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Influence of pumped storage operation on flow conditions near intake/outlet structures: in situ measurement using ADCP

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ABSTRACT: In the framework of a research project studying the influences of pumping/turbine modes on turbulence, flow fields and suspended sediments in reservoirs, prototype measurements are carried out at the Grimsel II pumped storage plant (Switzerland). In situ recordings comprise flow and velocity patterns in the lower reservoir. For the measurement of flow velocities, Acoustic Doppler Current Profiler (ADCP) devices have been fixed on the reservoir bottom in front of the intake/outlet structure. The temporal evolution of three-dimensional velocity profiles in front of the intake is compared to the operation data provided by the hydropower producer. Flow fields corresponding to the expected main direction of the in- and out-flowing jet are observed during both pumping and generating activity. Periods, where their orientation and the expected main direction of the jet do not correspond clearly are studied in more detail, splitting up data series in characteristic sequences and applying frequency analysis. Such signal processing reveals the correlation between the velocity profiles in front of the intake/outlet and the change between pumping and turbine mode.

Keywords: Pumped storage hydropower plant, Reservoir sedimentation, Turbulence, Flow and velocity patterns in reservoirs, Acoustic Doppler Current Profilers

1 INTRODUCTION

Modern power plants are expected to operate at variable speed in a wide range of output power with improved efficiency, flexibility and safety. Therefore, the pumped storage power generation has gained in importance since it allows storing and generating electricity to supply high peak demands by moving water back and forth between reservoirs at different elevations.

In the context of a project consortium called *HydroNet – Modern Methodologies for Design, Manufacturing and Operation of pumped storage power plants* aiming to converge towards a consistent standardized methodology for design, manufacturing, operation, monitoring and control of pumped storage power plants, a research project consists in the description and the control of sedimentation issues in the reservoirs of such hydropower schemes.

Reservoir sedimentation and the main measurements against reservoir sedimentation are well described (Morris et al., 2008, Nicklow, 2000, De Cesare et al., 2005, Morris, 1996, Oehy, 2002). However, the direct link between sedimentation problems and the more recent pumped storage hydropower projects remains poorly treated. Due to pumped storage operations suspended sediments are transferred from one reservoir of the system to the other. As the pumped storage activity is growing, flow conditions in the reservoir are alternating from one state to another during relatively short laps of time.

What are the effects of such changes between pumping and generating mode on the turbulence in the reservoirs and consequently the sedimentation process by fine sediments? How do discharge and duration of pumped storage operations affect the sedimentation processes in a reservoir? Are there conceptual solutions during the operation time of a pumped storage plant which allow using the alternating pumping and generating activities to positively influence the reservoir sustainability?

These are some of the questions which are to be examined in physical and numerical modeling in the framework of the Ph.D. thesis. As the *HydroNet* project focuses on prototype monitoring and control, fundamental research is completed with in situ measurements.

Such prototype data collection was carried out in autumn 2008 on the occasion of two field campaigns. With the objective of investigating flow conditions near an intake/outlet structure of a pumped storage plant, Acoustic Doppler Profilers were placed on the reservoir bottom, recording flow velocities over a period of three weeks. After data extraction, three-dimensional velocity profiles are established, their temporal evolution is compared to the pumped storage operation data provided by the power producer, and correlation between the flow fields in front of the intake/outlet structure and the pumped storage activity is studied.

The present paper covers the main characteristics of the study site and the measuring device and discusses the results of these first in situ recordings.

2 METHODS AND ANALYSIS

2.1 *Prototype characteristics*

In collaboration with the Swiss power producer *Kraftwerke Oberhasli AG (KWO)* prototype data recording and monitoring is carried out at the Grimsel II pumped storage plant, situated in the Central Alps of Switzerland downstream of the two glaciers of Ober- and Unteraar and upstream of Lake Brienz (Figure 1).

