INFLUENCE OF PUMPED-STORAGE OPERATION ON RESERVOIR SEDIMENTATION

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ABSTRACT

In Europe, renewable energy sources are rapidly growing but are often linked to a highly volatile production, as for solar and wind energy. Pumped-storage plants have become very important since they can ensure grid stability and safe power supply at any moment. In Alpine countries, many new pumped-storage schemes are planned or already under construction, often using the artificial lakes of existing storage power plants as upper or lower reservoir. The sustainable use of these reservoirs is endangered by sedimentation. In the framework of a research project it was studied for the first time if sedimentation behavior can be correlated to pumped-storage sequences. The relevant problem was addressed applying an integrated approach combining prototype measurements with systematic laboratory experiments and numerical simulations. Results are helpful in designing location and type of inlets and outlets aiming to maintain high turbulence in the reservoir to reduce settling of suspended sediments.

INTRODUCTION

Sedimentation is of major concern for many storage reservoirs and endangers reliability, efficiency as well as structural safety of hydropower schemes (ICOLD, 2009). During flood events, high erosion in the watershed leads to high sediment yield into the reservoirs. In Alpine catchments, turbidity currents are the most common source of reservoir sedimentation. From the river delta they follow the thalweg to the deepest part of the storage, often close to the dam and intake structures. In the so-called muddy lake fine sediments start settling down (De Cesare *et al.*, 2001; Sequeiros *et al.*, 2009). One solution against turbidity current driven sedimentation consists in routing the sediment-laden flow under water and through bottom outlets or turbines (venting). Other measures have been studied by Oehy *et al.* (2010) and Oehy and Schleiss (2007), i.e. obstacles stopping the current propagation or maintaining particles in suspension in front of intakes to be evacuated by the turbines. Jenzer Althaus (2011) investigated the effect of rotating jet induced flow close to intake structures on sediment mixing.

In pumped-storage schemes, the water body in the areas close to the intake/outlet structure is known to be submitted to fast and frequent changes between turbulent flow regimes during inflow and slow potential flow fields during outflow conditions. Thermal

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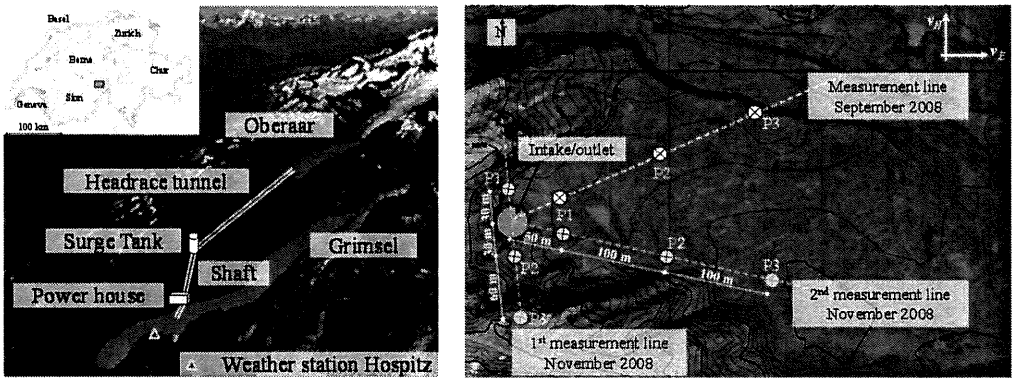
stratification, nutrient content and ecosystem issues can be altered. Sediment may sometimes be resuspended and entrained (Anderson, 2010; Potter *et al.*, 1982; US Bureau of Reclamation, 1993). The purpose of the present study was to use the turbulence induced by pumped-storage operation, to maintain fine sediment in suspension for evacuation through the headrace system or flushing facilities. The influence of in- and outflow sequences on flow patterns and suspended sediment behavior in reservoirs was investigated in prototype measurements and laboratory experiments, in combination with numerical modeling.

