Measurement of Flow Patterns within an Alpine Reservoir

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ABSTRACT: The runoff from Austria's largest glacier, Pasterze, is collected in the Margaritze reservoir. From there, the 11.6-km long Möll gallery diverts the flows to two high-level reservoirs of the Glockner-Kaprun group of power schemes. Having a capacity of no more than 3.2 million cubic metres, the Margaritze reservoir offers little space for holding the substantial amounts of sediments contained in the glacial runoff. In the past, reservoir sedimentation has already caused problems in the operation of the bottom outlet. For more than 13 years, owner Verbund Austrian Hydro Power AG (AHP) has conducted studies to develop an efficient sediment management scheme for this reservoir. The studies have yielded various ideas regarding possible remedial action in this particular situation. Some of the solutions considered have already been applied; others are still at the planning stage. At present, the sediments are being transferred within the reservoir to the shallow part. Partly due to unknown reasons the deposited material is remobilized and conveyed back to the steep part of the water body. In summer 2004 and 2005 measurements were conducted in order to survey the flow patterns, which connote the flow velocities and the concentrations of the suspended solids. The flow velocities were determined by an Acoustic Doppler Current Profiler, which gives 3 dimensional velocity patterns. The measurements were taken considering various boundary conditions, such as water level, transfer under progress, amount of inflows and outflows. Different cross sections and singular spots were carefully chosen for receiving the best overview of the reservoirs flow patterns. The results of the measurements demonstrate that the remobilization and transport of the deposited sediment are directly linked to the transfer of sediment to the shallow part of the reservoir.

1 SEDIMENTATION OF THE RESERVOIR

Situated in the heart of the alpine region, Margaritze reservoir is part of the Kaprun Hydro Power Scheme. Its major water inflow area lies at the foot of a glacier. These inflows exhibit average annual sediment concentrations of 40,000 m³. As a consequence of the increasing sediment deposition in the reservoir, two phenomena can be observed. On the one hand, its storage capacity – and at the same time its benefit for power economy – decreases. On the other hand, sedimentation tends to cause problems in the mechanical equipment parts. In order to keep reservoir facilities in full operation, incoming sediment loads have been removed since the late nineties. By means of a submersible pump, glacial silt is dredged from the gorge section and conveyed to the shallow portion of the reservoir, where it is deposited under certain conditions. So far it is unclear why parts of the sediment load which have been moved to the shallower section of the basin are later on remobilized and at an average 10 to 20 % of the transferred material gets back to the gorge section of the basin (Figure 1).

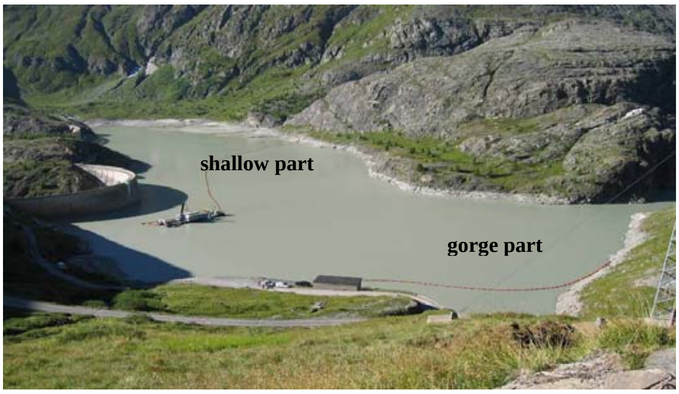

Figure 1: Margaritze Reservoir

Moreover, the question remains to be answered, as to whether sediment conveyance back to the gorge portion is probably already happening during ongoing excavation works. Water level fluctuations inside the reservoir as well as hydraulic inflow fluctuations and sediment flows already during dredging works, respectively, may cause a continuous sediment transfer.

The 2004 and 2005 measurement campaigns were aimed at explaining all relevant details regarding the reservoir flow situation. In addition to this, a possible change in current conditions during the dredging process is to be investigated.

2 MEASURING APPLIANCES

Apart from two 3-D velocity probes (an ADCP® and an Aquadopp® Profiler), a density current probe as well as a temperature and a conductivity probe were employed for the measurements at Margaritze reservoir in August 2004 and August 2005.

