Fine sediment release from a reservoir by controlled hydrodynamic mixing

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Abstract: *Reservoir sedimentation is worldwide a problem and requires a sustainable solution. The idea of maintaining sediment in suspension by a jet induced artificial turbulence and releasing it through the water intake was tested in laboratory experiments. Therefore, two jet configurations and the influence of their geometrical parameters and the jet discharge on the sediment release were investigated: (i) a circular jet configuration with four jets arranged in a circle on a horizontal plane and (ii) a linear jet configuration with four jets arranged on a line parallel to the front wall. Turbidity measurements accompanied by flow velocity measurements give information about the efficiency and its reasons. The circular jet arrangement was more efficient than the linear arrangement and reached with the highest tested discharge (ΣQ_j = 4050 l/h) an evacuated sediment ratio of 0.73. An optimal parameter set was identified having a release efficiency of between 1.5 and 2 compared to no jets, depending on time and discharge. The optimal jet configuration indicates best installation and discharge practice of the jets when fighting against reservoir sedimentation. A pilot prototype set-up underlines the experimentally found promising results.*

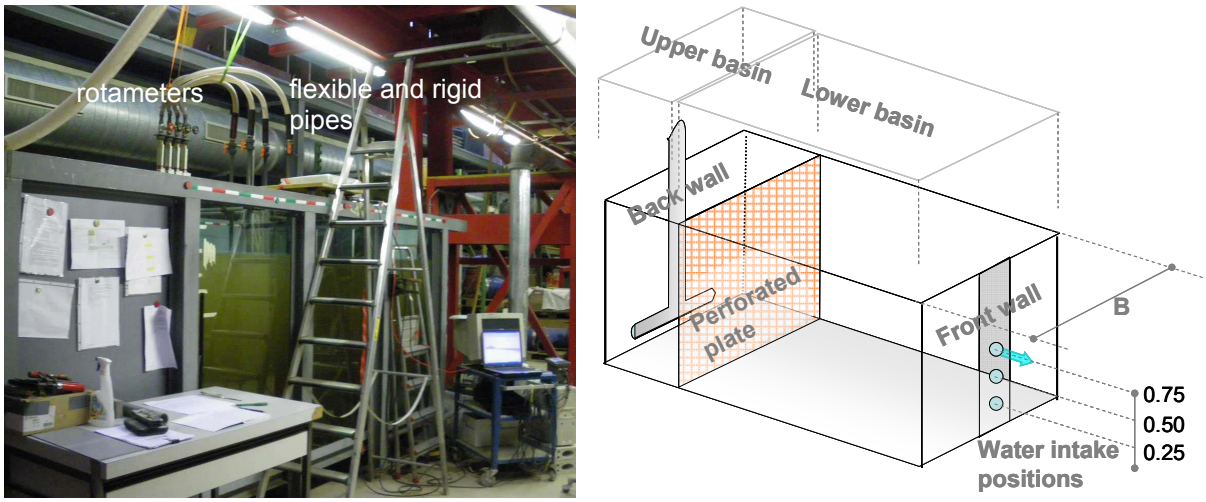
Keywords: *reservoir sedimentation, physical experiments, water jets, jet mixing, sediment release, prototype set-up*

