Short- and long-term storage volume recovery in a reservoir using a combined mixing-dredging device

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Long-term sustainable operation of hydropower plants and dam reservoirs is threated by reservoir sedimentation [1]. Settling of suspended sediment may reduce reservoir live storage available for hydropower production. Mitigation measures are then necessary to cope with the reservoir sedimentation challenge.

An innovative mixing device was studied recently in the Laboratory of Hydraulic Constructions (PL-LCH) at EPFL [2]. The device (called SEDMIX) induces an adequate level of upwind turbulence preventing sediment from settling near the dam, keeping them in suspension for progressive evacuation through the power intake during normal operation of the hydropower plant. This innovative system can be potentially installed in reservoirs to avoid reservoir siltation due to fine sediments transported by turbidity currents. Its efficiency has already been examined numerically in Trift reservoir [3,4] and for the present study, the performance of SEDMIX using thrusters instead of the previous configuration with water jets is assessed.

On the other hand, the HMS has designed and patented an unmanned floating unit dedicated to the removal of all types of sediments present in the basins. This floating ROV (Remoted Operated Vehicle) is governed by a precision GPS and underwater instrumentation that comes from the offshore experiences of Hydro Maintenance Service (HMS). The 3 D DREDGER ™ (3DD), this is the name of the ROV, operates 24/-24 hours, 365 days a year, removing sediment, with great cost savings being able to count on 8,000 operating hours. The 3 D DREDGER ™ can operate with a wide range of "tools": bucket, dredging pump, any special device useful to maintain safety conditions inside the basin.

A joint research and development project is then ongoing to promote the installation of the first prototype of SEDMIX-3DD in Alpine reservoirs. The project aims to demonstrate the effectiveness of the combined device, firstly to clean the reservoir and secondly to maintain it in long-term acceptable conditions. The mobile mixing device SEDMIX plus the 3DD that manages the SEDMIX mixer, will be tested in a selection of Alpine reservoirs to show its efficiency in different conditions. The expected outcome is (i) to validate the flushing efficiency as compared to laboratory development conditions; (ii) to characterize the dependence from local conditions; (iii) to identify practical difficulties and shortcomings of field implementation; (iv) to control the modifications to the sediment regime in the river downstream of the powerhouse as well as in the residual flow, and the resulting environmental impacts.

This paper discusses the performance of SEDMIX with thrusters the technical specifications of the combined SEDMIX-3DD device.

1. Two innovative systems

Reservoir sedimentation is a serious long term problem when incorporating a dam in a natural flow. The kinetic energy of the natural river flow decreases when entering to the reservoir along with its sediment transport capacity, which leads to a higher sediment deposition, reducing through time the global reservoir capacity and therefore affecting energy production, flood control and water management [5]. There are some mitigation measures to cope with reservoir sedimentation that are currently applied worldwide [6]. Some of the standard counter-measures are classified in Table 1.

Nevertheless, some of those methods are not always considered sustainable and its efficiency vary widely. Jenzer-Althaus (2011) tested an alternative method for fine sediment release that consists in a stirring device (SEDMIX) which is composed of a set of four water jets that provide the energy to generate a recirculating flow that keeps in suspension the fine sediments in water, enhancing its release through the power water intakes of the reservoir during the operation of the hydropower plant [2].

Table 1. Existing counter measures to mitigate sedimentation in reservoirs

Counter-measure	**Disadvantage**
Full draw-down flushing	Uncontrolled sediment concentration downstream
Sediment flushing downstream with a suction pipe	More controlled but high sediment concentration downstream
Removal of sediment by mechanical means with an empty basin.	Expensive, energy loss due to production stopping
Removal of sediment with dredgers	Expensive and technically difficult
Sediment bypass tunnel	Expensive
Desander basins	Not very efficient, only bed load transit

On the other hand, the HMS has designed and patented an unmanned floating unit dedicated to the removal of all types of sediments present in the basins (Figure 1). This floating ROV (Remoted Operated Vehicle) is governed by a precision GPS and underwater instrumentation that comes from the offshore experiences of HMS. The 3 D DREDGER ™ (3DD), this is the name of the ROV, operates 24/-24 hours, 365 days a year, removing sediment, with great cost savings being able to count on 8,000 operating hours. The 3 D DREDGER ™ can operate with a wide range of "tools": bucket, dredging pump, any special device useful to maintain safety conditions inside the basin.

