Computational hydraulic modelling of fine sediment stirring and evacuation through the power waterways at the Trift reservoir

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Summary
Taking advantage of the withdrawal of some glaciers, several new dams will eventually be constructed in Switzerland in the coming years as a part of the 2050 energy strategy. The Trift dam, located in Berner Oberlands in Switzerland, is one of these new projects. Reservoir sedimentation is however one of the main challenges for long-term sustainable operation of dam reservoirs that requires mitigation measures. Settling of suspended sediment may reduce reservoir live storage available for hydropower production and hamper operation of the bottom outlets.

Jenzer-Althaus (2011) has experimentally tested a stirring device (hereafter called SEDMIX) as a mitigation measure to prevent reservoir sedimentation. The device 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 several reservoirs in Switzerland and abroad to avoid reservoir siltation due to fine sediments mainly transported by turbidity currents.

The present study investigates the implementation of the SEDMIX device in the Trift reservoir by means of computational hydraulic modelling. The study proves the efficiency of the SEDMIX device in evacuating fine sediments during normal operation of the hydropower plant. The effect of other parameters such as the orientation and discharge of the SEDMIX jets, as well as the characteristics of the suspended sediments such as initial concentration and grain size, on the efficiency of the SEDMIX device will be evaluated in the future.

1. Introduction
With the current turn towards renewable energy sources and the withdrawal of some glaciers in Switzerland, new hydropower plants will be built in the upcoming years. However, sedimentation is a key issue for reservoir sustainability as it results in a loss of capacity storage thus also affecting the hydropower production capacity. A recent study by Jenzer-Althaus (2011) shed light on an innovative system (called SEDMIX) allowing to keep in suspension or resuspend the fine particles near the outlets and the dam thanks to specific water jet arrangements. With such a system, the suspended particles could be released with the reservoir water through the outlet during the normal operation of the hydropower plant [5, 6]. If experimental studies have shown the efficiency of such devices in simple cases, its performance has not yet been investigated in real-life reservoir conditions or implemented on a specific site. The project of a new dam reservoir in the Trift Valley currently being developed by Kraftwerke Oberhasli SA (KWO) is an opportunity to implement for the first time this new sediment management system. Located in the Bernese Highlands (Berner Oberland), the new dam in the Trift valley would enable the production of 118 GWh per year with a reservoir of 71.3 hm^3 [7].

This study aims at investigating the performance of the SEDMIX device on mitigation on the reservoir sedimentation in the specific case of the Trift reservoir, by means of computational hydraulic modelling. Some researchers opted for the numerical modeling in the past [8, 9] to study fine sediments hydrodynamics in reservoirs. Such models can provide significant information on the turbidity current's dynamics as well as the erosional and depositional characteristics [10, 11]. However, this project is the first in a broader context: the one of positioning, dimensioning and assessing the efficiency of the circular jet arrangements in a real case, which has a far more complex geometry than the one studied physically by Jenzer-Althaus (2011).

In this paper, first the current concepts of reservoir sediment management are reviewed and the innovative system previously studied by Jenzer-Althaus (2011) is described. Then, the global methodology and the characteristics used for numerical simulation of SEDMIX device in the Trift reservoir are given. Finally, conclusions are stated with support of the obtained results.

2. SEDMIX as an innovative solution for fine sediment management

2.1 Reservoir sedimentation and turbidity currents

When a new dam is built, the continuity of sediment transport is interrupted. Moreover, low flow velocities upstream the dam are favorable conditions for sediment deposition in the reservoir. Sediments are therefore trapped. The reservoir silts up which results in a loss of storage capacity. Hence, hydropower can only be considered as a renewable source if the sediments are managed in a sustainable way.

In Alpine reservoirs, turbidity currents are the main process for the deposit of sediments. Turbidity currents mainly occur during floods and are characterized by a higher density than the ambient water in the reservoir due to the high sediment concentration. This density difference results in the plunge of the turbidity current to the bottom of the reservoir which then follows the thalweg towards the deepest regions with a velocity dependent on the slope [12]. On its way, the turbidity current can also erode the sediments which were already deposited on the bottom of the reservoir and transport them further down, closer and closer to the dam [13, 14].