MONITORING OF FLOW PATTERNS AND SUSPENDED SEDIMENT CONCENTRATION IN AN ALPINE PUMPED-STORAGE RESERVOIR

Monitoring in hydropower plants is of major importance for the power producers to control the good functioning of their scheme, detect eventual damages in the system and optimize exploitation efficiency. Meticulous surveillance is often attached to mechanical or electrical equipment or important civil engineering works such as dams and pressurized shafts and tunnels. Real-time measurement of flow patterns in a reservoir or turbidity in the pressurized system is rather rare, but could provide important information about the water body's response to specific operation scenarios and the sediment concentration in the system. Two possible monitoring systems were applied in the lower reservoir and the pressurized shaft of the Grimsel 2 pumped-storage plant located in the Oberhasli Region (Switzerland, Figure 1a) and operated by *Kraftwerke Oberhasli AG.*

Site description

The Grimsel 2 plant is operating water between Lakes Oberaar (2303 m a.s.l.) and Grimsel (1909 m a.s.l.). The upper reservoir has a volume of 57 x 10^6 m^3, while the lower basin impounds 95 x 10^6 m^3. Maximum turbine discharge is Q_{Turb} = 93 m^3/s (Oa – Gr), while pumping discharges reach Q_{Pump} = 80 m^3/s. About 600 to 700 x 10^6 m^3 are pumped annually from Lake Grimsel into Lake Oberaar and moved back during turbine mode. A 4 km long headrace tunnel connects the trumpet shaped intake/outlet structure in Lake Oberaar to a vertical surge tank. From there, a 750 m long inclined steel-lined shaft guides the water toward the underground power house, where four independent pump-turbine units provide a capacity of 350 MW. Downstream, the power house is linked by a pressure tunnel to the intake/outlet structure in Lake Grimsel which is a submerged laterally open cylinder embedded in a recess of the lake topography.



(a) (b)

Figure 1. a) Location map and layout of the Grimsel 2 pumped-storage scheme, b) Lake Grimsel bathymetry and positions of the ADCP for the three measurement periods.

The catchment areas of the two reservoirs are partly glaciated, with denudation rates from 1 to 2 mm/year. The sediment characteristics of this "glacier milk" were recently studied by Bonalumi *et al.* (2011), measuring grain sizes of 0.2 to 40 μm with a mean diameter 3 to 4 μm. Suspended sediment concentration along the year varies between C = 50 and 200 mg/l in the two lakes. Bühler *et al.* (2004) detected turbidity currents arriving at the Spittellamm dam impounding Lake Grimsel by a significant increase of turbidity up to C = 700 mg/l in the pressurized system of the Grimsel 1 storage plant, located downstream of Lake Grimsel. Due to hydropower operation approximately 85% of the annual sediment supply of 272 kt/year settles in the reservoirs, while only 40 kt/year are released downstream (Anselmetti *et al.*, 2007). Based on CTD measurements, Bonalumi *et al.* (2011) described and modeled the particle balance of the two reservoirs with and without pumped-storage activity.

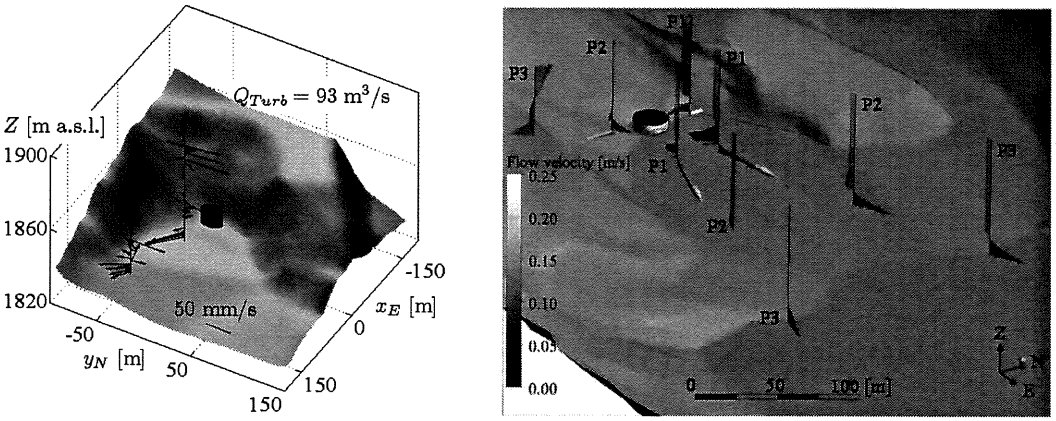
Monitoring of flow patterns in front of the intake/outlet structure