The 3D DREDGER system solves the problem of the presence of sediment with the following solutions.

1. An unmanned floating platform to allow stable flotation and the possibility of lowering sediment removal equipment shall operate on the surface of the dock.
2. The tool may consist of a dredging pump or an excavating bucket:
    a. The dredging pump is used if the sediment is exclusively fine - < 40 mm - In this case a pipe conveys the mixed sediment to the ground with aspirated water and is then treated.
    b. The bucket is used in all other cases. In this case, the raised, closed and full of sediment bucket is transported from the float to the shore where the open bucket discharges into an underwater hopper that conveys the sediment to the ground.
3. The floating platform is controlled by at least 3 mooring winches permanently positioned on the ground or on board so as to create the widest working field, positioned above the bank of sediments to be removed.
4. A precision GPS RTK (Real-time Kinetics) system and a programmable unit govern the cycle of sediment removal that takes place with "no stop" methodology, working 24/27-7/7-365/365.
5. Sensors integrated in the 3DD underwater and surface system allow to know in real time for example:
    a. the load of the bucket
    b. the configuration of the reservoir bottom
    c. the tension of the mooring lines
    d. wind speed and lake surface condition
    e. the presence of ice on the surface of the lake
6. The program that governs the system can implement a programmable and optimized "excavation strategy" in real time, with feedback that brings the 3DD system into the category of CNC systems (Continuous Numerical Control).

The DREDGER System 3 D is a strong innovation in the field of sediment management in water basins. It is the first application in the world of a complex, modular, structural system with the plant that acts continuously (24/24 – 7/7 – 365/365) to counteract an action that is continuous, avoiding expensive and "spot interventions" that often have special and ad-hoc designed equipment. The 3D DREDGER can also solve sedimentation problems in watercourses or ports where normal dredgers cannot work because of draughts or encumbrances. The 3 D DREDGER is very compact, so it can be used for small operations, manually operated.

Fig. 1. 3DD system with its three floaters

3. Background study

3.1 Experimental tests in a laboratory basin

Jenzer-Althaus (2011) studied experimentally and numerically the perpendicular configuration of four jets arranged in a horizontal plane and set in a regular tank of 2 m wide, 4 m long and 1.5 m deep. These jets generate a flow similar to the one produced by a mechanical mixer, and depending on the depth the device is located and the discharge of the jets, the flow behaves as if it was controlled by a radial or axial mixer. Various diameters of the water jets, discharges and depths of the device were tested and the optimal values for sediment release were obtained when the flow pattern resembled to an axial mixer flow for the traversal plane and to a radial mixer flow for the longitudinal plane.

The maximum sediment release efficiency in the tank was of 73% after 4 hours using the SEDMIX device, versus 37% without it. In order to assess the efficiency of the configuration of the device, the Evacuated Sediment Ratio was used, which is expressed as the evacuated sediment weight P_{out} divided by the sediment weight supplied initially P_{int} [2].

$$ESR = \frac{P_{out}}{P_{int}} \qquad (1)$$

3.2 Numerical simulations of SEDMIX using jets inside the Trift reservoir

Experimental studies have previously reported that the SEDMIX device has a high efficiency, and this method has found to be sustainable and environmentally friendly [2-4], however, its performance has never been tested in a real-life reservoir.

Due to the current glacier retreat, Switzerland is planning to build various dams to promote the generation of sustainable energy as part of its 2050 energy strategy, and one of those projects is the Trift dam, developed by Kraftwerke Oberhasli SA (KWO) and located in Berner Oberland which is intended to have a volume of 85 million cubic meters and produce 118GWh per year [3]. The SEDMIX device could be implemented for the first time in this reservoir, therefore this has been selected as case of study to test numerically the SEDMIX device performance for the present investigation using a configuration of thrusters and in past studies using water jets [3,4].