Table 1: Overview of the measuring appliances

Measuring appliances	**Conducted measurements**
3D - Aquadopp Profiler®	3D – velocity measurements in transverse profiles and continuous single point meas.
3D – ADCP® Workhorse	3D – Velocity measurement (in profiles and continuous single point meas.)
Temperature and conductivity probe	Temperature and conductivity probes in transverse profiles and single points
Density current probe	Density current probes in transverse profiles and single points
Tracer (sodium chloride) and conductivity probe	Tracer tests

3 THE 3-D ULTRASONIC PROBES

For this project the AQUADOPP® Profiler and the ADCP® Workhorse have been employed measuring velocities by means of Doppler-technology. Unlike single point measurements, these two profilers depict velocities at certain, pre-defined intervals along a depth profile. Compared to single point measurements, its fundamental advantage is its ability to produce a comprehensive recording of the depth profile by way of only a single test. Consequently, a lot of time is being saved. Apart from its high, three-dimensional dissolution, a further advantage of these profilers is the fact that it can be used for extremely low velocities. The employment of the probes required particular adaptations.

The Aquadopp® 3D – velocity probe was fastened to a measuring device, which had been exclusively manufactured for this measuring campaign (Figure 2 and Figure 3**)**. The device comprised four floats and an aluminium framework, to the latter of which the Aquadopp® Profiler had been secured in a 45° angle. This "pontoon" was fastened to a guide rope which was stretched along the profile all across the artificial water basin. In this way, the measuring device was gradually drawn over the cross-section while measurements were conducted at intervals ranging from 4 to 12 meters. While velocity measurements were taking place, also temperature and conductivity measurements were carried out. The respective measuring devices were again fixed to the meter-marked rope and then submerged meter after meter at every single measuring point.

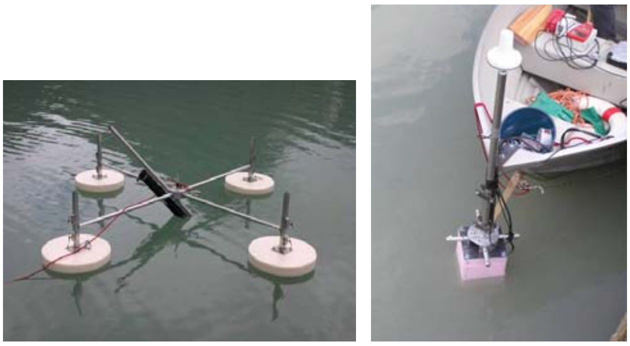

Figure 2: Fixation of the ultrasonic probes (AQUADOPP-left; ADCP-right)

The results gained in all theses measurements clearly reflect a connection between the sediment transport at the bottom of the basin and the operation of the submersible pump. During dredging operations, a suspended sediment load accumulated in the bed of the shallow portion of the reservoir, which then flowed at a speed of about 0.1 m/s and a concentration of approx. 1 g/l towards the gorge section.

Table 2: Technical data of the ultrasonic probes

	AQUADOPP®	ADCP®
Acoustic frequency	2000 kHz / 3 beams	600 kHz/4 beams
Max. ranges	5 m - 12 m	< 70 m
Min. cell size	0.1 m	0.25 m
Measuring area	±10 m/s	±3 m/s
Measuring accuracy	1% of the data	0.25% of the data

4 PARAMETERS OF THE MEASURING CAMPAIGNS

4.1 *Overview*

In August 2004 as well as in August 2005 two measuring campaigns were launched to realize the flow pattern situation according to different parameters at the reservoir (inflow, outflow and water level). Great efforts have been taken to ensure that each transverse profile measurement was performed under approximately the same conditions. That is to say that, as long as a measurement was conducted, there would not be any substantial variation as far as the inflow and outflow conditions, the water level or the dredging system were concerned. Any kind of change in the factors mentioned above was recorded by continuous velocity measurements. As for the arrangement of continuous measurements, altered velocity distributions caused by the dredging system were particularly taken into consideration.