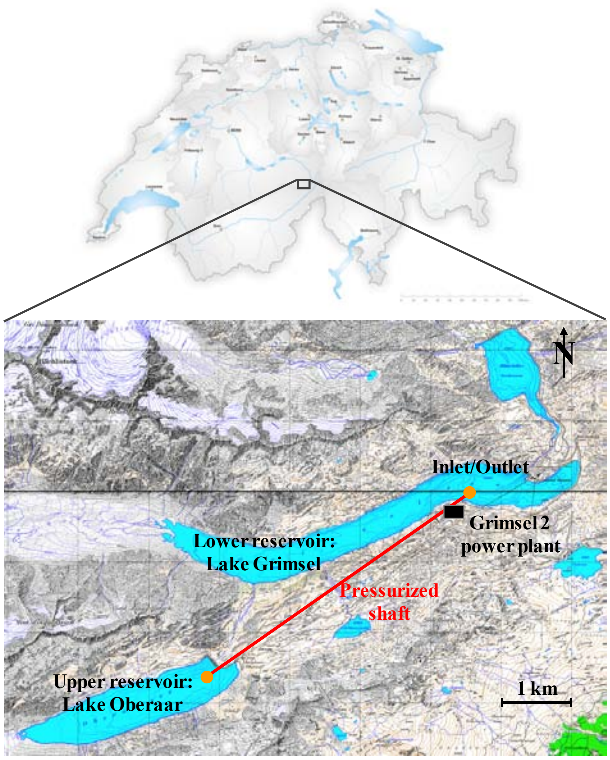

Figure 1. Location map and situation of the pumped storage scheme Grimsel II, Switzerland

The underground powerhouse of this pumped storage plant exploits water of the upper reservoir Lake Oberaar (2303 m a.s.l.) and the lower reservoir Lake Grimsel (1909 m a.s.l.), where the present study of flow conditions near intake and outlet structure has been carried out. Lake Grimsel, impounded by the Spittellamm arch dam and the Seeuferegg gravity dam, is characterized by a surface of 2.72 km^2, a gross storage volume of 95×10^6 m^3 and a maximum depth of 100 m.

The major driving forces for sediment movement in narrow and rather steep alpine reservoirs such as Lake Grimsel are turbidity currents (Fan & Morris, 1992, De Cesare et al., 2001, Schleiss & Oehy, 2002). This mechanism, mainly occurring during flood events and transporting large amounts of suspended sediments to the deepest zones of the reservoir near the dam, has been investigated and applied to the lower reservoir of Grimsel II power plant by Oehy (2002).

The Lake Grimsel intake/outlet is characterized by a shape similar to a morning glory spillway embedded in a recess of the lake topography with its foundation platform situated at a level of 1942 m a.s.l. The lateral open cylinder has an effective height of 6.25 m and a diameter of 21.70 m and is equipped with ten guiding walls which are supposed to distribute the out-flowing discharge equally on the ten side openings of the tulip (Figure 2).

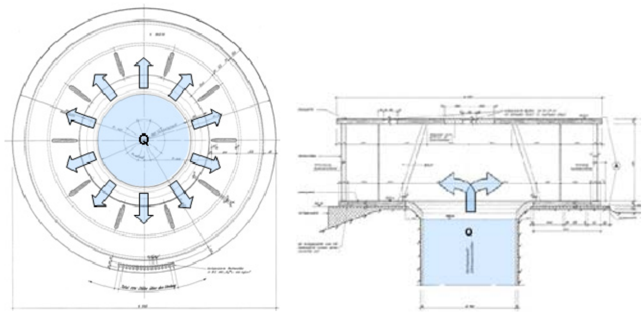

Figure 2. Grimsel II intake/outlet structure in Lake Grimsel; schematic plan view (left) and cross section (right)

The connection to the Grimsel II powerhouse is assured by a pressure conduit of 7.50 m in diameter which, during generating activity, ejects discharges up to 100 m^3/s through the cylinder and into Lake Grimsel. During pumping mode, a maximum discharge of 80 m^3/s is ingested by the intake structure and led to the four pumped storage units of Grimsel II.

2.2 *Data collection*

2.2.1 *Acoustic Doppler Current Profilers*

3D flow velocity data was collected by using three 300 kHz Acoustic Doppler Current Profilers (ADCPs). The three Teledyne RDI units were frame-mounted and placed on the bottom of the Grimsel reservoir. In early autumn 2008, the ADCP data were recorded for 5 days from September 15th to 20th. In November 2008, sampling went on for two more weeks from November 6th to 20th.

