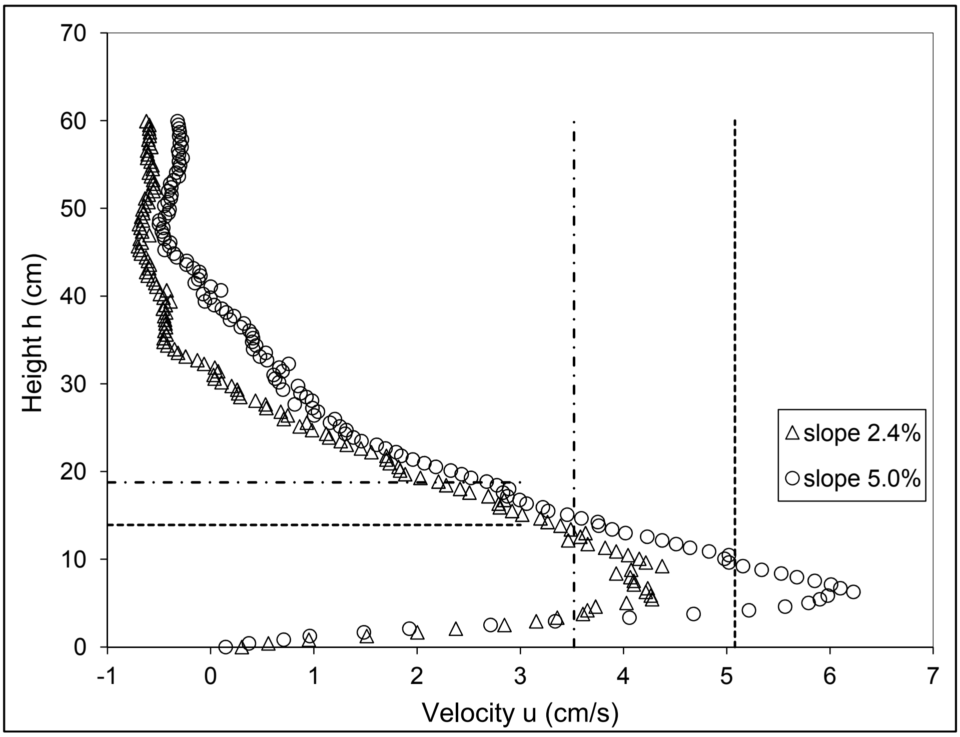

Figure 3. Averaged velocity profiles obtained on the 2.4% and the 5.0% slopes.

3.3 Deposition

The variation of deposition in time and space is shown in Figure 4. Each of the curves corresponds to the deposition in space accumulated during a time step of $\Delta t = 30s$. The gray curve corresponds to the deposition obtained when the current reaches the wall and venting starts.

Spatially, the highest deposition occurs close to the inlet due to the phase of development of the current where the coarse sediments settle. While it advances, the deposition mass decreases because the sediments contained in the current become finer. Temporally, a first phase of high depositional rate can be observed which is also explained by the phase of development of the current. This is followed by a decrease approaching a steady rate of deposition. This is probably linked to the arrival of the current to the wall and the formation of the muddy lake. At this stage, the deposition decreases and more sediments are suspended. A better assessment of the temporal variation of the deposition is done by plotting the integral of the sediment mass in time.