Purpose. Settling of small particles near the intake/outlet occurs if flow velocities are tending to very low values, i.e. when energy available for mixing is insufficient. An estimation based on formulas given by Anderson (2010) reveals that in Lake Grimsel, the turbulent kinetic energy (TKE) input induced by power generation is about 25 times higher than the natural TKE input by wind-forcing. Thus, the potential of keeping fine sediments in suspension by this high energy input exists in Lake Grimsel. Knowledge of flow conditions in front of intake/outlet structures during in- and outflow sequences provides information about main flow directions and flow velocities which could serve for optimizing of the intake/outlet geometry and orientation.

Methods. Lake Grimsel was equipped with three 300 kHz Acoustic Doppler Current Profilers (ADCP, Figure 1b) which continuously sampled flow velocities in the intake/outlet surroundings during three weeks in September and November 2008. Every five minutes, the instruments sampled East- and North flow velocity components on every meter along the water column. After data extraction, 1D and 2D flow patterns were established and compared to the pumped-storage operation of the plant. To compare

results and to carry out a sensitivity analysis on the temperature difference between resident and inflowing water, the flow conditions corresponding to the measurement periods were simulated numerically in a 3D-ANSYS-CFD model.

Flow patterns due to pumped-storage operation. The one- and two-dimensional velocity profiles reveal that pumping (withdrawal from the reservoir) only affects the water body close to the intake. At 30 m from the intake/outlet, flow velocities of about v = 6 cm/s were recorded and at 150 m velocity profiles are not anymore influenced by the withdrawal. Periods without pumped-storage activities show rather random velocity fluctuations in the water body. During turbine mode (inflow into the reservoir), flow velocities up to v = 12 cm/s were measured, even at 150 m from the outlet. This operation mode systematically generates flow patterns with important backflow between 5 and 20 m above the reservoir bottom and a main outflow sector in E-SE direction (Figure 2a). The natural confinement generates a large scale circulation cell, rotating counterclockwise in the basin in front of the intake/outlet. Numerical model simulations confirmed the in situ observations, reproducing the main characteristics of the flow patterns in front of the intake/outlet. The reservoir's response to hydropower operation could be studied. Steady flow fields were observed only after 150 minutes of continuous turbine operation (Figure 2b). Scenarios comprising a temperature difference of ΔT_w = +/- 5 °C between the inflowing and the resident water showed no significant change in flow patterns.



(a) (b)

Figure 2. a) Measured and b) numerically simulated 2D-velocity profiles near the Grimsel 2 intake/outlet structure during turbine mode (inflow).