1. INTRODUCTION

Reservoir sedimentation is a problem for reservoir sustainable use. As the accumulating sediments successively reduce the water storage capacity, in the long-term the reservoir operates only at reduced functional efficiency. Declining storage volume reduces and eventually eliminates the capacity for flow regulation and therefore all benefits of water supply, energy and flood control (Graf 1984, ICOLD 1989). Due to reservoir sedimentation water intake operation can be hindered and sediment entrained in waterway systems of hydropower schemes. Depending on the degree of sediment accumulation, the outlet works may be clogged by the sediments leading to a severe safety problem (Boillat and Delley 1992, Schleiss et al. 1996, De Cesare 1998).
Reservoir sedimentation reduces the value of or even nullifies the investment of dam construction. Suitable measures should be devised for adequate sedimentation management. The use for which a reservoir was built can be sustainable or represent a renewable source of energy only where sedimentation is controlled. In principle, even if hydropower in general is a sustainable energy, reservoir sedimentation can threaten the use of storage power plants (Schleiss et al. 2009). Lasting use of reservoirs in terms of water resources management involves the need for desiltation.
In view of the current mitigation measures (Schleiss and Oehy 2002) alternative and more sustainable solutions are required in mid and long term. This challenge motivated the present study with the purpose to develop an alternative efficient method to release sediment out of a reservoir. The concept is based on the release of sediment through the headrace tunnel and turbines whereby a special focus was set on the fine sediment in the area in front of the power intakes. Specific jet arrangements can provide the energy and generate the adequate circulation needed to maintain the sediment in suspension and increase its flux into the power intake during turbining sequences. Physical experiments were performed to determine the most efficient jet arrangement regarding sediment release.

2. EXPERIMENTAL SET-UP

The physical experiments were carried out in a rectangular tank with vertical walls (Jenzer Althaus et al. 2009). Different jet arrangements as well as reference tests without jets were performed. Since it is a priori assumed that the influence of the proposed jet arrangements on the flow is locally limited, the tank only represents a limited part of the reservoir located upstream of the dam. It has an elongated shape with a total inner basin length of 4 m, an inner width of B = 1.97 m and a total basin height of 1.50 m. The front wall of the tank is considered to represent the dam, and the two lateral walls confine the reservoir volume in analogy to valley slopes (Figure 1b).
When preparing the experiment a water-sediment mixture was spread on the bottom of the empty tank. Thereafter, the tank was slowly filled with laboratory water from the back wall, while the sediment is maintained in suspension by pressurized air in order to achieve a uniform sediment concentration within the tank for initial conditions.
During the experiments clear water is fed by jets (jet experiments) or through the back wall (reference experiments without jets), respectively, while sediment laden water of equal flow rate is drawn out of the tank through the water intake. Thus, the water level in the tank is kept constant.
The position of the jets as well as the nozzle diameter could be varied (3, 6 and 8 mm). Equal flow rate on each of the jets is guaranteed by the use of four rotameters (Figure 1a).
The perforated plate tranquilizes the water flowing into the tank during reference experiments. Measurements are only executed within the lower basin part (downstream of the perforated plate).



a) b)

Figure 1 a) Picture of the tank during an experiment with the four rotameters and flexible and rigid pipes leading the water down to the nozzles. The jets are under water. The glass walls confine the lower tank part, the metal wall the upper part. B) Schema of the experimental installation, water intake height indications in [m].

2.1. Measurement devices

2.1.1. Flow velocity measurements

For the required flow velocity measurements an L-shaped rack was built with two wings hosting five equally spaced Ultrasonic Velocity Profilers (UVP-transducers), each. This rack was fixed at the lower end of a vertical rod. The lateral distance from one sensor to another was 200 *mm*; the distance between the sensors and the wall was 230 *mm* (Jenzer Althaus et al. 2010). Flow velocities were measured on two vertical planes: on the transversal axis passing through the jet arrangement centre (Figure 2a) and the longitudinal middle axis corresponding to the water intake axis (Figure 2b).

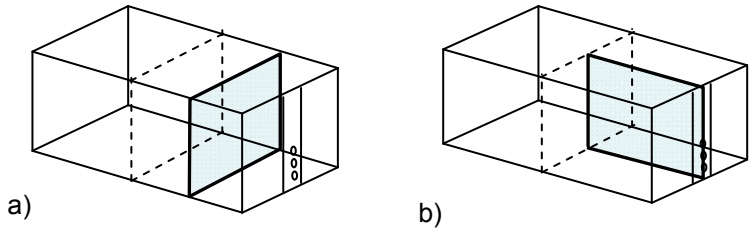


Figure 2 Schematic view of the position of the UVP-sensor-frame for, a) transversal 2D-flow pattern, b) longitudinal 2D-flow pattern.