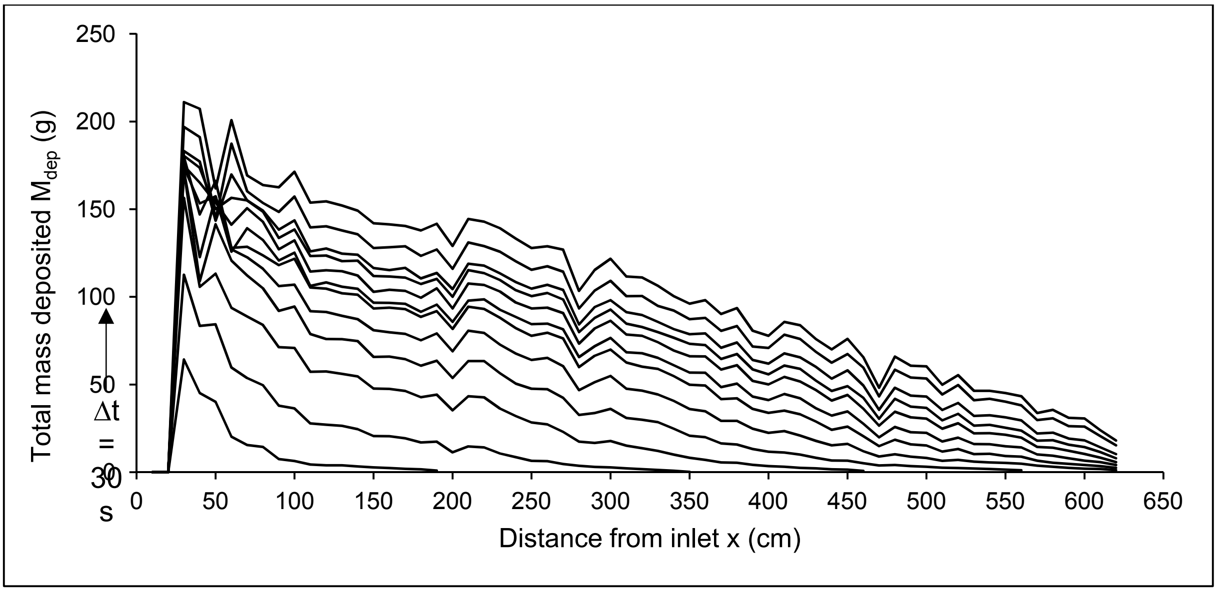

Figure 4. Variation of deposition in time and space obtained on the 2.4% bed slope using a venting degree Φ = 50%.

Figure 5 and Figure 6 below show the variation of the total deposited mass M_{deptot}, normalized by the total inflow mass M_{TCtot} relatively to time t (t = 0 corresponds to the beginning of the test) for each of the slopes used and for the three cases of outlet discharge (Φ = 0%; 50% and 100%). Reference lines were added for the cases where venting was performed and correspond to the time at which the outlet was opened (arrival of the current to the wall).

First of all, the currents are shown to be highly depositive. Deposition increases the most during the phase before the current reaches the wall, which corresponds to more or less the first 150s for all cases. Then, around the time where the current reaches the wall, a slow decrease in deposition is observed, for all the cases. The variation of the relative deposition is very similar when comparing the reference test (Φ = 0%) with the tests where venting was applied with Φ = 50% and Φ = 100%. This means that the venting operation itself does not induce an effect on the deposition and unlike flushing for instance, does not cause a retrogressive erosion. However, one shall note that deposition is measured until 620 cm from the inlet while the wall is located at 670 cm. The effect on deposition might be present in the closer vicinity of the wall where deposition is not measured.

The major effect on the variation of deposition seems to be due to the arrival of the turbidity current to the wall, rather than to the operation of venting. When it reaches the wall, the turbidity current rebounds and is reflected upstream. Therefore, more sediments are suspended and deposition is slowed down due to the formation of the muddy lake.

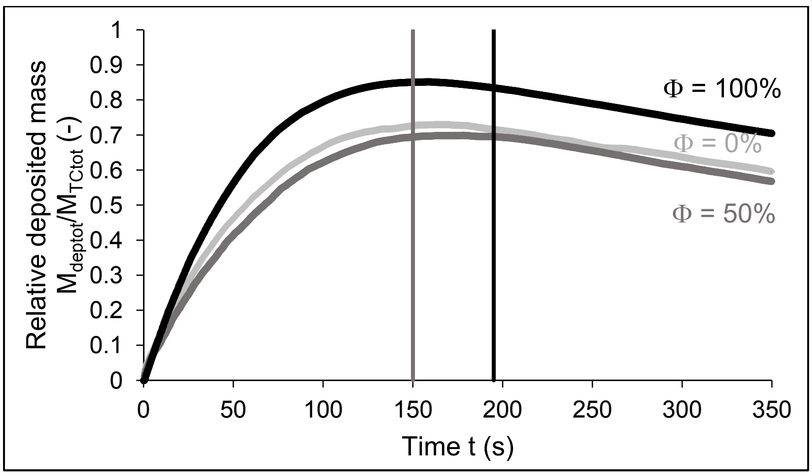

Figure 5. Variation of the relative deposited mass in time for the 2.4% slope.

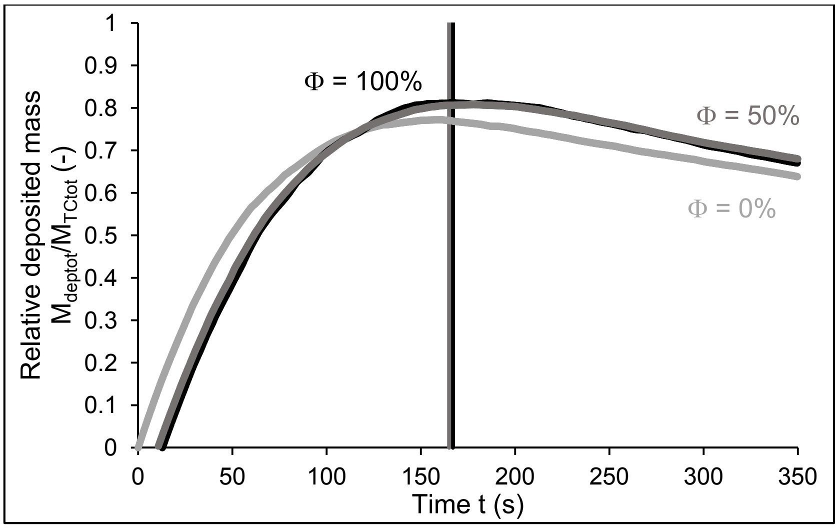

Figure 6. Variation of the relative deposited mass in time for the 5.0% slope.