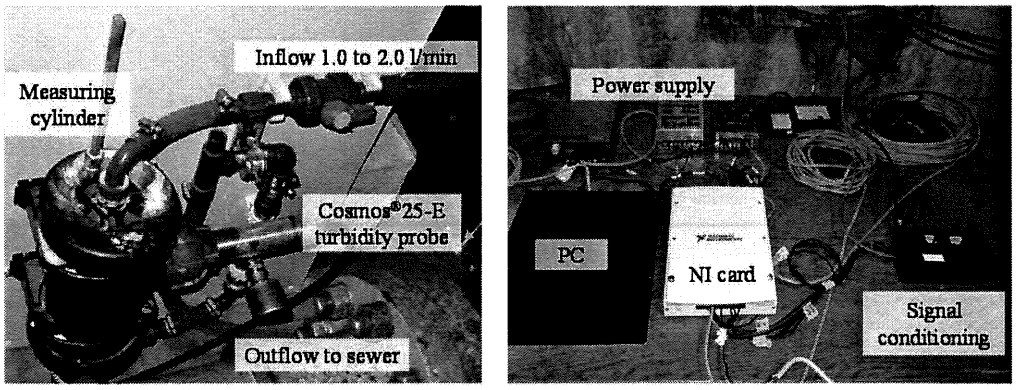
Wind-induced forces are able to generate internal oscillations (seiches) of big water bodies. The frequency of these seiches depends on the depth and the surface of the lake. In order to demonstrate that the ADCP velocity records in Lake Grimsel were not disturbed by such large scale movements but correlate with the pumped-storage operation, a spectral analysis of the recorded velocity signal was carried out. The main period of discharge and ADCP signals correlate well, especially for the E-velocity component, indicating and confirming the main flow direction in the studied area. The

predominant period is $1/f = 1$ day, corresponding to the daily pumped-storage cycles of the plant. Seiche frequencies were not discovered in the velocity spectra.

Long-term observation of suspended sediment transport

Purpose. A continuous monitoring of suspended sediment concentration in the pressurized system would allow plant owners a quantification of the sediment mass moved during pumped-storage operation and detect the arrival of turbidity currents in front of intake/outlet structures. Furthermore, the sediment balance between two reservoirs could be established and the influence of hydropower operation estimated.

Methods. The pressurized shaft of the Grimsel 2 plant was equipped with a turbidity sampling system which monitored suspended sediment transport continuously over eight months. From the sampling location, $Q = 1$ to 2 l/min passed through a cylinder where turbidity was measured by a *Cosmos®25-E* probe (Züllig AG, Switzerland, Figure 3a). The probe was connected to a *b-line II* amplifier generating an output signal between 4 and 20 mA correlated with a user defined turbidity range. The signal was then transmitted to an acquisition card and an industrial computer (Figure 3b) where a LabVIEW based data acquisition tool sampled with a frequency of $f = 0.2$ Hz and stored data series every 30 minutes. Online controlling of the system as well as data download was possible through a Virtual Private Networking internet connection (VPN).



(a) (b)

Figure 3. Turbidity monitoring system at the Grimsel 2 pumped-storage plant. a) Sampling and b) acquisition facilities

Suspended sediment concentration. Weekly monitoring plots reveal the temporal evolution of suspended sediment concentration in the pressurized system. In late 2010, a monthly mean concentration between $C_m = 80$ and 90 mg/l was measured (Figure 4a), before dropping to values from $C_m = 55$ to 60 mg/l in February to April 2011 (Figure 4b). In winter, sediment inputs are known to be reduced due to the ice- and snow covered catchment area. After snowmelt in spring 2011, suspended sediment concentration increased again to $C_m = 75$ to 85 mg/l.

In addition, short term sediment concentration variations correlating with the pumped-storage operation were observed. The quotient between C_{Pump} und C_{Turb} shows which quantity of sediment is moved in one or the other exploitation direction of the plant. Temporarily, particle load during pumping mode was 16% higher than during the precedent or following turbine sequences ($C_{m,Pump}/C_{m,Turb}$= 1.16). Reservoir levels play a predominant role, as increased concentration in pumping mode was observed for low Lake Grimsel level, whereas low Lake Oberaar levels resulted in systematically higher particle load in turbine mode.