The present study presents the performance of the SEDMIX device using a set of thrusters instead of water jets to produce the upward whirling flow needed to maintain in suspension and later release the fine sediments in water in the Thrift reservoir using computational hydraulic modelling, considering the optimum location and dimensions previously determined by Amini et al. (2019) [8].

According to Jenzer-Althaus (2011), to upscale the device to real-life dimensions for the Trift reservoir two conditions should be satisfied: The circulation velocity should be equal or higher than the settling velocity and Froude similarity should be reached, which relies on the geometrical factor l_L expressed as the discharge ratio between the real case and the prototype.

$$l_L = l_Q^{\frac{2}{5}} \qquad (2)$$

For the study carried out by Amini et al. (2019), the scaling factor l_L obtained was 38 considering a total discharge of 5 m^3/s [8].
For the Trift reservoir, several simulations have been developed in the past using water jets and considering steady state and transient flow conditions, single phase (no sediments) and multiphase scenarios, different discharges and variating the position of the SEDMIX device with relation to water intake [3,4]. Amini et al. (2017) obtained an evacuated sediment ratio of 70% when using the SEDMIX device with a different configuration and a jet discharge of 1m3/s, being the evacuation of only 14% when SEDMIX was not used, which demonstrated an increase the sediment release to the downstream when using the stirring device. Furthermore, Chraibi et al. (2018) [4] confirmed that the SEDMIX device does create a vortex flow pattern, which move the sediments upward increasing the volume fraction in the higher fluid layers. His research also determined that the optimal discharge for the SEDMIX water jet configuration was 5 m^3/s and that the optimal position for the highest evacuation of sediments is right in front of the water intake

4. Methodology

4.1 Using Thrusters

The use of thruster in the SEDMIX device has been proposed as an alternative to avoid dealing with head losses encountered in the previous prototype that used water jets, supposedly decreasing operational costs due to less power requirements. The configuration of the thrusters would be the same as the one for the water jets, four thrusters with the same diameter arranged in a square in a horizontal plane and facing perpendicularly to the neighbouring thruster so a rotational flow can be produced. For the joint project, SEDMIX would be attached to the 3D DREDGER's floating platform as it is shown in Figure 2.
For the selection of the adequate thrusters to use for the SEDMIX device, the efflux velocity is calculated, which is the mean axial flow velocity just in front of the thruster, in order to determine the maximum flow, the thrusters would be able to provide. Albertson et al (1948) [9] derived the following efflux velocity formula by using the axial momentum theory:

$$U_0 \approx 1.60 \cdot n \cdot D \cdot \sqrt{K_t} \tag{3}$$

Where U_0 is the efflux velocity in m/s, n is the rotational speed of the propeller in RPS, D is the diameter of the propeller in m and K_t is the thrust coefficient, which according to Blaauw & Van de Kaa (1978) [10] it is calculated using the following formula:

$$K_t = \frac{T}{\rho \cdot n^2 \cdot D^4} \tag{4}$$

Where ρ is the water density in kg/m^3 and T is the thrust in Newton.

Fig. 2. Schematic view of SEDMIX device with thrusters attached to the 3DD floating platform.

5. Numerical simulation of SEDMIX with thrusters in a laboratory tank

5.1. Geometry and model setup

In a first instance, in order to compare the behaviour of the thrusters with the water jets, the simulation of the SEDMIX device in a regular tank was carried out using ANSYS 2019 R1 software (Figure 3), in order to obtain their flow patterns and compare them with the experimental ones obtained by Jenzer-Althaus (2011) [2]. Various numerical simulations were performed considering the same dimensions of the tank as in [2], changing the bottom clearance to C/B = 0.1, 0.175 and 0.25, using the k-ε turbulence model and running in steady state, and considering a single-phase flow. The jets were modelled as inner sources and the thrusters as a combination of inner sinks and sources to avoid having to refine elements in the device region [3]. The diameter of the jets was set as 3 mm and the diameter of the thruster as 75 mm.

