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ABSRACT Continuous monitoring of suspended sediment and bed load is important for a better understanding and management of sediment related processes in rivers and hydraulic facilities such as reservoirs and hydropower plants. Selected results from recent real-time in-situ measurements of bed load and suspended sediment at two sites in the Swiss Alps using geophones as well as turbidimeters, an acoustic method and a laser diffractometer, respectively, are presented and the measuring capabilities of these techniques are evaluated.

Keywords: Bed load, suspended sediment, real-time monitoring, geophone, laser diffractometer, LISST, turbidimeter, acoustic

1 Introduction

Sediment yield in the Alpine region tends to increase due to glacier retreat under the strong impact of climate change. With respect to the sustainable use of hydropower, this adds to the challenges in terms of reservoir sedimentation and wear of turbines and steel hydraulics parts of hydropower plants (HPPs) and other hydraulic structures.

As an effective and sustainable measure against reservoir sedimentation, sediment bypass tunnels (SBTs) also restore the natural sediment continuity in the river system by diverting sediment-laden discharges (Sumi *et al.* 2012, Facchini *et al.* 2015). A major problem affecting nearly all SBTs is severe hydro-abrasion on tunnel inverts due to the high flow velocities and the large amount of coarse sediment transport (Auel and Boes 2011). Depending on site-specific operating conditions and sediment properties, i.e. size, hardness and shape, invert abrasion can cause considerable refurbishment costs.

Even with well-designed sand traps, desilting facilities or flushable reservoirs, mineral particles cannot be completely removed from the water which passes the turbines. At high- and medium-head HPPs substantial turbine wear may occur which leads to significant maintenance cost and negative impact on power generation and revenues (Felix *et al*. 2013b).

For optimized design and operation of HPPs with respect to sustainable sediment management and cost efficiency, there is an increasing need for continuous real-time monitoring of both suspended sediment and bed load transport.

This paper presents measuring techniques employed in two on-going sediment transport monitoring studies at HPPs in the Swiss Alps. One study deals with suspended sediment in the penstock of a high-head HPP and the other focusses on bed load transport in a SBT. From the studies, the experimental set-ups and selected recent results are presented and the measuring capabilities of the techniques are evaluated.

2 Measuring techniques and devices

2.1 Suspended sediment concentration

Overview

Suspended sediment mass concentration (SSC, in g/l) of mineral particles can be determined by gravimetric laboratory analysis of bottle samples (discontinuous, non-real-time) or using mainly acoustic or optical instruments (continuous, real or non-real-time). A general overview on suspended sediment measurements for field applications is given by Wren *et al.* (2000).

Bottle samples

Bottle sampling can be manually or automatically made and is a direct, widely used and reliable technique. However, it has many disadvantages such as time-consuming laboratory analysis of the samples, effort of transporting bottles from the study sites to the laboratory, having poor temporal resolution and giving results not in real-time (Wren *et al.* 2000).

Turbidimeters

As an optical technique, turbidimeters are relatively inexpensive and widely used for suspended sediment monitoring (SSM) at rivers (e.g. Spraefico *et al.* 2005). These devices measure either the scattering (also called optical backscatter probes) or the absorption (transmission) of near infrared or laser light. Output values are given in optical units (e.g. Formazine Nephelometric Unit, FNU). For conversion to SSC, a calibration based on the particle properties (size, shape, colour and composition) is required. In general, a linear calibration curve (conversion factor) is assumed.

Laser Diffractometers

Devices based on laser diffraction such as Laser in-situ Scattering and Transmissiometry (LISST, Sequoia Scientific, USA) have become available for SSM (Agrawal and Pottsmith 2000). The working principle of a LISST is based on the mathematical inversion of the measured scattering pattern and transmission. SSC obtained from LISST have the advantage of being not or less dependent from temporally variable particle size, since particle size is considered. However, with highly non-spherical particles, a site-specific SSC-correction factor should be applied (Felix *et al.* 2013c).

Acoustic techniques

Furthermore, acoustic techniques can be employed for SSM. Among many possibilities such as using active sensors like Acoustic Doppler Current Profiler (ADCP, e.g. Haught *et al.* 2014) the method of measuring the attenuation of ultrasonic pulses sent through the sediment-laden water in penstocks or channels lends itself particularly in cases where installations for acoustic discharge measurement (ADM) already exist. Such facilities can be upgraded to be used for SSM. Similar to turbidimeters, the attenuation of the ultrasonic signal is correlated with SSC (Costa *et al.* 2012, Felix *et al.* 2013a).