If the turbidity current reaches the front of the dam, the sediments settle there and can potentially hamper the operation of the bottom outlets or the water intakes. Systems to block, dilute or divert the turbidity current can be installed in the reservoir to prevent these issues.For instance, the operation of outlet-jet induced reservoir hydrodynamic may allow preventing sediment settling up to some extent, in particular for fairly small reservoirs with multiple water inflows and outflow structures [21]. Alternatively, venting of turbidity current sediments during a flood event can prevent the deposition of the main income of sediments, although with some water release [15, 16].

2.2 Measures for sedimentation management

The sustainable use of reservoirs requires sedimentation management. This management is not limited to the reservoir itself but can take place at three levels, namely in the catchment area, in the reservoir and at the dam. The possible measures according to these three levels are discussed by Morris and Fang (1997). Some of these measures such as flushing, dredging and dam heightening have been tried in several reservoirs worldwide in the past. Combinations are analyzed such that often, several measures are implemented simultaneously to optimize the sustainability [17].

However, most of these solutions cannot be generally considered sustainable (e.g. continuous dam heightening), efficient (e.g. settling basins), economically attractive (e.g. dredging) and environmentally friendly (e.g. flushing) simultaneously and for every site; a solution meeting all these requirements is yet to be found.

2.3 An innovative technique: circular water jet arrangement

The current study is based on a solution elaborated by the Laboratory of Hydraulic Constructions (LCH) which allows to set or keep in motion fine sediments [4].

The disposition of four jets in a circle on a horizontal plane was studied in a 2 m wide, 4 m long and 1.5 m deep rectangular tank (Figure 1) both experimentally and numerically by Jenzer-Althaus. These jets create a rotational current which plays the role of a radial or axial mixer depending on various characteristics of the jets and the geometry of the tank. When the rotational flow creates an upward motion, the circular jet arrangement can be beneficial for sediment release as it enables the mixing of sediment and can even lead to resuspension in certain cases. The sediment in suspension in front of the water intakes into the power plant can then be sent downstream, thus increasing the sediment release.

The efficiency of such a system is assessed by the Evacuated Sediment Ratio, ESR, defined as the ratio between the total evacuated sediment weight, $W_{s,out}$, and the initially supplied sediment weight, $W_{s,in}$:

$$ESR = W_{s,out}/W_{s,in} \qquad \text{Eq. 1}$$

The optimal values concerning the jet and the geometric characteristics normalized by the width of the tank were found experimentally and are presented in Table 1, for which the different notations are defined in Figure 1. These values enabled to reach in the laboratory tank an evacuation efficiency of 73% after four hours against only 37% without jets in the same conditions.

Table 1: Optimal device parameters (see Figure 1) [4]

Parameter	Optimal value
Off-bottom clearance	$C/B = 0.175$
Water intake height	$h_i/B = 0.25$
Distance between neighbouring jets	$L_j/B=0.15$
Distance of jet circle centre to front wall	$D_{axis}/B=0.525$
Water height in the tank	$h/B=0.6$

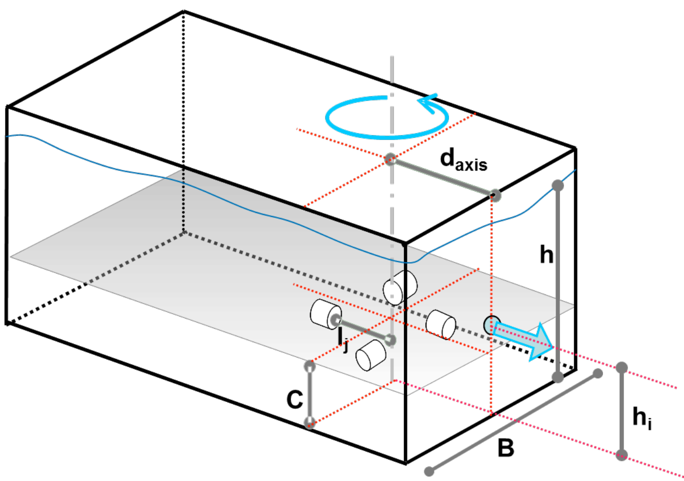

Figure 1. Definition of the tank and jet parameters (the blue arrow indicates the water intake through which fine sediments are released) [4]

The optimal values correspond to a favorable flow pattern: an axial mixer-like flow pattern in the transversal plane which is beneficial for suspension. In the longitudinal plane, a radial mixer-like flow pattern was found to be the most advantageous, if the current in the horizontal direction heads straight towards the water intake. The sediment released was found to increase quasi-linearly with the jet's discharge.