The RDI profilers covered the whole water column and operated with 85 1-meter size bins and recorded mean currents every 5 minutes. The mooring of the device on the bottom and the blind zone of the instrument place the first bin at about 5.0 m above the lake bottom. Since acoustic backscattering at the free surface strongly disturbs current data for the bins near the surface, the last bins were omitted. Consequently, current profiles from 5.0 m up to 80 m above the lake bottom (depending on the reservoir level) were recorded. Horizontal velocity resolution is better than 0.12 m/s in this configuration.

2.2.2 *Profiler position*

The location of the ADCP near the intake/outlet structure takes into account implementation criteria for the RDI units. Minimal distance of 25 m from the intake/outlet structure and 5 m below the horizontal intake axis limits interference between the emitted beam and the concrete civil engineering works. Sidelobe interference between the instruments can be limited by respecting a distance of 50 m between two profilers.

Furthermore, the alignment of the three ADCPs is based on the intake/outlet geometry. It is assumed that at the ten outlet sectors shown in Figure 2 the main direction of the out-flowing jet corresponds to the axis of these sectors. Hence, measurement axes are orientated in this same direction as the axes of intake/outlet sectors.

However, Lake Grimsel bathymetry is the main parameter governing the implementation position of the measuring devices. To the West, the structure is surrounded by relatively steep rock slopes and to the East, in the direction of Spittellamm dam, the reservoir bottom is flat and situated almost 10 m below the intake level (Figure 3).

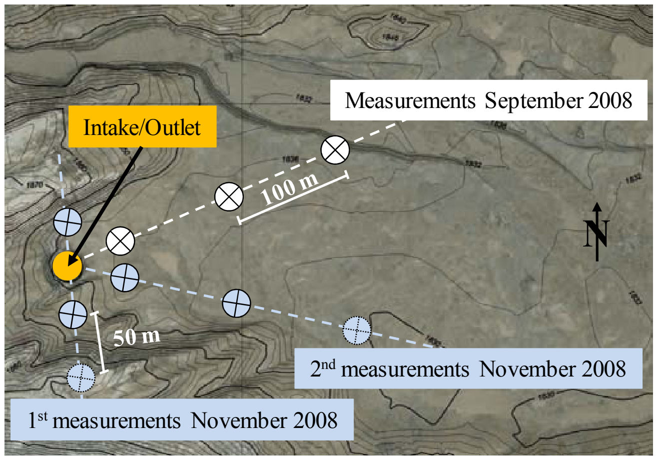

Figure 3. Lake Grimsel bathymetry and positions of the Acoustic Doppler Current Profilers for the three measurement campaigns

This NE-ESE sector of the plain suits best for the velocity sampling since it guarantees a stable position of the frame-mounted ADCP and limits the risk of losing important velocity data within the blind zone of the instrument.

The September 2008 measurement axis is thus orientated in ENE direction and situated in the flat part of the reservoir bottom. Concurrently, this alignment corresponds to the principal geographical orientation of Lake Grimsel. According to the results of this sampling period, two additional measurement axes have been determined, the first one almost exactly in N-S, the other one in ESE-direction. Apart from revealing influences of reservoir bathymetry and pumped storage operation on flow conditions near the intake/outlet, this measurement configuration could allow detecting eventual internal longitudinal or transversal movement of the entire lake (internal seiches). Such large scale dynamics have been investigated by Stevens & Lawrence (1997) for several reservoirs in Canada, as well as by Bouffard (2008) and Lemmin (2005) for Lake Geneva and could also occur in Lake Grimsel. Whether these oscillations are affected by the pumped storage operation remains to be studied.

The correct position of the ADCPs was determined by GPS from a small vessel and controlled measuring the water depth at the lowering point by manual echo sounder. When the profiler reaches the reservoir bottom, a system of a two plane articulation allows orientating the measuring device in an exact upward-looking position. The two angles related to vertical and horizontal positions are recorded by the instrument, in order to know at what moment the measuring device stabilizes. Constant values of these two angular parameters indicate the beginning of a reliable recording period.