2.1.2. Turbidity measurements

Two SOLITAX sc sensors (brand Hach) were employed for measuring turbidity by infrared absorption scattered light technique. The relationship between the suspended sediment concentration and the turbidity signal was derived in the laboratory by placing the probe in suspensions of known crushed walnut shells concentrations. The obtained calibration relationship is linear.
One of the turbidity sensors is installed in the dissipation basin right below the exit of the headrace tunnel and measures outflowing suspended sediment concentration continuously.
The other one is used to measure 5 to 8 times per experiment suspended sediment concentration at different positions within the experimental tank.

2.2. Properties of the sediment materials

For the present study ground walnut shell powder was used. This material has been tested in former studies of sedimentation in shallow reservoirs (Kantoush 2008 among others) and has been found to perform very well. It is very easy to mix, lightweight (ρ_s = 1500 kg/m^3) and, since the problematic of cohesion was not subject of the present study, almost cohesionless. The particle size distribution is relatively narrow and the mean settling velocity is small (according to Stokes' theory: $w_s \approx$ 0.8 mm/s in water at 15°C). The particles have a median diameter of $d_m = d_{60}$ = 0.06 mm. With a standard deviation σ_g = 2.4 some grain sorting effects can be expected to occur. The particles are not spherical, but have slightly angular shapes, like natural sediments.

2.3. Circular and linear jet arrangement

Two different jet arrangements were investigated and are presented hereafter: a circular and a linear jet arrangement. In both arrangements the discharge inflowing by the jets equaled the outflowing discharge through the water intake. The initial condition was in all experiments a quasi homogeneous sediment suspension representing the muddy layer remaining after a turbidity current in front of the dam.

2.3.1. Circular jet arrangement

The circular jet experiments were arranged as follows: The jet configuration consisted of four water jets with equal nozzle diameter and jet velocity, arranged in a circle in a horizontal plane. Each jet was pointing in a 90°-angle to the axis of the neighbouring jet (Figure 3). This jet arrangement was installed near the downstream end of the tank. The parameters influencing the jet efficiency regarding sediment release were the jet velocity, jet diameter, and the geometry of their arrangement. The geometrical parameters which were varied are presented in Figure 4.

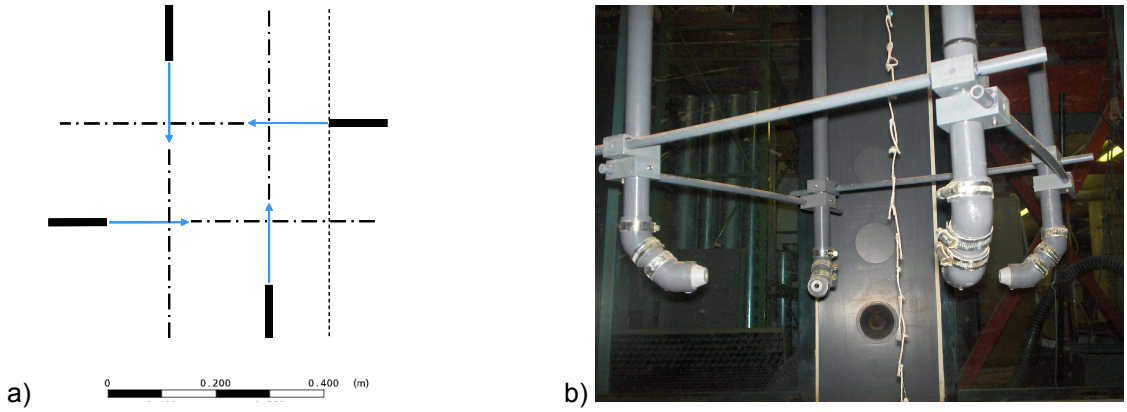


Figure 3 a) Schematic top view of the circular jet configuration. Each jet points on the transition zone of its neighboring jet. b) Circular jet arrangement in front of the front wall with the water intake.