With regards to the results gained in the 2004 and 2005 measurement campaigns, profile measurements may be distinguished from single point measurements (Figure 3). In profiles 1 to 5 velocity (ADCP®) and AQUADOPP®, turbidity, temperature and conductivity were dealt with whereas in profiles 6 to 11 only turbidity, temperature, conductivity and velocity with the ADCP® probe could be measured because of the considerable water depth. Additionally further 10 single points were largely located in the gorge section, where details concerning temperature, turbidity and conductivity were gathered.

Permanent velocity measurements took place at the marked points in the transverse profiles ("Aquadopp Duration", Figure 3). On average, each profile measurement took two hours depending, however, on both measurement duration and the number of marks on each transverse profile. Measurements on each point took between 150 and 300 sec.

Measurements at Margaritze reservoir can be classified as follows.

4.2 *Transverse profile measurements ("ADCP Profil x" in Figure 3):*

- Velocity transverse profiles (3-dimensional)
- Temperature transverse profiles
- Conductivity transverse profiles
- Density current transverse profiles

4.3 *Single point measurements:*

- Continuous velocity measurements (3–D)
- Temperature depth profiles
- Conductivity depth profiles
- Density current depth profiles
- Tracer tests

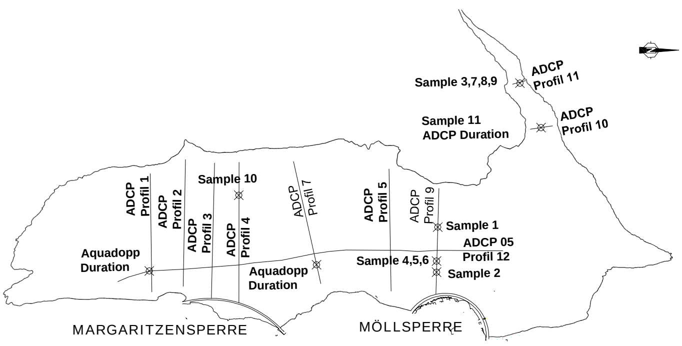

Figure 3: Location of measurements

5 BOUNDARY CONDITIONS

In Figure 4 the rate of inflow respectively outflow of the Margaritze reservoir, the hydrograph of the water level and the working hours of the dredging system are illustrated, exemplary for 2004. The graphs for 2005 show a similar output.

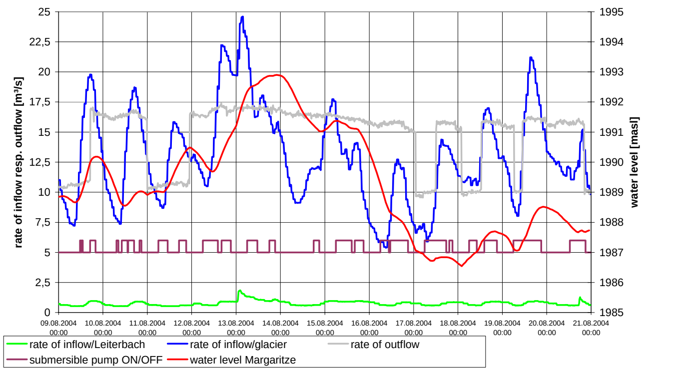

Figure 4: Margaritze reservoir in August 2004: rate of inflow (blue) and outflow (grey), submersible pump ON/OFF (violet) and water level (red)

6 RESULTS

6.1 *Profile 1, submersible pump OFF*

When this described measurement of profile 1 (shallow part, Figure 3) was performed, the submersible pump was out of order. The stemming level rose from 1989.0 to 1989.6 masl, which corresponds to a rising speed of 17 cm/h. The velocity profile towards the north (Figure 5) shows mainly negative velocity patterns. Water flows towards the south. This process may be explained by the increase in the hydrograph. This fact principally involves that water has to flow from the northern section of the reservoir to the southern part.