Sediment balance. Over the eight months monitoring period, more than 45,000 t of fine sediment were moved by the pumped-storage operations. Assuming a density of 1500 kg/m^3 (Bühler *et al.*, 2004), this corresponds to a total volume of about 30,000 m^3. A comparison to the calculations of Anselmetti *et al.* (2007), who give total sedimentation rates for Lake Oberaar and Grimsel of 22,200 and 74,650 m^3 respectively, emphasizes how much suspended sediment is constantly moved up and down by the hydropower exploitation in the Grimsel 2 system. Nevertheless, the suspended sediment balance due to pumped-storage operations was equilibrated over the period from October 2010 to 2011, i.e. no net sediment exchange occurred between the two reservoirs.

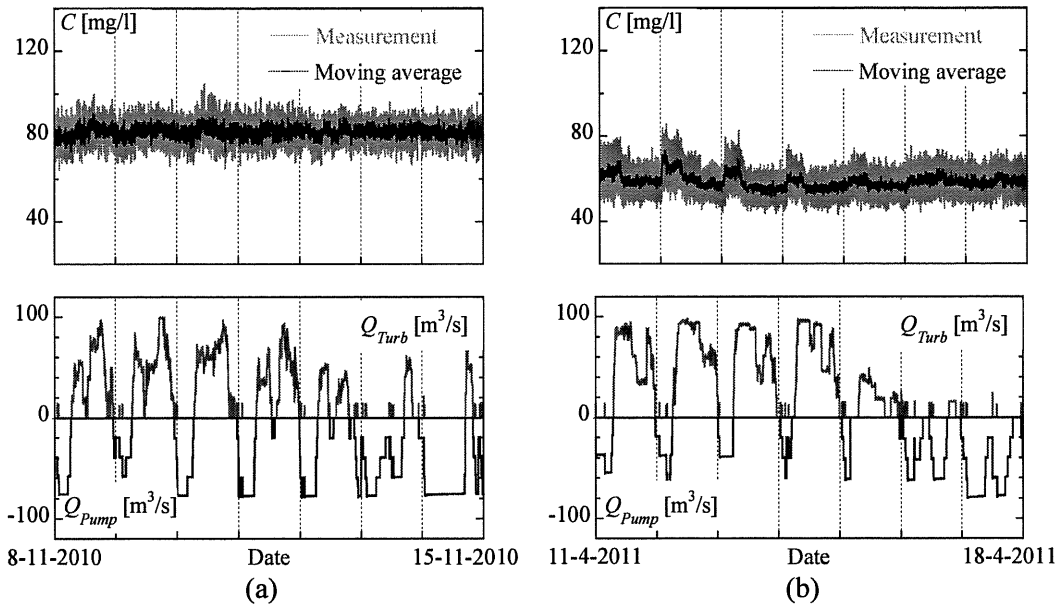


Figure 4. Evolution of suspended sediment concentration C and discharge $Q_{Pump,\ Turb}$.
a) Period from 08. - 15.11.2010, reservoir levels 2298 m asl. (Oa) and 1900 m asl. (Gr),
b) Period from 11. - 18.04.2011, reservoir levels 2265 m asl. and 1900 m asl.

EXPERIMENTS ON THE INFLUENCE OF PUMPED-STORAGE SEQUENCES ON THE SETTLING BEHAVIOR OF SUSPENDED SEDIMENT

In hydraulic engineering, the understanding of flow behavior in reservoirs allows specific design of intake/outlet structures as well as sluice gates and helps describing entrainment

and settling processes of suspended particles. Kantoush *et al.* (2008) focused on flow patterns and sedimentation behavior in shallow reservoirs and Jenzer Althaus (2011) investigated the effect of a rotating jet induced flow close to intake structures on sediment mixing. The effect of repetitive in- and outflow sequences and the influence of their amplitude and frequency on flow patterns and fine sediment behavior have not been investigated so far and were addressed in the presented experimental work.

Experimental facility and parameters

Laboratory set-up. Two basins were interconnected by a reversible water circuit for generating in- and outflow sequences (Figure 5a). In the front wall of the 12 m^3 rectangular main basin (subscript *MB*), a trumpet shaped intake/outlet structure was implemented. The mixing tank (subscript *MT*) provided mixing possibility and storage volume to move water from or to the main basin. Both reservoirs were equipped with a turbidity sensor which continuously sampled sediment concentration. In the main basin, seventeen 2 MHz Ultrasonic Velocity Profilers (UVP) were installed for horizontal 2D flow mapping.