l_j	the horizontal distance between two neighbouring jets
C	the off-bottom clearance
d_{axis}	the horizontal distance from the jet circle axis to the front wall
B	the width of the basin characterizing one of the boundary conditions
h	the water height in the tank
h_i	the water intake height
θ	the jet direction angle with respect to the horizontal

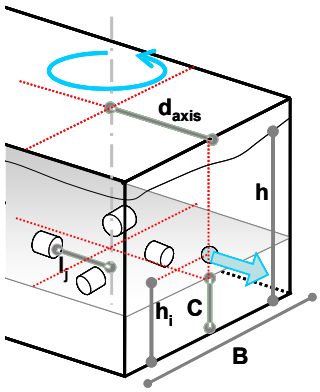


Figure 4 Geometrical parameters varied in the circular jet configuration.

2.3.2. Linear jet arrangement

Four jets were installed along a line parallel to the front wall. All of the four jets pointed towards the front wall. The lateral distance between the jets was 0.2 *m*, and the set was installed at mid-width of the tank. Their height over bottom was always 0.1 *m*. The distance of the jets to the front wall as well as the jet inclination angle were systematically varied.

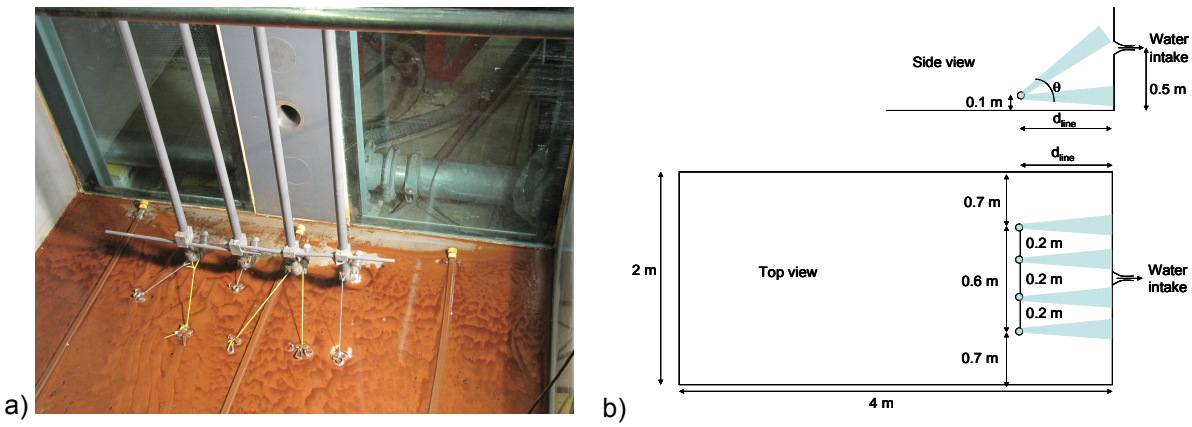


Figure 5 Linear jet arrangement with four jets pointing to the front wall after an experiment. a) Photograph, b) Schematic view

3. OPTIMAL FLOW CIRCULATION REGARDING SEDIMENT RELEASE

3.1. Experiments without jets

In the experiments without jets carried out as reference configuration the sediment load released through the water intake was examined while the outflowing water was continuously replaced by clear water through the back wall. Apart from the slow flow through the back wall and the potential flow generated by the water intake no circulation was induced.
These experiments showed an almost linear relation between the sediment release and the discharge within the tested range: the higher the discharge, the higher the evacuated sediment ratio.
The evacuated sediment ratio (*ESR*) defined as being the quotient of the evacuated sediment weight P_{out} divided by the initially sediment weight added to the tank P_{in}, quantifies the sediment release.
For the tested discharge range the sediment release was between *ESR* = 0.09 and 0.37 after four hours (Figure 6).