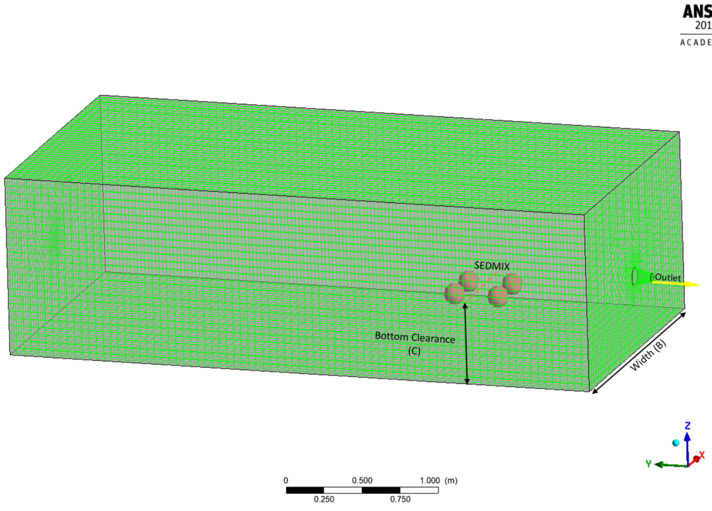


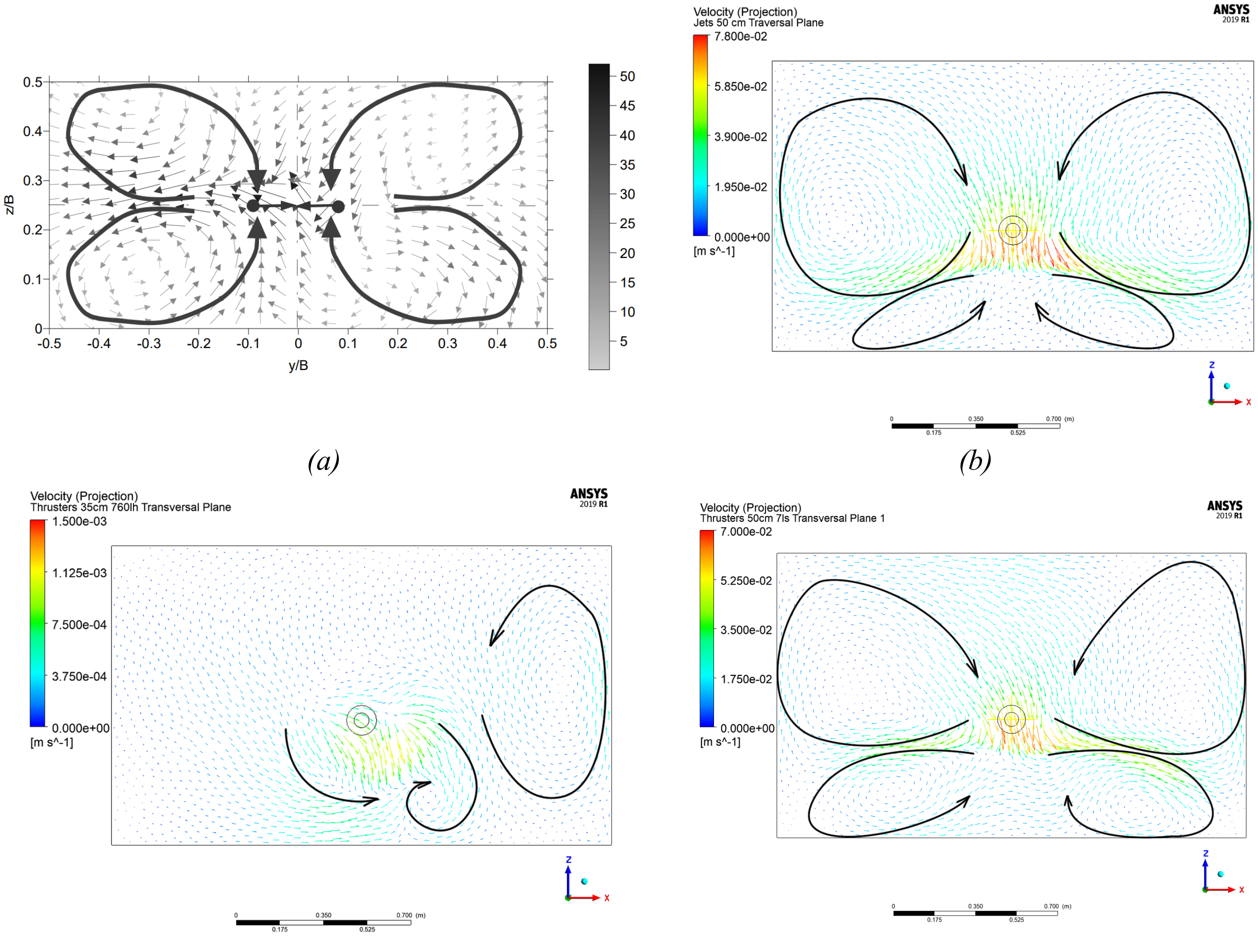
Fig. 3. Numerical model of the regular tank.