The main basin width B_{MB} was chosen for normalizing lengths. Velocities and time are normalized by the approach flow velocity in the pipe $v_0 = Q_{IN,OUT}/A$ and the mean residence time $t_m = V_{MB}/Q_{IN,OUT}$ respectively. Latter was proposed by Stefan and Gu (1992) for normalization of time in jet mixing problems and can also be calculated for real pumped-storage plants. For the presented experiments, t_m is 8,000 to 30,000 s. Based on the volumes of the two volumes, the design of the water intake/outlet as well as real case pumped-storage cycles, the experiments were carried out for five different discharges (cycle magnitude) from $Q = 0.3$ to 1.1 l/s.

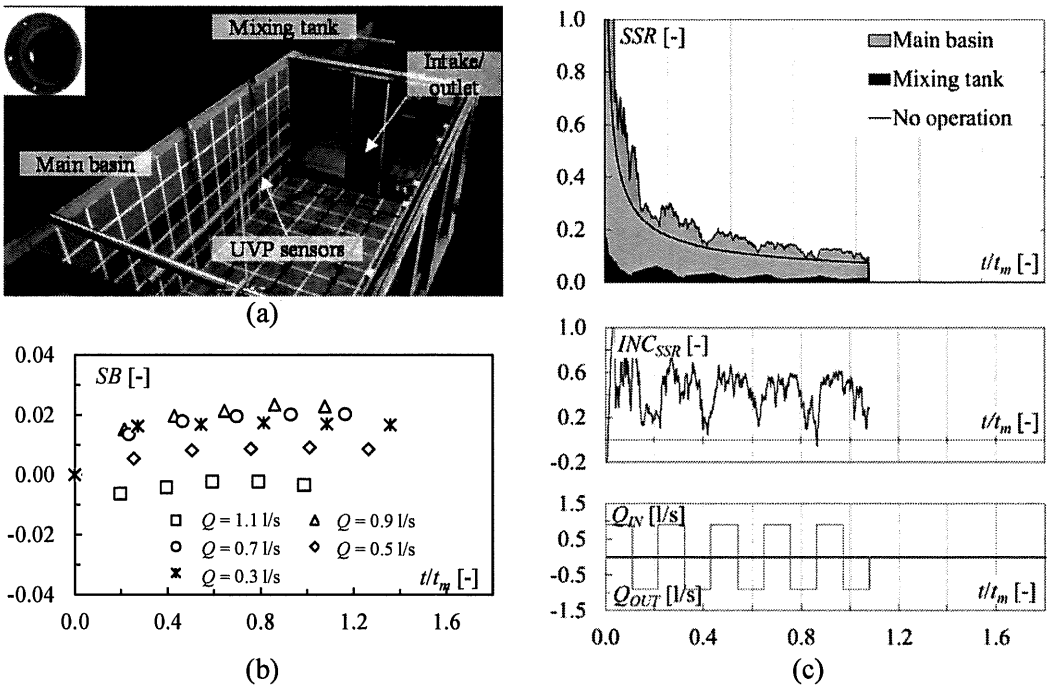
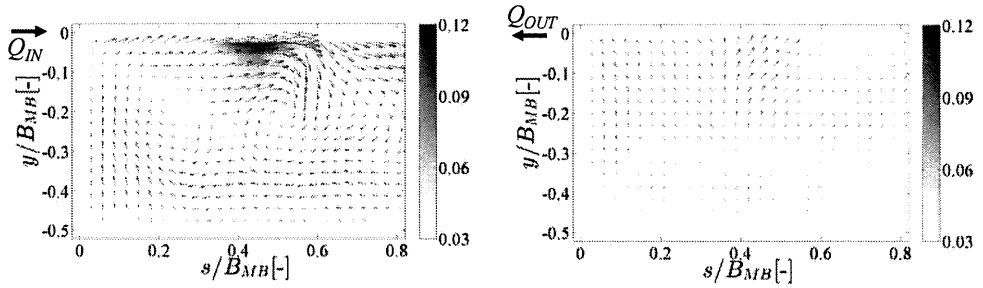