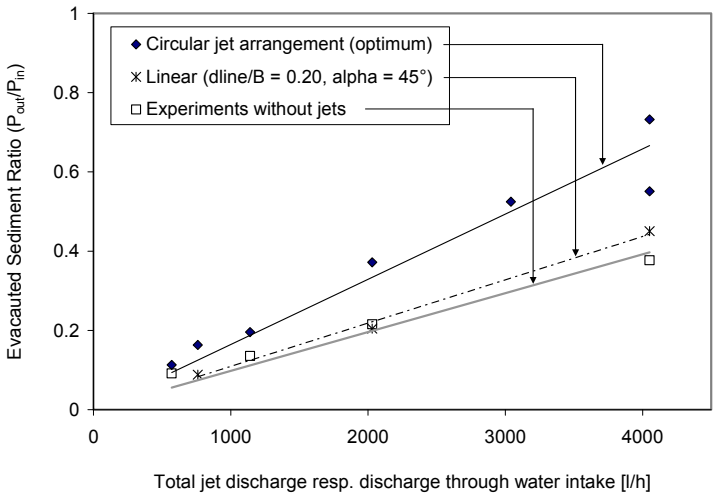


Figure 6 Evacuated sediment ratio (ESR) for optimal circular jet arrangement regarding sediment release, for best linear jet arrangement and for experiments without jets as a function of the discharge.

3.2. Experiments with circular jet arrangement

According to Sharma and Shaikh (2003) the flow pattern from an axial flow impeller is more favourable for suspension in comparison to the flow pattern produced by a radial flow impeller (Figure 7).

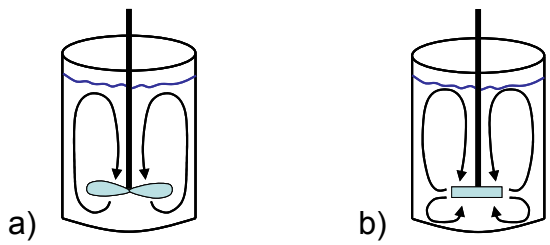
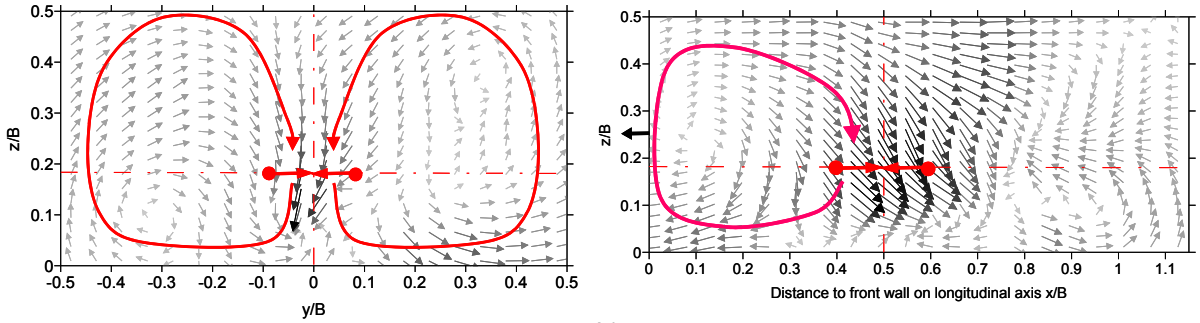


Figure 7 a) Axial and b) radial impeller type and their typical flow pattern

Accordingly, in the present study the circular jet configuration induced circulations with axial mixer-like flow patterns revealed the highest sediment release.
Regarding sediment release the optimal combination of geometrical parameters was identified: off-bottom clearance of the jet arrangement: C/B = 0.175, water intake height h_i/B = 0.25, horizontal distance between two neighbouring jets l_j/B = 0.15, horizontal distance from the rotational axis to the front wall d_{axis}/B = 0.525, water height in the tank h/B = 0.6, jet angle to the horizontal θ = 0°. For the tested circular jet arrangement a quasi linear relationship between the jet discharge and the sediment release was found: the higher the discharge the more sediment is released (Figure 6).