5.2. Boundary and initial conditions

The boundary conditions applied to the model were: no-slip wall, smooth surface condition for the free surface, no-slip wall condition for the bottom and tank walls, an incoming flow Q_{in} of 760 l/h supplied by the source points as inlet in the water jets scenario, and at the back of the tank for the thrusters' scenario. The thrusters had a flow equal to the water provided by the inlet in a preliminary simulation, to later be increased to 7.2 l/s as explained before. The outlet considered a relative pressure of 0 at the water intake.

5.3. Results and analysis

The flow patterns obtained through the numerical simulation of the regular tank and the SEDMIX device with water jets are similar to the ones obtained by Jenzer-Althaus (2011) [2] (Figure 4a) for the three bottom clearance values tested, as it is shown in Figure 4b. Using the same SEDMIX configuration, the jets were replaced for thrusters maintaining the same flow as the one considered for the jets (760 l/h for the whole system), nevertheless, being the diameter of the thrusters considerably bigger than the diameter of the jets, the thruster velocity was too small to reproduce the flow patterns expected, as it can be seen in Figure 4c, therefore, the thrusters flow was adjusted to consider a higher velocity at each thruster, obtaining a similar flow pattern when applying a discharge of 7.2 l/s, as shown in Figure 4d.



(a) *(b)*

(c) *(d)*

Fig. 4. a) Flow pattern obtained experimentally for jets for a bottom clearance of 0.5 m [2]. b) Flow pattern of numerical simulation for jets 760 l/h. c) Flow pattern of numerical simulation for thrusters using a flow of 760 l/h. d) Flow pattern of numerical simulation for thrusters using a flow of 7.2 l/s.

6. Numerical simulation of SEDMIX with thrusters in Trift reservoir

6.1. Geometry and model setup

The geometrical dimensions of the SEDMIX device and its location in the Trift reservoir was kept the same as the optimal determined by Chraibi et al. (2018) [4] for the implementation of the thrusters' configuration (Figure 5). The device was placed close to the dam just in front of the water intake. As for the simulations in the tank, the thrusters were modelled as a set of sink and source points, and various numerical simulations were performed using the k-ε turbulence model and running in steady state, with a multiphase flow with a constant flowrate of 21002.7 kg/s, considering sediments with a concentration of 0.7 g/L, a mean particle diameter (D_s) of 0.1mm, and with a density (ρ_s) of 2600 kg/m^3. Three different diameters of thrusters were considered for the simulations: 27 cm, 37.5 cm and 42 cm. Each of those thrusters had its own thrust force and rotational speed.