2.3 *Data analysis*

During the entire measuring periods, KWO provided relevant data related to the Grimsel II plant, namely pumped storage discharge and the level of Lake Grimsel. Comparing the reservoir level to the pressure measurement given by the ADCPs, a second control of depth at the lowering point was possible and correct positioning of the instruments could be confirmed.

Water temperature is measured and registered by the ADCP and provides additional information about the conditions on the lake bottom near the intake/outlet structure and about the temperature difference between the two reservoirs. Generally, in winter, the reservoirs are covered by ice and inversely stratified, with increasing temperature from 0 °C at the surface to 2.5 °C at the bottom. In summer, both reservoirs are ice-free and thermally normally stratified, with surface temperatures reaching 10 °C. In the upper reservoir, the thermocline is located at 15 m depth and bottom temperature is about 4 °C. In Lake Grimsel, no well defined thermocline is measured and bottom temperature reaches some 5 °C (Bonalumi, 2009). These observations are confirmed by the ADCP recordings which do not reveal temperature differences due to pumped storage operation at the intake/outlet depth.

For the reliable recording period, each RDI unit provides North and East velocity components of the flow on every meter of the water column. In a first step, data points with either velocity values smaller than the measurement error or no reasonable record (indicated by the ADCP setting the velocity to a very high specific value) are set to zero. This process leads to gaps in the velocity time series at correspondent water depths and to abrupt unreasonable changes between reliable velocity value and zero within the given time step of 5 minutes. Therefore, the velocity has been averaged over five time steps at every position, allowing smoothing the series without losing information about the dynamics of the movements in the Lake.

During the first field campaign in September 2008, reliable data is available for a period of three and a half weekdays, from September 16th to 19th (midday). As shown in figure 4a, this measuring term is characterized by three main generating sequences, with only marginal pumping activity at night.