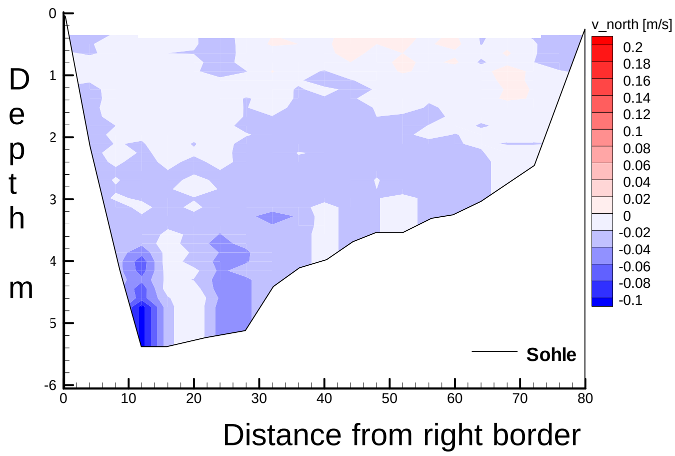

Figure 5: Profile 1, submersible pump OFF, interpolated velocity profile towards the north

Velocities to the east and vertical are less relevant. However, it can be observed that the flow direction in the upper half of the profile tends to head westwards and downwards whereas it moves rather eastwards and upwards in the lower half of the profile. Suspended sediment concentration comes virtually throughout the whole profile to a standard rate of 0.25 g/l. The temperature profile illustrates a layer structure which is most typical for a lake. Near the bottom of the basin the temperature was 4°C while in higher layers it was up to 8°C.

6.2 *Profile 1, submersible pump ON*

Unlike the above under 6.1 described measurement of profile 1, the submersible pump was in operation during measurement 2. The pipe ended in the southern section of the reservoir. The stemming level remained virtually constant on 1989.8 masl. The velocity profile towards the north (Figure 6) now distinctly reveals positive velocity patterns in the deep channel. Water flows to the north. Positive velocities came to 10 cm/s. Compared to measurement 1, velocities to the east and upwards changed only to an inconsiderable degree. Suspended sediment concentration, however, increased drastically from 0.25 g/l to 1.3 g/l in exactly those areas of the deep channel in which northwards velocity had remarkably risen.

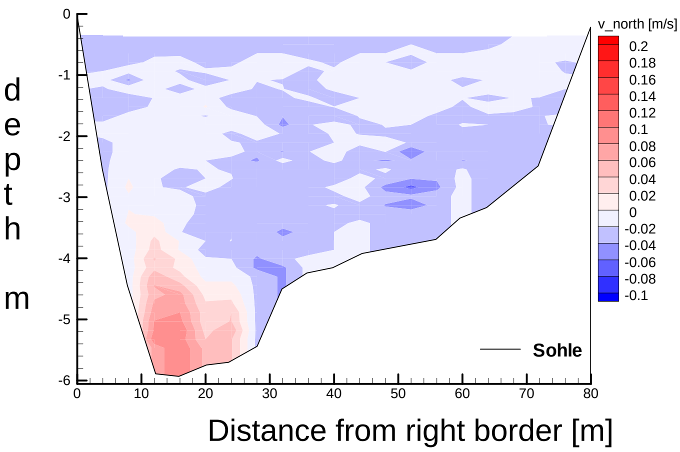

Figure 6: Profile 1, submersible pump ON, interpolated velocity profile towards the north

6.3 *Profile 9, submersible pump ON*

The location of the transverse profile 9 is illustrated in Figure 3. This profile is located at the border between the shallow and the gorge part of the reservoir. The submersible pump was in operation during this measurement. The pipe ended in the southern section of the reservoir. The stemming level remained virtually constant on 1990.0 masl. The velocity profile towards the north (Figure 7) now distinctly reveals positive velocity patterns in the deep channel. Water flows to the north. Positive velocities came to 13 cm/s. Suspended sediment concentration, however, came to 1 g/l in exactly those areas of the deep channel in which northwards velocity had remarkably risen.