3.4 Efficiency of venting

The efficiency of venting is evaluated using the criteria of the local venting efficiency LVE (Chamoun et al., 2017) which is defined by the ratio between the total vented mass of sediments $M_{VENTtot}$ to the total inflow (turbidity current) mass of sediments M_{TCtot} while subtracting the total deposited mass from the total inflowing mass M_{deptot}. This subtraction is done due to the fact that there is not retrogressive erosion caused during venting. By accounting for the deposited sediments within the inflowing sediments, the efficiency of venting will be artificially decreased. In Figure 7 and Figure 8 below, LVE = $M_{VENTtot}/(M_{TCtot}-M_{deptot})$ is applied at each time step and the results are compared for the two cases of bed slopes and for two different venting discharges Φ = 50% and Φ = 100%. The time $t-T_v$ where T_v is the time at which venting begins.

The results show that by increasing the bed slopes, higher venting efficiencies are obtained. Venting efficiencies generally increase at the beginning of the operation for both slopes before stabilizing or slowing decreasing for the rest of the venting duration. The increase is due to the arrival of the turbidity current and the formation of the concentrated muddy lake. The slow decrease can be explained by the upstream reflection of the continuously-fed turbidity current.

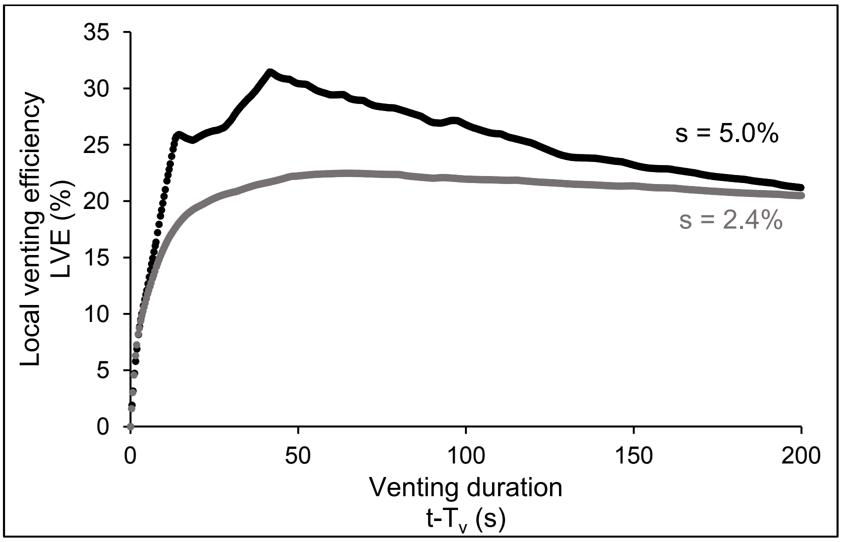

Figure 7. Local venting efficiency LVE in time for the two different slopes using a venting degree Φ = 100%.

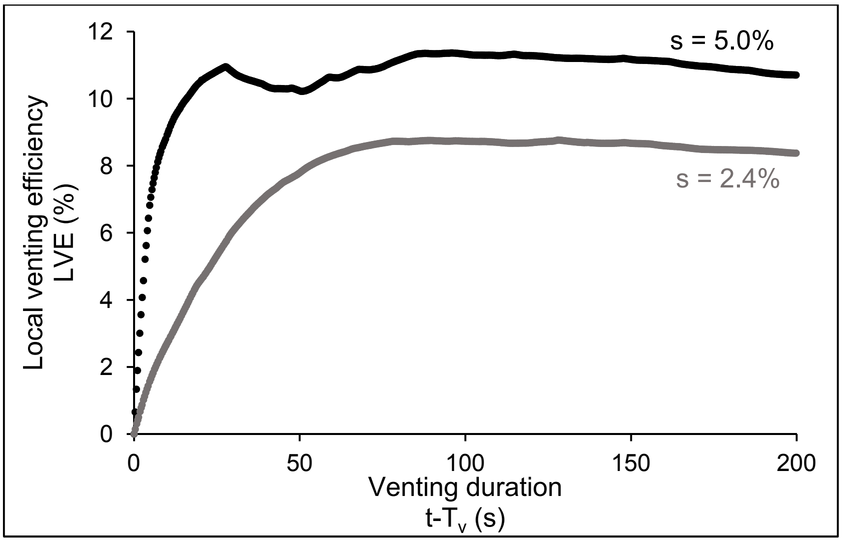

Figure 8. Local venting efficiency LVE in time for the two different slopes using a venting degree Φ = 50%.