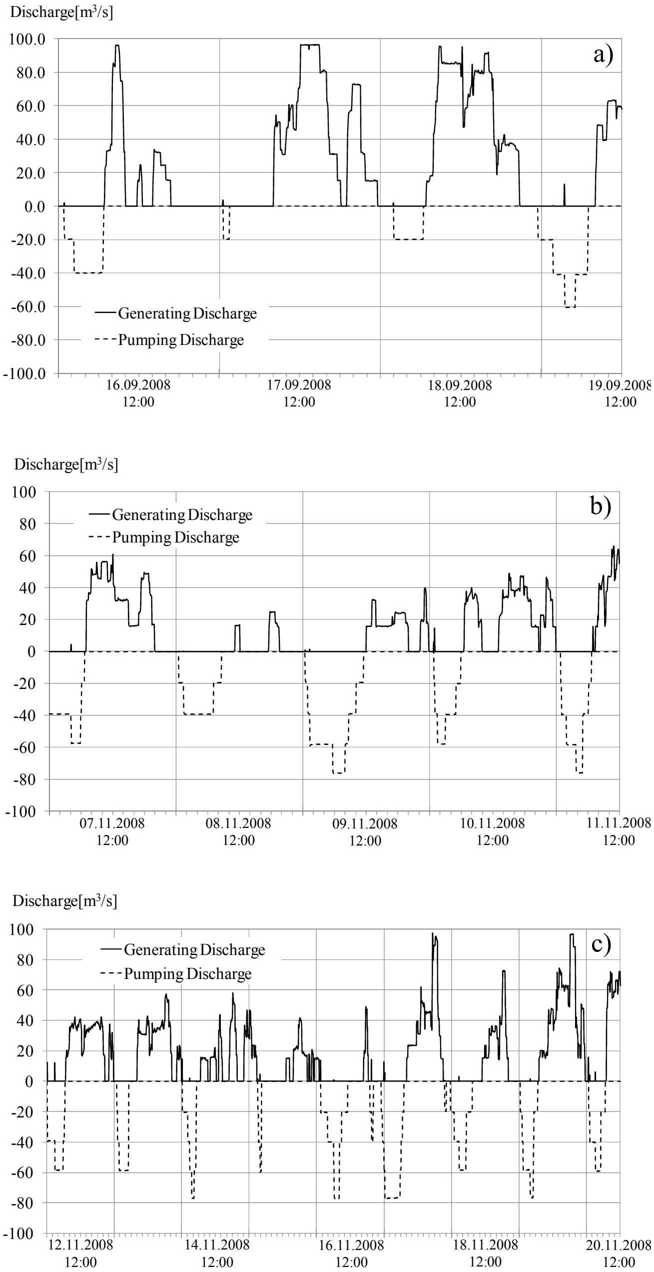

Figure 4. Pumped storage operation data of Grimsel II plant during the velocity sampling periods in a) September 2008, b) and c) November 2008

When extracting data from the RDI units after the second measurement campaign, one instrument turned out to have suffered from a short circuit probably when lowered onto the reservoir bottom. Consequently, results from only two ADCPs are available for the period in November 2008. This time, the instruments remained in the lake during 15 days, resulting in velocity profiles for periods of six (1st measurement axis) and eight days (2nd measurement axis, Figure 3). As shown in Figures 4b and 4c, data has been gathered not only for weekly pumped storage operation with main generating sequences interrupted by short terms of pumping activity, but also during weekends when water is pumped back into the upper reservoir during several hours of the day.

Consequently, the two campaigns allowed recording flow velocities related to short term sequences, with generating mode during the day, and pumping activity at night, as well as midterm sequences consisting of successive upper reservoir drawdown along the week and pumping activity during weekends.

3 RESULTS AND DISCUSSION

3.1 *3D velocity fields in front of intake and outlet*

After data extraction and treatment, time dependent, three-dimensional velocity profiles are generated in the reservoir with the objective to obtain information about flow conditions in front of the intake/outlet structure. The visualization by a movie allows comparing the temporal evolution of the velocity profiles to the pumped storage operation data provided by the power producer in order to detect whether the orientation of the flow field could be linked to the expected main direction of the in- or out-flowing water masses.

Characteristic velocity profiles, averaged over five time steps, observed while the power plant operates in generating mode are shown in Figures 5a to 5c, for the three different measurement axes. In the plain to the East of the outlet, the velocity vectors are leading away from the outlet in a radial direction, which corresponds to the expected orientation of the jet (5a and 5c). In contrast, the velocity profiles recorded to the North and South of the outlet do not point away from the structure but are directed eastwards again towards the flat reservoir bottom (5b). This redirection of the out-flowing jet is probably due to the lake topography with its steep slopes to the West of the outlet which do not allow a uniform circular flow distribution around the structure.

Apart from the orientation of velocity vectors, some general properties of the profiles can be pointed out which are observed for either measurement axes. Each profile can be divided in four zones on the water column.

From the reservoir bottom up to the top of the intake/outlet structure only small or even no velocities have been registered. Thus, the bottom layer of the lake seems not to be influenced by the pumped storage activity due to its position on a small platform situated about 10 m above the reservoir bottom.