The results of the study were obtained under specific test conditions: the tank was rectangular, the tested jet diameters were 3, 6 and 8 mm and the total jet discharges from 570 to 4050 lh^{-1}. Furthermore, only one type of sediment material was used, a specific type of crushed walnut shells (d_{50} = 50 µm and r_s = 1500 kgm^{-3} respectively) and therefore the influence of the density and grain size of the material is yet unknown. Therefore, if the results are applicable for similar conditions, the efficiency in other cases remains uncertain.

The concept was also tested numerically for steady state conditions and considering only one phase (water). The aim of these simulations was to observe the flow patterns and check the coherence between the experimental and numerical velocities. The simulations showed that the velocities were in agreement. Slight flow instabilities were also detected but their influence on sediment release was not assessed.

This new device was therefore found to be effective, sustainable but also environmentally friendly as the sediments can be released during the normal operation of the hydropower station. In other terms, this system would allow to come closer to the natural conditions downstream without the dam regarding the sediment transfer to downstream. Moreover, the water in neighboring catchments can be transferred in order to provide the energy for the jets thanks to the drop height. To summarize, this innovative device could meet the different requirements for an optimal management system which justifies the current interest in this innovative technology.

2.4 Remaining questions and the present contribution
However, many questions remain following Jenzer Althaus' study:

- the effect of the lake volume inertia on the jets set-up time (t_{lag}) as in Figure 2;
- the effect of the lake volume inertia on the lifetime ($t_{lifetime}$) of the mixing once the jets have been stopped;
- the influence of the reservoir morphology;
- the influence of the reservoir water levels on the jets;
- the amount of moment/energy to input via the jets for optimal mixing;
- the effect of the relative position of the jets and other existing outlets on the sediment release;
- the effect of the incoming water flux on the jets and the mixing (in case of subsequent floods).

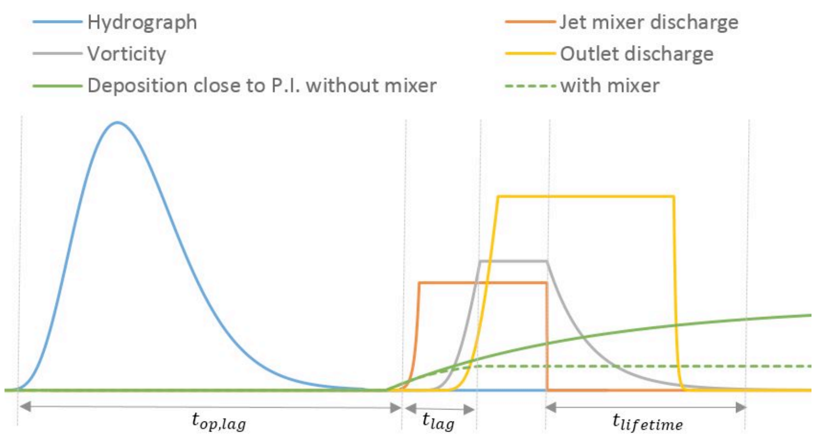

Figure 2. Conceptual graph of the main parameters involved in the timing of SEDMIX device operation

Further to Jenzer Althaus numerical simulations, the current study partly deals with transient simulations, in the presence of two phases (water and sediments) and is an application on a real case study (more complex morphology). Some of the topics mentioned above are tackled in this project. Moreover, the influence of the jets on the mixing in the reservoir is also investigated thanks to numerical simulations. The present simulations also allow to study the flow pattern (number of cells, symmetry, etc.), the sediment transport and areas of deposition in the Trift reservoir. The output of this study may be used to inform decisions of the subsequent design and future operation of the dam's bottom outlet and HPP water intake.

3. Methodology

The ANSYS-CFX three-dimensional finite volume model for multiphase flows is used to simulate the SEDMIX device in the Trift reservoir.