Figure 5. a) Photo of the laboratory set-up, b) sediment balance *SB* as a function of dimensionless time t/t_m for different cycle magnitudes Q, and c) suspended sediment ratio *SSR*, dimensionless increase INC_{SSR} and Q as a function of t/t_m.

Sediment characteristics. To allow the reproduction of prototype ratios between flow velocities and settling velocities in reservoirs, suspended sediment in the experiments were reproduced by walnut shell powder. This homogeneous material was characterized by a mean particle diameter of 121 μm, a specific density of 1480 kg/m^3 and a slightly angular particle shape. As sediment concentration influences the settling velocity in a fluid, tests were carried out for three initial concentrations.

Description of flow patterns

Jet behavior. 1D-UVP-measurements allowed characterization of the jet during inflow-sequences and comparison with values for jet velocities given in literature. For the applied geometry, the evolution of the centerline velocity reveals a jet with a very short core and a fast drop of centerline velocities in the transition zone. Hence, centerline velocity decreases by increasing distance to the nozzle, following quite well the curves from literature (Jirka, 2004).



(a) (b)

Figure 6. UVP sampled horizontal flow patterns at z/B_{MB} = 0.25 (intake axis) for Q = 1.1 l/s and Kt_P = 0.8. a) Inflow-sequence, b) outflow-sequence

2D flow patterns. The analysis of horizontal 2D flow patterns and the calculation of kinetic energy in the main basin allowed the determination of the time to reach steady state conditions and thus constant kinetic energy in the test volume. This "time to peak" between t_P/t_m = 0.099 and 0.136 defined the experimental test duration for different discharges. The basic test configuration then consisted in five in- and outflow sequences, with duration of t_P/t_m each. Further, this duration was multiplied by the parameter Kt_P, resulting in four different cycle frequencies. Higher frequencies Kt_P = 0.6 and 0.8 implicate faster changes in operation mode and reduce the time to reach steady state conditions in the test volume. Kt_P = 1.2 is assumed to prolongate the steady conditions in the basin before the inversion of flow direction. Flow patterns sampled at three levels in the main basin show jet oscillations and recirculation cells for inflow sequences (Figure 6a). At the beginning of outflow sequences, an influence of the preceding inflow sequence was measured. Then a very low potential flow field was measured very close to the intake/outlet (Figure 6b). Otherwise no tendency could be observed regarding systematic movement of the water body. Measures above and below the jet axis indicate backflow zones toward the intake/outlet close to the bottom during inflow sequences and mainly for high discharges. The upper and lower horizontal sections present the same recirculation cells as in the jet axis, with lower velocity magnitudes.

Cycle magnitude considerably affects the kinetic energy in the basin. According to the experimental results, a discharge of Q = 1.1 l/s generates up to three times more energy than one of Q = 0.3 l/s. Numerical results even predict a ratio of ten between maximum and minimum discharge. Cycle frequency has less influence, while an intake position closer to the bottom or the free water surface leads to considerably higher energy levels.

Suspended sediment behavior

After having determined the reference settling curve of the sediment under no operation conditions, the suspended sediment ratio *SSR* was defined as the time-dependent quotient between the sediment mass remaining in suspension during the experiment over the total initial sediment mass. The efficiency of in- and outflow sequences on keeping the fine sediments in suspension was defined by the normalized increase INC_{SSR} of suspended sediment ratio with and without in- and outflow cycles. High values of INC_{SSR} represent

high impact of the tested sequences. Values close to 0 indicate that the settling behavior is similar to a no operation scenario without in- and outflow sequences.