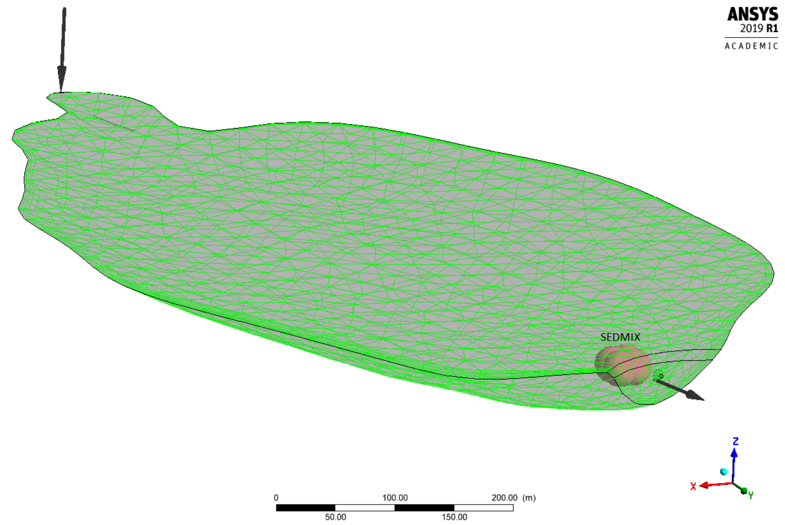


Fig. 5 Numerical model of the Trift Reservoir.

6.2 Initial and boundary conditions

The boundary conditions applied to the model were: no-slip wall, smooth surface condition for the free surface, no-slip wall condition for the bottom and tank walls with a roughness of 0.1 m. At the inlet, a constant inflow Q_{in} of 21m^3/s is set and the outlet considered a relative pressure of 0 at the water intake to avoid convergence problems. Several simulations were run with various flows supplied by the thrusters for the diameters considered, depending on the maximum efflux velocity that they could provide, in order to determine what would be the characteristics of a thruster capable of obtaining a comparable sediment release as the one achieved with water jets configuration.

6.3. Results and analysis

The performance of three thrusters with diameters of 0.27, 0.375 and 0.42 m was tested at the Thrift reservoir, considering various global flows for SEDMIX and obtaining the sediment release at the water intake. The released sediment discharge of those experiences is shown in Figure 6. When implementing a flow of ~2.3 m^3/s (which was the maximum flow the SEDMIX device could reach when using thrusters with a diameter of 0.27 m) the three different thrusters considered had a similar sediment discharge of around ~15.8 kg/s. Nevertheless, when increasing the flow, the performance of the thrusters with a diameter of 0.375 m was better than the one obtained for the thruster with a diameter of 0.42 m, possibly because the efflux velocities reached by the 0.375 m thrusters were higher. However, these thrusters reached to their maximum flow without obtaining a comparable sediment discharge as the one obtained using water jets [4] (~16.58 kg/m). Nevertheless, the thrusters with a diameter of 0.42 m did when implementing a flow of ~12.8 m^3/s, to later drastically decrease the sediment discharge when considering their maximum flow.

Figure 7 shows the variation of sediment velocity with depth at the centre point of the device for the water jets and the three diameters of thrusters used in the SEDMIX device when considering their maximum flow (in the case of the diameters of 0.27 and 0.375 m), and the optimum flow for the highest sediment release (in the case of the thruster with diameter of 0.42 m). As it can be seen in the figure, for a set of thrusters with a diameter of 0.42 m and a flow of 12.8 m^3/s, the sediment velocity profile is really similar to the one obtained when using water jets and a discharge of 5 m^3/s. For the other sets of thrusters considered, despite they generate a higher velocity at the depth they are located (~20m), the velocity obtained for deeper locations is smaller, being more likely to allow a higher sediment deposition and therefore a lower sediment release.