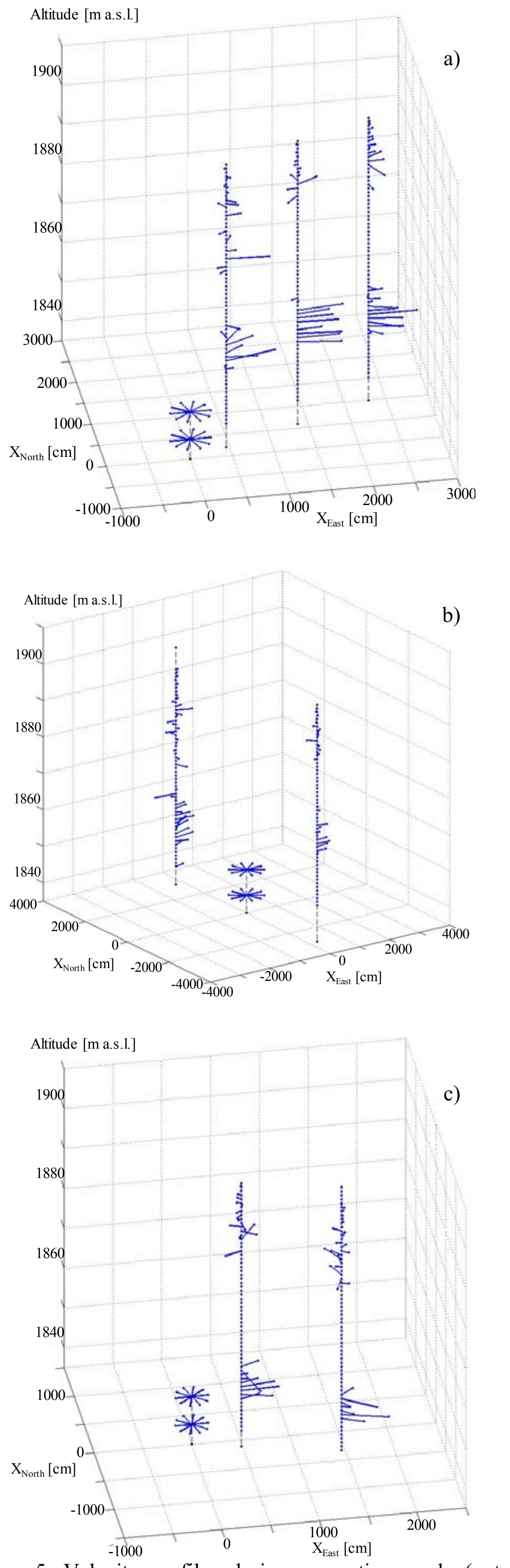

Figure 5. Velocity profiles during generating mode (out-flowing jet) in front of the Grimsel II intake/outlet structure; a) September 2008, b) 1st measurements in November 2008, c) 2nd measurements in November 2008

The main velocity field induced by the generating activity of Grimsel II plant has a height of 5 to 10 m and is not situated on the level of the horizontal axis of the outlet, but slightly above. When being ejected from the pressure conduit into the cylinder, the jet has an important vertical velocity component which could lead to this vertical shift of the velocity profile.

In the central part of the lake, as for the bottom layer, no velocities were recorded by the instruments. Apparently, no horizontal movement is occurring in this zone of the reservoir.

The water masses close to the lake surface present small velocities often pointing in opposite direction of the velocity vectors in the jet zone, indicating a circulation of the lake. Nevertheless, as surface velocities are strongly affected by wind, it cannot be assumed that only the leaving the outlet jet is provoking a big circulation cell in the entire lake.

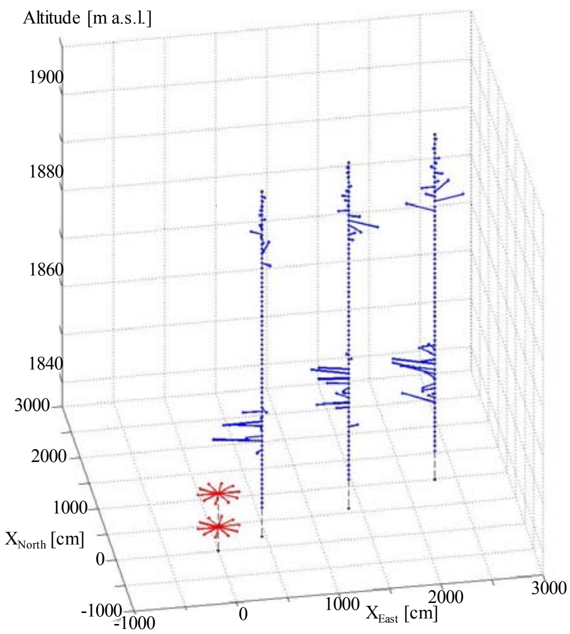

Figure 6. Velocity profiles during pumping mode (inflowing discharge) in front of the Grimsel II intake/outlet structure; September 2008 measurement axis

Figure 6 shows the flow field in front of the intake measured during a pumping sequence in September 2008. The velocity vectors are this time directed towards the intake structure, again orientated quite precisely in the axis of one of the ten intake sectors. Except for the orientation, the profile characteristics are similar to what has been observed in generating mode. The main field covers between 5 and 10 m of the water column and is situated slightly above the level of the intake. Again, neither the zone close to the reservoir bottom nor the central layer present measurable velocities, they remain stable and are not affected by the pumping activity. Surface velocities cannot be linked to the direction of inflowing discharge, they seem presenting mainly random directions or the same orientation as during generating mode.