3.1Numerical model set-up
The unsteady Reynolds-averaged Navier–Stokes equations are solved on the unstructured grid using the classical hydrostatic pressure approximation under the Boussinesq assumption and the eddy viscosities from conventional linear turbulence model. To provide an accurate resolution at the bed and the free surface, the governing equations are solved in the multi-layer system (the vertical plane of the domain is subdivided into fixed thickness layers).

The k–e turbulence solver is used for closure and the related algebraic eddy coefficients are modified to account for the solid phase flow and some secondary effects appearing from complex channel morphology in the natural rivers with meandering open channels. The model uses temporal implicit time-stepping Second Order Backward Euler scheme for numerical time integration to guarantee high degree of mass conservation in compliance with the CFL restriction [18].

The water intake location and geometry is derived from previous studies [7]. As shown in Figure 3, the water intake is located in the left bank at 1634 m asl. The power waterway has a diameter of 4 m. The bottom outlet and water intake share the same intake structure which has a diameter of 10 m. The dam has a total height of 192 m, the crest reaches an altitude of 1757.5 m asl. The reservoir created can retain 71.3 hm^3 of water.

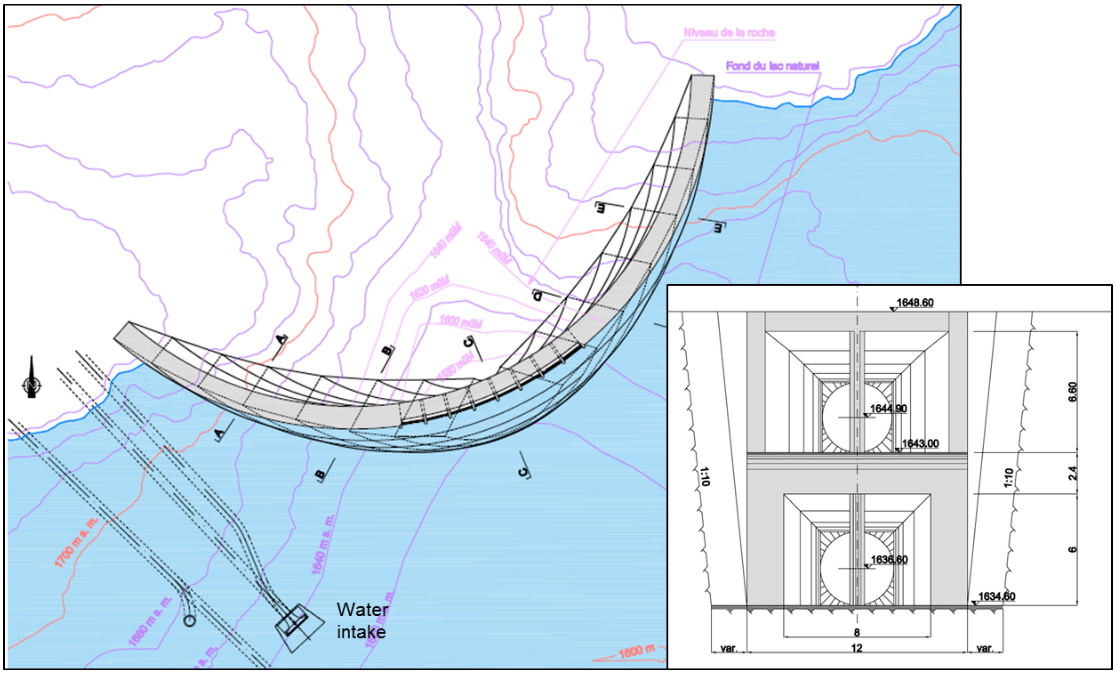

Figure 3. Dam layout [7]

The jets are modelled as inner sources to avoid having to refine elements in the jet region. However, as it is shown in Figure 4 the mesh is finer near the water intakes in order to represent correctly their real dimensions.