2.2 Suspended sediment particle size distribution

Besides SSC, particle size distribution (PSD) is an important parameter for sediment dynamics and hydro-abrasive wear. The primary method to obtain PSDs is by sieve analysis of dried particles. Especially for smaller particles, laser diffraction has been used in laboratories for decades. However, as mentioned above, analysing collected samples in the laboratory has many disadvantages and limitations. With LISST, practical real-time monitoring devices for both SSC and PSD in field studies have become available.

2.3 Bed load transport monitoring

Overview

Bed load transport can be monitored either directly by sediment trapping, collecting moving particles and using tracer particles or indirectly by active and passive sensors. Active sensors are typically ADCP, radar and sonar. Passive sensors do not emit any signal but only register acoustic, magnetic or seismic signals (Bogen and Møen 2001, Gottesfeld and Tunnicliffe 2003, Møen *et al.* 2010). Such techniques are hydrophone, geophone or vibrational sensors (Rickenmann and McArdell 2007). Direct methods can provide accurate data during the sampling time but are often laborious and risky, whereas indirect methods allow continuous and real-time monitoring but require calibration.

Swiss plate geophone system

An indirect method using a passive sensor is implemented in the so called Swiss plate geophone (Rickenmann and McArdell 2007, Rickenmann *et al.* 2012, & 2014). It is a robust, submersible device developed at the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL). The device consists of an elastically bedded steel plate installed flush to the channel bottom. A geophone sensor (GS-*20DX*) is mounted beneath the plate in a waterproof aluminium casing and registers the oscillations caused by gravel grains and stones impinging on the plate (**Fehler! Verweisquelle konnte nicht gefunden werden.**).

Figure 1: Swiss plate geophone system with steel plate ① (before assembly), geophone sensor ② and elastomer bearing ③ on the aluminum casing (VAW)

The number of impulses, defined as the signal exceeding a threshold, correlates linearly with the bed load volume (Rickenmann 1997, Rickenmann *et al.* 2012). The relation between impulses and bed load volume depends on site specific conditions like flow velocity, grain size and shape. A laboratory study demonstrated that smaller and a larger number of grains can be detected by inclining the geophone plate by 10 °against the bottom slope (Morach 2011). Recent investigations reveal that also the grain size distribution can be estimated based on the amplitude of the geophone signal (Wyss *et al.* 2014).

3 Methodology and set-up of field investigations

3.1 HPP Fieschertal

HPP Fieschertal is a high-head scheme located in Valais, Switzerland, at a tributary of the upper Rhone river in a highly glaciated area with relatively high yield of fine sediments. The HPP is equipped with gravel and sand traps at the intake to remove particles > 0.3 mm.

In this study, two in-line turbidimeters are used and relevant with respect to the results shown in this paper: (1) *AquaScat* from Sigrist Photometer, Switzerland, measuring light scattering at an angle of 90° at a free-falling jet and (2) *TF16-N* from Optek Danulat, Germany, measuring light attenuation over a path length of 10 mm in pressurized flow. The turbidimeters were installed in a valve chamber at the upstream end of the penstock in summer 2012 to quantify the suspended sediment load. They are fed from the penstock by a sampling pipe (d_i = 20 mm). The *LISST-100X* was installed in a bucket at the end of the sampling pipe. It has a nominal particle size measuring range from 2 to 380 µm in the calculation mode for so called 'random shaped' particles (Agrawal *et al.* 2008). Practically, particle sizes ≥ 5 µm can be measured. Furthermore, to extend the range of SSC, its optical path length was reduced from 50 to 5 mm with a glass cylinder.

Bottle samples were pumped from the bucket using an automatic sampler *Isco 3700*. The sampler was controlled by a program developed at VAW to take 0.5 liter samples every three days and more frequently if turbidity exceeded predefined threshold values.

Additionally, the existing ADM (from Rittmeyer) at the top of the penstock with four acoustic paths (each 2.27 m long) operating at 1 MHz was used for SSM.

Data from the turbidimeters and the acoustic method were recorded at 1 Hz, while the LISST was set to work at 1/60 Hz. The SSC time series in **Fehler! Verweisquelle konnte nicht gefunden werden.** were obtained by calibrating the devices' output signals to the gravimetrically determined SSC from bottle samples.

3.2 SBT Solis

The Solis reservoir located in Grisons in the Swiss Alps lies in a gorge and has a length of about 2.7 km. To maintain the active storage, a SBT was constructed and has been commissioned in 2012. Its intake is located 500 m upstream of the dam. The design discharge of the SBT is 170 m^3/s, corresponding to a 5-year-flood.