Suspended sediment ratio. Experimental results reveal an initial settling phase of particles which is only marginally influenced by the tested in- and outflow cycles. Approximately 60% of settling takes place during $t/t_m = 0.2$, corresponding to the first or the first two cycles, according to discharge. For low discharge, the evolution of suspended sediment ratio *SSR* is not clearly correlated to the in- and outflow cycles, but compared to conditions without operation *SSR* can be increased by 10 to 40%. For high discharge, the evolution of concentration correlates with discharge cycles and leads to suspended sediment ratios between 50 to 80% higher than in calm water conditions (Figure 5c). Especially during the first settling period, cycle frequency is a key parameter for the efficiency of the operational sequence. If high cycle frequency and high cycle magnitude are applied in the starting period, *SSR* can be considerably increased: even after $t/t_m = 1.6$, *SSR* remained about 60% higher than without operation. Further experiments shows that *SSR* increases for intake positions closer to the bottom or to the free water surface. The resulting flow conditions with more vertical movement in the water body keep more particles in suspension. Varying relative sequence duration increase *SSR*. When inflow sequences are intercepted by shorter outflow sequences, particle settling is reduced due to increased turbulence in the test volume.

Sediment exchange rates. The overall sediment balance *SB* remained equilibrated over the test period and was smaller than 4% for all tested configurations (Figure 5b). Thus, the sediment balance in the system is not significantly influenced by the in- and outflow sequences even if the total moved mass during in- and outflow sequences is high. As suspended sediment concentration decreases rapidly at the beginning of the settling phase, the exploitation direction of the first sequence defines if the sediment balance of the main basin is positive or negative over the entire test duration.

CONCLUSIONS AND RECOMMENDATIONS

Both prototype measurements and laboratory experiments reveal the effect of pumped-storage activities (in- and outflow sequences) on flow patterns as well as on settling behavior of fine sediment in reservoirs. Outflow (withdrawal) has less impact on flow patterns, as the velocity field is only locally influenced near the intake structure. During inflow sequences the jet is mixing the water body and can generate big recirculation cells. These phenomena are influenced by the intake/outlet position and geometry as well as by the shape of the storage volume. The evolution of the suspended sediment ratio is correlated to the magnitude and frequency of the in- and outflow cycles for a certain discharge threshold. The prototype monitoring of sediment concentration reflected the pumped-storage sequences at low reservoir levels. Both approaches indicate that the global sediment balance of pumped-storage operations is equilibrated. As long as suspended sediment concentration is similar in both reservoirs, the sediment balance is thus essentially correlated to the pumped-storage operation.

In the real case of the arrival and deposition of a turbidity current in the area of pumped-storage intake/outlet structures, it is expected that an important settling occurs during the first hours after the event, which cannot entirely be avoided by an adequate plant operation. However, according to experimental results, the quantity of fine sediment kept in suspension can be considerably increased when operating the plant at high discharge and with short pumped-storage sequences in this phase. Later on, pumped-storage operation at high cycle magnitude is the most promising measure to slow down sediment settling. Prototype monitoring did not reveal net sediment exchanges but it has been shown in former research that pumped-storage operation can contribute to sediment redistribution, especially during summer months, when natural sediment input is usually highest.

In future, the increased demand of grid regulation and peak energy supply will probably lead to quite short and frequent pumped-storage cycles with the corresponding effects on the water body close to the intake/outlet structures. Considering the influence of the in- and outflow sequences on fine sediment behavior at an early stage of the planning and design of the intake/outlet structures of pumped-storage power plants will allow implementing adequate sediment management of their reservoirs. From a reservoir sedimentation point of view, the orientation of the intake/outlet structure as well as a high kinetic energy input to generate high turbulence in the zones near the structure are two key parameters. In fact, the kinetic energy provides a quantifiable parameter with important influence on sedimentation by fine particles and can be determined based on numerical computations or in situ measurements of flow velocities.

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