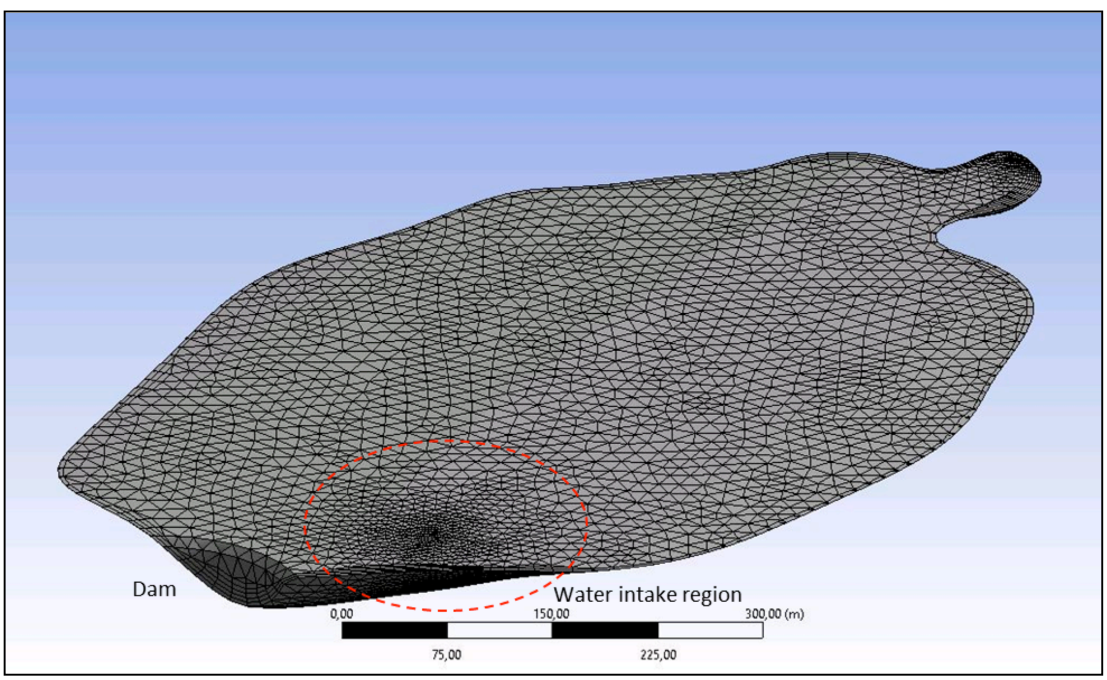

Figure 4. Numerical model mesh built in ANSYS-CFX

3.2Boundary and initial conditions

Upstream boundary condition:
As the upstream boundary condition, the yearly flood with a total duration of 30 hours is considered (Figure 5). The sediment concentration of 700 mgl^{-1} [19] with a mean particle diameter of 0.1mm (100 micron) is assumed [20] and a sediment density of r_s = 2600 kgm^{-3} is considered. The corresponding sediment discharge is also illustrated in Figure 5.

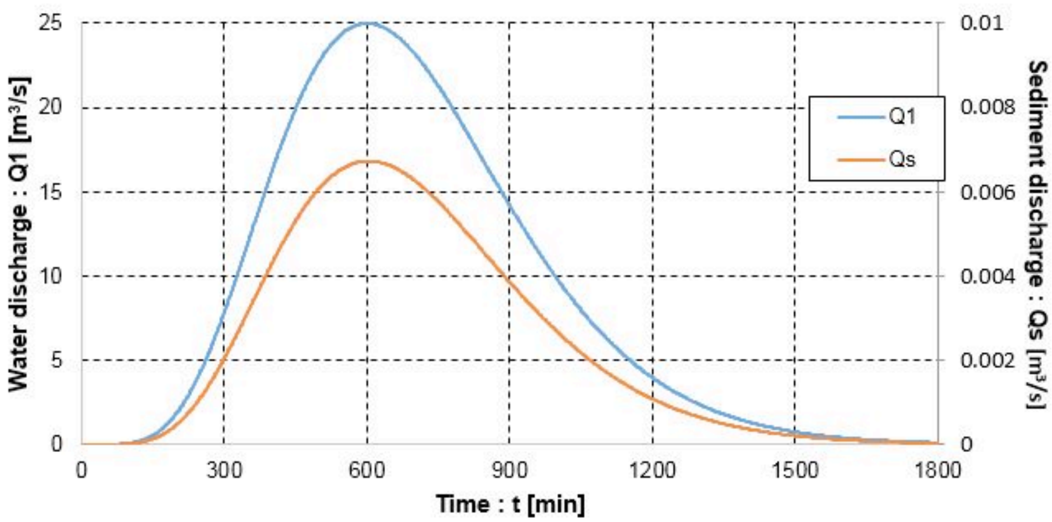

Figure 5. Hydrograph and solidograph of a 1-year flood event in trift reservoir

Downstream boundary condition:
As downstream boundary condition, hydrostatic pressure condition is set at the water intake. A hydrostatic boundary condition is chosen among other options (e.g. defined outflow discharge, defined outflow velocity) as it gives more plausible results in terms of flow pattern in the reservoir.