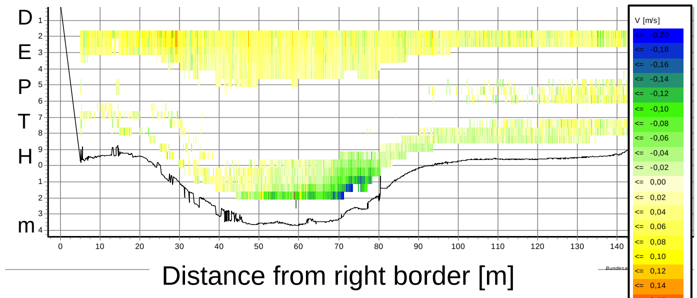

Figure 7: Profile 9, submersible pump ON, interpolated velocity profile towards the south

7 IMPACT OF THE DREDGING SYSTEM

Judging from the measurements described under 6.1, 6.2 and 6.3, it has become evident, that the operating dredging system has a direct impact on the deep channel sediment transport of profile 1. While during the measurements without submersible pump no conspicuous flows or suspended sediment concentrations had been detected, in measurements when the submersible pump was operating exceptionally high velocities towards the north combined with high suspended sediment concentrations (Figure 8) have been found.

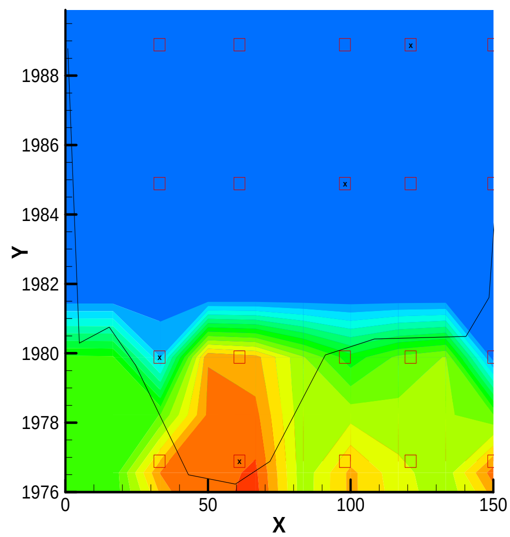

Figure 8: Profile 9, submersible pump ON, interpolated suspended sediment concentration, towards the south

8 TRACER TEST RESULTS

During measurement the sediment inflow mark was located in the southern section of the reservoir. Conductivity was measured at a distance of 160 m from the point where the excavator pump pipes had been submerged. The tracer inflow took place at 00:00 o'clock. The measurement was conducted in various water depths at intervals of 30 sec. 40 kg of dissolved sodium chloride were added to the sediment-water-mixture. The result has been illustrated in Figure 9. The x-axis of the graph shows the measuring duration whereas the z-axis provides data concerning the conductivity in [µS/cm]. A distinct conductivity increase in t=6 m, t=7 m und t=8 m can be observed with its maximum rate occurring at t=7 m, whereas in t=3 m no kind of conductivity increase could be found. Flowing time was 10 cm/s.

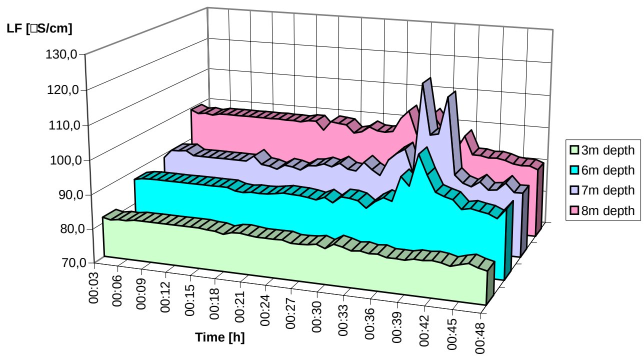

Figure 9: Tracer test results

The tracer method made it possible to determine the origin of the density current. Similarly, it worked most effectively when it came to detecting the average flowing time. In particular, flowing times accurately correspond with the velocity patterns gained in the Aquadopp® Profiler measurements.

Finally, the density current distribution along the bottom of the basin matches the velocity distribution in the ultrasonic measurements. The results obtained from the conductivity profile draw attention to the fact that inside the deep channel increased conductivity has been recorded. Rates rise from average 100 µS/cm to 115 µS/cm. The extent of increased conductivity corresponds to that of increased suspended sediment concentration