a) b)

Figure 8 Flow pattern due to circular jet arrangement with optimal geometrical parameters. Left: transversal plane, right: longitudinal plane

With these parameters the jets were efficiently mixing: after roughly half an hour the standard deviation of the suspended sediment concentration was approximately 5 %, which in chemistry is considered as homogeneous (Wasewar 2006). Consequently, less sediment was settled and, hence, the sediment release was higher than without jets and reached, for the highest tested discharge (ΣQ_j = 4050 *l/h*), an *ESR* = 0.73 (Figure 6). The evacuated sediment ratio (*ESR*) is defined as being the quotient of the evacuated sediment weight P_{out} divided by the initially sediment weight added to the tank P_{in}.

Moreover, contrary to the experiments without jets, with a circular jet configuration resuspension of settled sediment was observed. Resuspension started once steady state conditions for the circulation were reached and for discharges higher than an experimentally determined threshold (ΣQ_j = 2030 *l/h*). The observed evolution of the resuspension rate suggests that for times significantly larger than the basin residence time all of the initially supplied sediment can be evacuated.

In accordance to the research field of impellers the tank width *B* was chosen for non-dimensionalization of horizontal as well as of vertical lengths.

3.3. Experiments with linear jet arrangement

The linear jet arrangement was found to be much less favourable in view of sediment release. Its results were in the same magnitude as for the experiments without jets (Figure 6, *ESR* between 0.37 and 0.45). This is due to the direction of the induced flow pattern which is unfavourable regarding sediment suspension: the sediment is drawn to the bottom where it is settled and difficult to be put in suspension again (Figure 9).

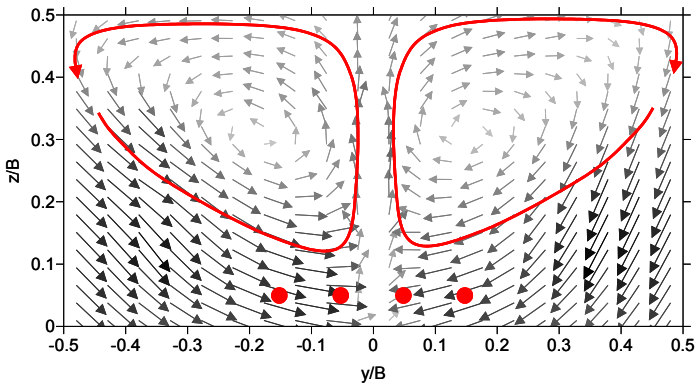


Figure 9 Velocity vectors in the transversal plane for off-bottom clearance *C/B* = 0.05, distance of jet line to front wall d_{line}/B = 0.2, water height *h/B* = 0.6, angle θ = 45°, total jet discharge $\Sigma Q_j = Q_{out}$ = 4050 *l/h*.

3.4. Efficiency of circular jet arrangement

The efficiency of the jets was established by comparing the sediment release obtained under different conditions: once when jets were employed, once without jets. It is defined by the released sediment ratio obtained with jets, ESR_{jet}, divided by the released sediment ratio obtained without jets, $ESR_{no\ jets}$.

$$Efficiency = \frac{ESR_{jet}}{ESR_{no\ jets}} \tag{1}$$

The predicted efficiency based on time and discharge independent empirical relationships is around 1.7 for the optimum jet configuration. Using the measured data the efficiency depends on discharge and increases with time. At the end of the transient phase and when resuspension started the efficiency was approximately 1.5. With the highest tested discharge (ΣQ_j = 4050 l/h) the efficiency reached after four hours almost 2 (Figure 10).