Initial condition:
The initial concentration of sediments in the reservoir is zero. As the occurrence of turbidity currents is more likely during spring floods, the minimum operation level (1656.1 m asl) is selected as the initial water elevation for the simulations. This level will stay fixed during the simulations. A spillway is defined on the dam crest to assure the mass balance in the model.

3.3 Upscaling to prototype dimensions

To design the device in the case of the Trift reservoir, the optimal values found empirically by Jenzer-Althaus (2011) and given Table 1 are used. These are normalized by the reservoir width B_{res}. The upscaling relies on Froude similarity which leads to the definition of the geometrical scale factor, l_L , as

$$l_L = l_Q^{2/5} \quad \text{Eq. 2}$$

with l_Q referring to the discharge ratio between the real case and the experimental prototype. On the other hand, l_L = B_{res} /B_{mode} where B_{res} and B_{mode} represent the reservoir and model width. Knowing that B_{model} = 2m in the experiments and considering B_{res} equal to 70 m, l_L is calculated to be 35. As such, the distance between neighboring jets for the prototype is set to 20 m, while the total jet discharge is 1 m^3/s, i.e. 250 ls^{-1} for each jet. Applying Equation 2, the discharge remains in the range of validity of Jenzer-Althaus study.

3.4 Simulation scenarios

In a preliminary phase, over thirty (30) trial simulations have been done with/without sediments both in steady state and transient flow conditions. Once the model parameters were adjusted, the SEDMIX device was implemented into the model. The device location is presented Figure 6. It is placed close to the dam at a distance of about 100 m from the water intake. The results are then compared to the reference case, i.e. identical conditions but without jets.

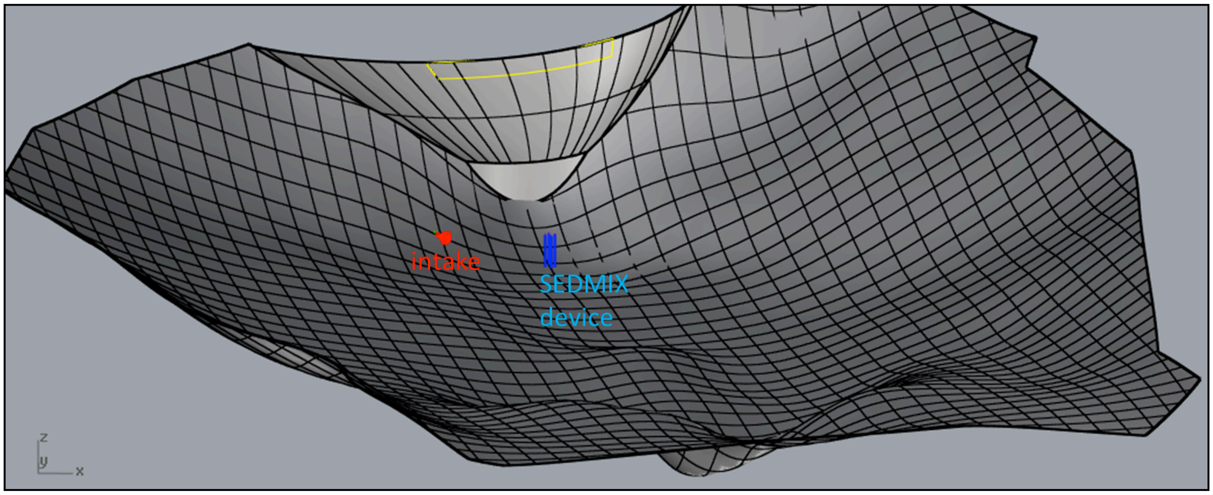

Figure 6. Water intake and SEDMIX device location

4. Analysis and results

To evaluate the efficiency of the operation of the jets, the latter are launched to run for approximately 30 hours to overcome the stagnation inertia of the reservoir, in parallel with the flood event. Figure 7 illustrates the flow pattern in the reservoir for the simulation with SEDMIX after 30 hours. By that time the flood discharge is very low and the flow pattern is mainly influenced by the operation of the jets. The figure highlights the role of SEDMIX device in producing rotational flow in the reservoir, namely near the water intake and the dam, that may keep fine sediments in suspension.