9 GRADING CURVE OF THE SUSPENDED SEDIMENTS

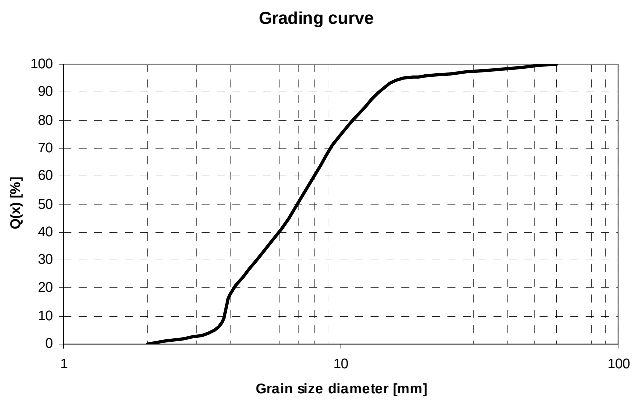

Figure 10: Profile 9, grading curve, water depth 1977 masl

Apart from the long term measurements in 2005 a set of 12 samples were collected to determine the suspended sediment concentration of the supposed density current. The sieve analysis show similar results concerning similar parameters (inflow and outflow to the reservoir, operating hours of the dredging system, water level). The graph in Figure 10 shows the results from profile 9 at a depth of approximately 13 m.

10 MODEL OF STREAM PATTERNS

On account of the results gained in all the measurements dealt with in this study, various models have been designed to provide a detailed description of the various processes going on inside the reservoir. In the following the concept for a model which includes the operation of a submersible pump will be presented in the diagram of Figure 11. The illustration depicts a longitudinal section of the reservoir.

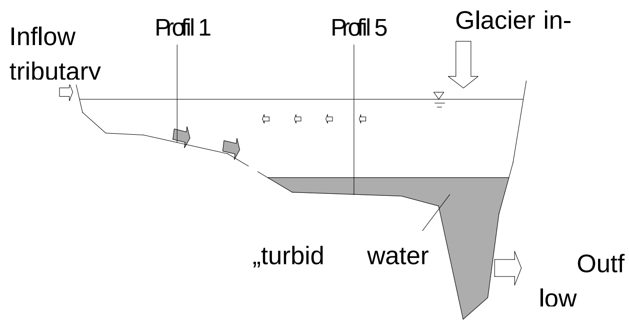

Figure 11: Model of stream patterns, submersible pump ON

If sediment transfer is performed at constant water level by means of a submersible pump, sediment loads will flow along the bottom of the basin towards the north. This fact has been proven to be accurate by both velocity and density current measurements in profiles 1 to 11.

11 CONCLUSIONS

The substantial glacial silt inflow at Margaritze reservoir results into an average annual sediment deposition of as much as 40,000 m³. In order to keep the mechanical facilities in full operation, incoming sediment loads are currently transferred by means of a submersible pump from the gorge section to the shallower portion of the basin. It has been unclear, why some of the transferred sediments are remobilized and how they are transported back into the gorge section of the reservoir. Furthermore, it was unknown as to whether the conveyance back to the gorge portion was already happening during the dredging.

The task of the 2004 and 2005 measurement campaigns were to explain all the facts about the reservoir flow situation as well as to investigate possible changes in current conditions due to sediment transfer by dredging. Measurements comprised transverse profile measurements, single point measurements and continuous measurements in single points as well as tracer tests.

The results gained in all theses measurements clearly reflect a connection between the sediment transport at the bottom of the basin and the operation of the submersible pump. During dredging operations, a suspended sediment load accumulated in the bed of the shallow portion of the reservoir, which then flowed at a speed of about 0.1 m/s and a concentration of approx. 1 g/l towards the gorge section.

REFERENCES

Bühler, J.: Trübeströme im Grimselsee; in “Wasser, Energie, Luft”, Jahrgang 96, Heft 5/6, Baden, 2004

De Cesare, G., Schleiss, A., Hermann, F.: Impact of turbidity currents on reservoir sedimentation, Journal of Hydraulic Engineering, January 2001

Hartmann, S.: Sediment management of alpine reservoirs considering ecological and economical effects, 9th International Symposium on River Sedimentation, 2004, Yichang, China

Lohrmann, A.: Monitoring Sediment Concentration with Acoustic Backscattering Instruments, Nortek Technical Note No.: 003, October 2001

Staubli, T., Baumann, S.: Comparative measurements of velocity distributions with acoustic methods, IGHEM 2002, Toronto, Canada