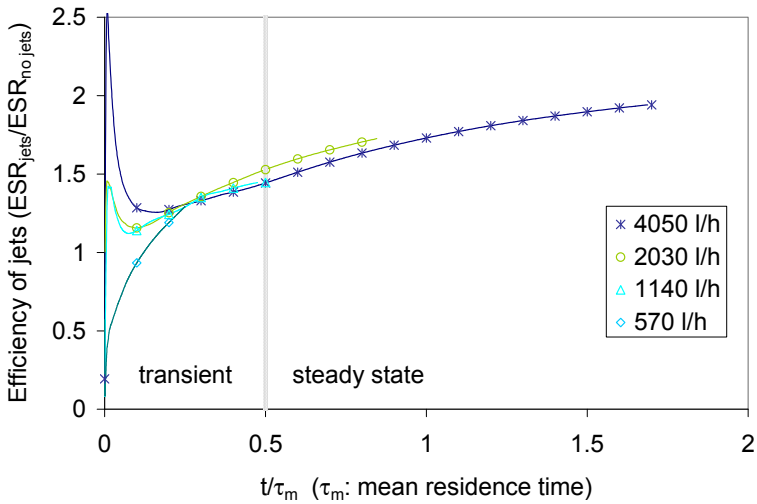


Figure 10 Efficiency of jets by comparing the evacuated sediment ratio obtained with and without jets, respectively.

4. PRELIMINARY PROTOTYPE SET-UP

The location of the water intake and the bathymetry of a real reservoir are obviously different from the rectangular laboratory tank. The water for the jets is planned to be derived from water transfer tunnels conveying the water from neighbouring catchments. The proportion between the reservoir dimensions and the available head and discharge of a real water transfer tunnel is usually different from the laboratory conditions.

Nevertheless, for the reservoir ($220 \cdot 10^6$ m^3) of Mauvoisin, created by a 250 m high arch dam creating a large reservoir in Switzerland, a possible position for a circular jet arrangement was proposed where the resulting circulation is confined on two sides: by the dam and by the left valley slope. The jet forced circulation flow is difficult to predict. For better understanding of the flow and a better estimate of the quantitative effect of the jets on the circulation and the sediment release numerical simulations have to be done.

Even though tests at a natural scale were not performed, by means of the jets a much higher sediment release is expected than without jets. Moreover, sediment deposition in the area upstream of the water intake will be greatly reduced and the problem of clogging can be ruled out.

A comparison between the annual costs of equivalent sediment volume extraction, on one hand due to mechanical removal and on the other hand due to release with jet mixing, states that the jet option is more profitable. Even if only 7 % of the yearly incoming sediment amount is released by means of the jets, a circular jet installation is still economical and strongly recommended in view of a sustainable reservoir operation.

5. CONCLUSION AND RECOMMENDATION

Physical experiments in a rectangular tank were performed to investigate the influence of two different jet arrangements on the circulation, sediment behavior and sediment release. For both tested jet arrangements (circular and linear) a quasi linear relationship between the jet discharge and the sediment release was found: the higher the discharge the more sediment is evacuated. Nevertheless, the circular jet arrangement is much more favorable in view of sediment release than the linear arrangement. With the geometrical parameter combination determined as optimal for the circular jet arrangement, a sediment release approximately 1.7 times higher than without jets was achieved after four hours duration (corresponding to approx. 1.7 τ_m, where τ_m is the mean residence time).
For this combination and for discharges exceeding an experimentally determined threshold even resuspension was observed. It may be assumed that at continuous operation for times much larger than the mean tank residence time all initially supplied sediment can be released. Moreover, the results show that even with small jet discharges more sediment is evacuated than without jets.
A preliminary attempt of a prototype set-up shows that even if the jet forced flow is still difficult to predict a much higher sediment amount is expected to be released through the water intake than without jets. Specifically the area in front of the water intake can be released of sediments and clogging can be avoided. The study shows that a circular jet installation compared to conventional mitigation measures (e.g. mechanical removal) is economical and highly efficient. Thus, with the jets a more sustainable use of storage power plants can be achieved even with no moving mechanical parts.

6. ACKNOWLEDGEMENTS

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