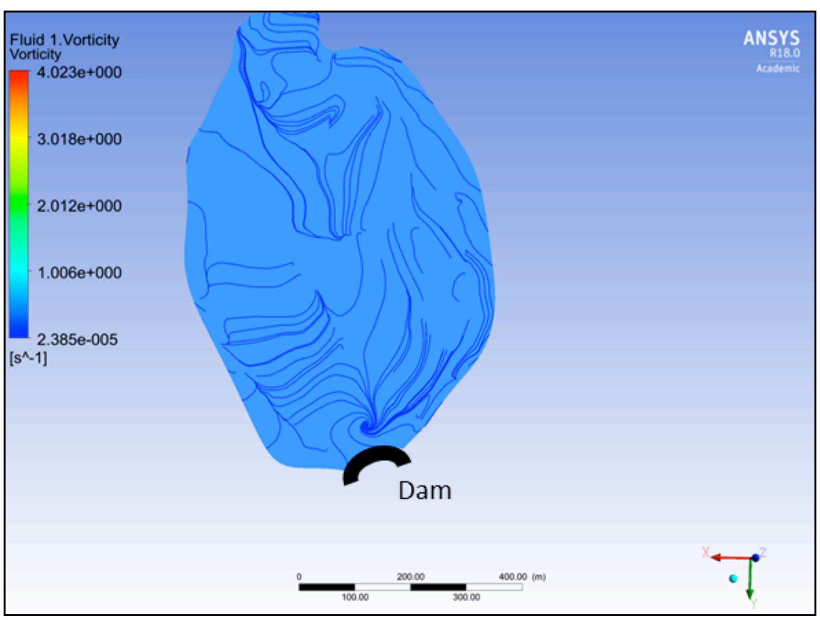

Figure 7. Flow pattern in the reservoir with SEDMIX (t=30 h)

For each scenario, the weight of sediment that pass through the water intakes for 30 hours is obtained directly as output from the software. The evacuated sediment ratio, ESR, (Eq. 1) is then calculated as the ratio between the total sediment weight evacuated and the total sediment weight introduced in the reservoir.

Table 2: Sediment evacuation ratio through water intake during HPP operation: results from numerical simulations

Simulation	Sediment weight in [t]	Sediment weight out [t]	ESR [%]
Without SEDMIX	760	107	14
With SEDMIX	760	538	71

The evacuated sediment ratio (defined in Equation 1) is equal to 14% for the reference case without SEDMIX jets. However, the presence of SEDMIX device increase the evacuation rate up to about 70%. This result brings out the efficiency of SEDMIX device in increasing the sediment release to the downstream

5. Discussion and outlook

The paper presents a preliminary study of transient routing of fine sediments through a reservoir outlet (in this case the water intake) during and after a sediment-laden flood event, and points out the potential contribution that the operation of the SEDMIX device may have in facilitating sediment suspension and release. A three-dimensional model of a prototype reservoir equipped with the SEDMIX device has been developed and can be used as a basis for any future research projects on the Trift reservoir.

Moreover, at the current stage and with a preliminary choice of the jets position, this study shows high contribution of jets in keeping fine sediments in suspension and evacuation through the water intakes during normal operation of the hydropower plant. Numerical simulations have been successfully launched. However, due to the complex morphology of the reservoir, the hydrodynamic behavior needs further investigation.

The next step is then to launch simulations when no flood is coming to the reservoir and with an initial suspended sediment concentration. As such, the effect of jets can be assessed without being influenced by the dominant flood flow. The effect of other parameters such as the orientation and power of the SEDMIX jets, the contribution of other jets (e.g. diversions from neighbouring catchments, outlets from upstream or pumping stages [21]) as well as the characteristics of the suspended sediments such as initial concentration, cohesion and grain size, on the efficiency of the SEDMIX device will be also evaluated in the future.

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