4 CONCLUSIONS

Reservoir sedimentation is a global issue causing the loss of storage capacity of reservoirs as well as the blockage and abrasion of outlet structures and hydraulic machineries. Downstream impoverishment also results due to the lack of sediments transited. In the case where sedimentation is due to the presence of turbidity currents, venting through outlets or intakes should be considered.

In the present work, venting of turbidity currents through a bottom outlet is investigated experimentally using two different bed slopes (i.e., 2.4% and 5.0%). Two venting degrees (relative outlet discharge) are discussed (i.e., 50% and 100%) as well as reference tests where venting was not applied.

The measuring instruments used throughout the tests allowed a good understanding of the type of turbidity currents vented, by determining the regime, the Reynolds number and characterizing height and velocity. This information is useful when upscaling to prototype conditions. On another hand, deposition showed that the venting operation did not induce any retrogressive erosion as far as 50 cm from the outlet. Additionally, venting efficiencies were assessed in time and showed an increase with an increasing slope and for the same venting degree. Therefore, the steeper the thalweg in the vicinity of the dam, the higher the venting efficiencies.

Finally, venting of turbidity currents is one of the most favorable technique of sediment mitigation in reservoirs in both economic and environmental terms. Many parameters can affect the efficiency of this operation. These can be related to the morphology, hydrology, shape of the reservoir, outlet characteristics and the operation itself. However, for a healthy downstream environment, both coarse and fine sediments are required. Therefore, venting should also be combined with other techniques that is able to transport the coarse sediments located mostly at the upstream region of reservoirs.

ACKNOWLEDGMENTS

The study titled ''Efficiency of turbidity currents venting under varied outflow discharge'' was funded by Swisselectric Research and the Swiss Committee on Dams.

REFERENCES

Brandt, S.A. (2000). A Review of Reservoir Desiltation. *International Journal of Sediment Research*, 15(3), 321–342.
Chamoun, S., De Cesare, G. & Schleiss, A.J. (2016a). Managing Reservoir Sedimentation by Venting Turbidity Currents: A Review. *International Journal of Sediment Research*, 31(3), 195–204.
Chamoun, S., Zordan, J., De Cesare, G. & Franca, M.J. (2016b). Measurement of the Deposition of Fine Sediments in a Channel Bed. *Flow Measurement and Instrumentation*, 50, 49–56.
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*, 1-15.
Cheng, N. (1997). Simplified Settling Velocity Formula for Sediment Particle. *Journal of Hydraulic Engineering*, 123(2), 149–152.
De Rooij, F., Dalziel, S.B. & Linden, P.F. (1999). Electrical Measurement of Sediment Layer Thickness under Suspension Flows. *Experiments in Fluids*, 26(5), 470–474.
Ellison, T.H. & Turner, J.S. (1959). Turbulent Entrainment in Stratified Flows. *Journal of Fluid Mechanics*, 6(3), 423–448.

Fan, J. (1986). Turbid Density Currents in Reservoirs. *Water International*, 11(3), 107–116.

Fan, J. & Morris, G.L. (1992). Reservoir Sedimentation II: Reservoir Desiltation and Long-Term Storage Capacity. *Journal of Hydraulic Engineering*, 118(3), 370–384.

Kantoush, S. A. & Sumi, T. (2010). River Morphology and Sediment Management Strategies for Sustainable Reservoir in Japan and European Alps. In *Annuals of Disaster Preventive Research Institute, 53,* 821–839. Kyoto, Japan.

Kneller, B. & Buckee, C. (2000). The Structure and Fluid Mechanics of Turbidity Currents : A Review of Some Recent Studies and their Geological Implications. *Sedimentology*, 47(s1), 62–94.

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.

Lu, X. (1992). An Approximate Method for Calculating The Efficiency of Venting Density Current Through Outlet. In *5th International Symposium on River Sedimentation,* 829–835. Karlsruhe.

Metflow, S. (2014). *UVP Monitor - User's guide*, Lausanne, Switzerland.

Morris, G. & Fan, J. (1997). *Reservoir Sedimentation Handbook: Design and Management of Dams, Reservoirs, and Watersheds for Sustainable Use*. McGraw-Hill, New York.