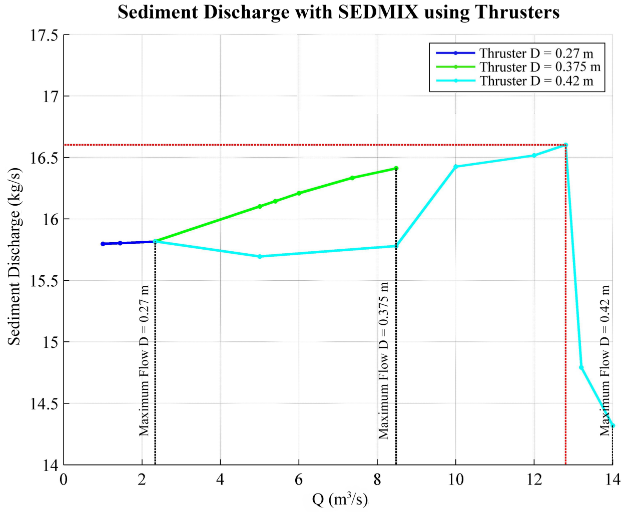


Fig. 6 Sediment discharge at the outlet with SEDMIX using thrusters of various diameters.

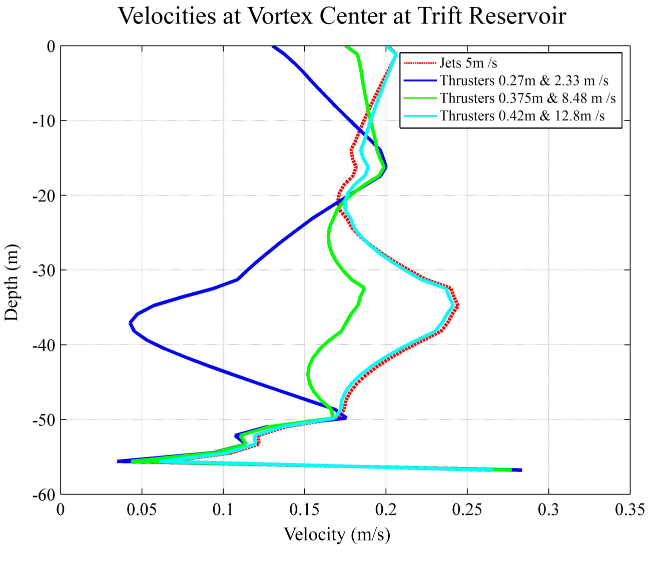


Fig. 7 Variation of sediment velocity with depth when implementing SEDMIX with water jets and thrusters of different diameters and flows.

As mentioned before, the use of thrusters for the SEDMIX device would avoid dealing with head losses, and the consumption of energy would be limited to the amount needed by the motor to generate the mechanical rotation of the thrusters. As shown in Figure 8, the thrusters are able to generate the necessary inertia to produce a rotational flow.

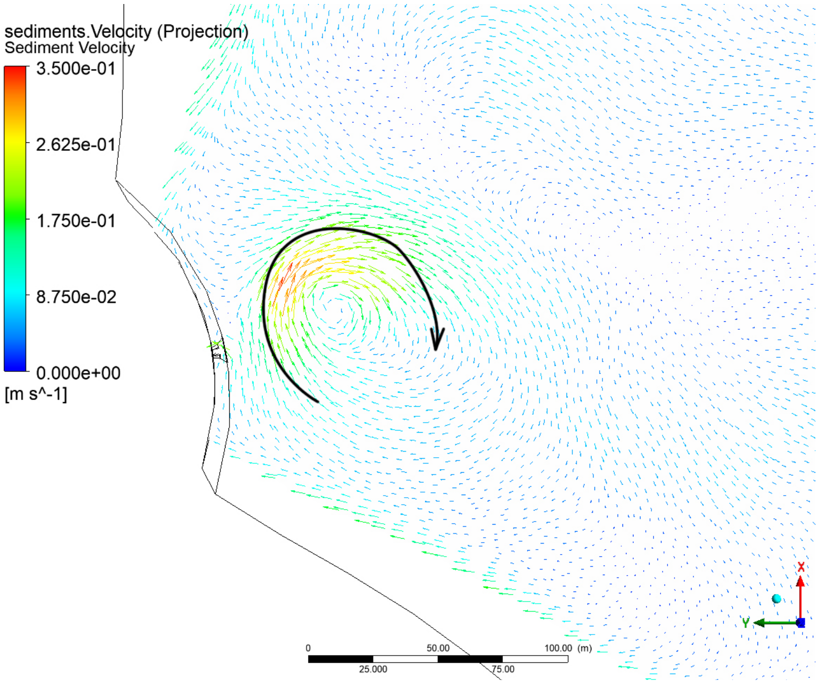


Fig. 8. Rotational flow generated when using SEDMIX with thrusters of 0.42 m of diameter considering a steady state condition.