3.2 *Statistical signal processing*

Flow fields corresponding to the expected main direction of the in- and out-flowing jet are observed during both pumping and generating activity. However, there are periods where the orientation of the velocity vectors and the expected main direction of the jet do not correspond clearly. Especially right after changes from one operation mode to the other, velocity profiles keep their initial orientation during a certain time before redirecting according to pumping or generating mode. Furthermore, water masses are in movement even though there is no pumped storage activity. At first view, no preferential orientation of the flow direction can be observed in these periods.

In order to determine whether the recorded velocities are directly correlated to the pumped storage activity, power spectra of the data series and the discharge data have been compared. This approach, based on the Fast Fourier Transform (FFT) method, is often used in signal processing and allows finding the main frequencies of a data series (Lyons 2004).

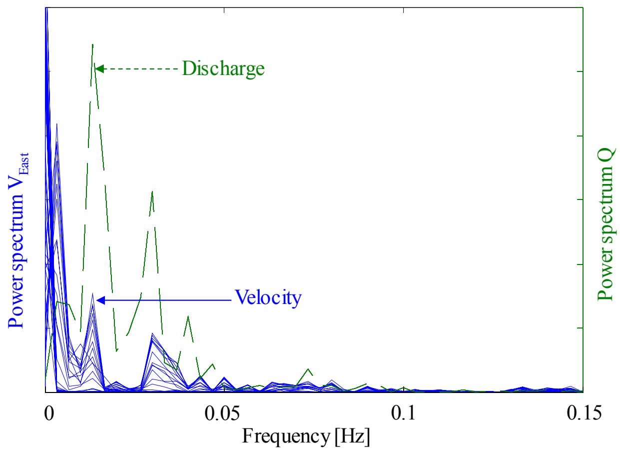

Figure 7. Power spectra of East velocity component and discharge data, 1st measurement November 2008, profiler 1 (to the north of the intake/outlet, Figure 3)

Figure 7 reveals that the main frequencies of the two signals (peaks) are close to each other and therefore foreshadow a direct link between the recorded velocities and the pumped storage discharge.

In order to get better information about correlation between velocity and discharge, raw ADCP data is used for the establishment of power spectra. Velocity has thus been split into its two components (North and East) and signal processing reveals that East velocity shows equal main frequency as discharge data while North velocity cannot be linked to the pumped storage activity.

3.3 *Outlook*

The processes induced by pumped storage activity in Lake Grimsel are to be studied in more detail in order to confirm the observations presented in this paper and to understand the ongoing flow phenomena more in detail.

Especially the influence of bathymetrical conditions have to be analyzed since the Grimsel II intake/outlet structure is embedded in a very complex topography which influences directly on the flow conditions and the redirection of the outflowing jet. The importance of such topographical effects on flow distribution near intake/outlet structures has been revealed by earlier field investigations using ADCP, for example in the reservoirs of the Okumino hydropower plant (Goto & Tsuchiyama, 1998). A numerical model of Lake Grimsel will therefore be set up containing the Grimsel II intake/outlet structure, but also all other hydraulic works which are supposed to interact with the flow fields in the lake. ANSYS CFX 12, a CFD package including a solver based on finite volume method and pre- and post processing tools, will then be used for the calculation of flow fields.

Surface velocity profiles will be compared to wind data provided by KWO and the Swiss Federal Office of Meteorology and Climatology in order to evaluate the origin of circulation cells in Lake Grimsel and eventually link them to the pumped storage operations.

Additional signal processing is carried out in order to detect or reject correlations between the flow velocities and the in- and out-flowing jet.

Further research includes physical modeling of the influence of turbulence induced by pumped storage activity on the suspended sediments in a simple reservoir geometry.

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