7. Conclusions

This study confirms the feasibility of changing the former configuration of the SEDMIX device using water jets by the implementation thrusters which produce a whirl-up flow like jets and thus avoid the sedimentation of the fine solids present in the Trift reservoir.

The numerical simulations of SEDMIX using thrusters showed a similarity on flow patterns when using jets, however, a higher flow is needed by the thrusters to be able to replicate the upward whirling flow generated by the jets. In the same way, the numerical simulations of the device in the Trift reservoir suggested that a comparable sediment release to the one obtained using jets can be achieved when selecting a set of thrusters with an optimal diameter and adjusting the flow needed so it can reach an efficient operation.

Numerical simulations of this new configuration for the SEDMIX device have been carried out successfully, nevertheless, the experimental studies of the device using thrusters is highly advised.

A joint project is then ongoing to promote the installation of the first prototype of SEDMIX-3DD in Alpine reservoirs. The project aims to demonstrate the effectiveness of the combined device, firstly to clean the reservoir and secondly to maintain it in long-term acceptable conditions. The mobile mixing device SEDMIX plus the 3DD that manages the SEDMIX mixer, will be tested in a selection of Alpine reservoirs to show its efficiency in different conditions.

References

1. Schleiss A. J., Franca M. J., Juez C., and De Cesare G., “Reservoir sedimentation”. Journal of Hydraulic Research, 54(6), 595–614, 2016
2. Jenzer-Althaus, J. Sediment evacuation from reservoirs through intakes by jet induced flow. PhD Thesis 1820, Ecole Polytechnique Fédérale de Lausanne; and Communication 45, Laboratory of Hydraulic Constructions (LCH), A. Schleiss, ed. EPFL, Lausanne, Switzerland, 2011.
3. Amini, A.; Manso, P.; Venuleo, S.; Lindsay, N.; Leuipi, C.; Schleiss, A. Computational hydraulic modelling of fine sediment stirring and evacuation through the power waterways at the Trift reservoir.; Hydro 2017, Seville, Spain.
4. Chraibi, A. Amini, A. Manso, P. Schleiss, A.J. Controlled fine sediment release through the power waterways by using a mixing device. SCCER-SoE Annual Conference. Switzerland, 2018.
5. Jenzer-Althaus J., De Cesare G., and Schleiss A. J., “Sediment evacuation from reservoirs through intakes by jet-induced flow”. Journal of Hydraulic Engineering, 141 (2), 2014
6. Basson, G. R. Sedimentation and sustainable use of reservoirs and river systems, International Commission on Large Dams (ICOLD). ICOLD bulletin 147: Sedimentation Committee, 2010.
7. White, W. R. Evacuation of Sediments from Reservoirs. London: Thomas Telford, 2001.
8. Amini, A, Chraibi A., Manso P., Numerical simulations of an innovative water stirring device for fine sediment release: The case study of the future Trift reservoir.; SimHydro 2019 – Nice, France.

9. Albertson, M., Dai, Y., Jensen, R., & Rouse, H. Diffusion of submerged jets. ASCE Transactions, 1948. 648-697.
10. Blaauw, H., & Van de Kaa, E. Erosion of bottom and sloping banks caused by the screw race of manoeuvring ships, publication 202. Delft: Delft Hydraulics Laboratory, 1978.
11. Mongiardino B., Binder F. M., De Cesare G., "Floating modular unit for controlled sediment flushing regarding sediment size and concentration". Hydro 2018, Gdansk, Poland.

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