As part of a research study dealing with the abrasion resistance of various invert materials, suspended sediment and bed load transport in Solis SBT are monitored using two submersible turbidimeter probes *TurbiMax W CUS41* (Endress+Hauser) installed in the right and left tunnel walls 0.22 m above the invert, and eight Swiss plate geophones installed at the outlet of the SBT, respectively. The geophones are placed across the whole tunnel width of 4.40 m and have an inclination of 10° against the invert slope. Furthermore, the water levels in the reservoir and in the tunnel as well as the tunnel intake gate position are monitored. Data recording is triggered by the opening of the intake gate. The sampling rates are 1/60 Hz in general and 10 kHz for the geophone system.

The turbidimeter data were converted to SSC based on gravimetrically determined SSCs of bottle samples taken from the river at an existing gauging station1 km upstream of the reservoir. The geophone system was calibrated in the laboratory using natural stones with grain sizes similar to the field conditions.

4 Results and Discussion

4.1 HPP Fieschertal

From the suspended sediment measurements in the turbine water of HPP Fieschertal recorded from 2012 to 2014, an extract of four days is presented in **Fehler! Verweisquelle konnte nicht gefunden werden.**. The median particle size d_{50} stands for the diameter of graded particles, of which 50% by mass are smaller.

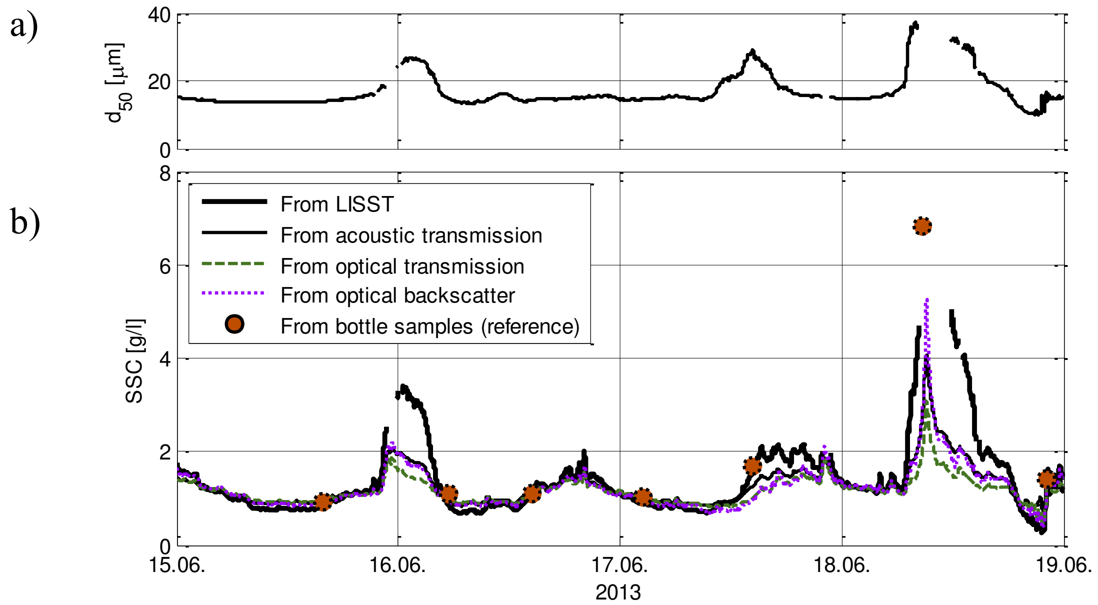

Figure 2: Time series of a) d_{50} from LISST and b) SSCs obtained from various methods after calibrating to bottle samples, measured in the turbine water of HPP Fieschertal

During these days in early summer 2013, the SSC occasionally rose to several g/l within a few hours. When the SSC was above 5 g/l, as captured by a bottle sample, no LISST results were available as the optical transmission was too low. The median particle size d_{50} had a base level of about 15 µm and rose up to approx. 35 µm at high SSCs. In many such events, the maximum d_{50} occurred after the SSC peak (time lag).

In periods of usual SSCs all devices yielded similar SSC values. During high SSCs, however, the acoustic method and the turbidimeters underestimated the SSCs. This is attributed to temporal changes in particle size. When particles are coarser than the normally prevailing ones, less damping or scattering occurs. This was also observed in laboratory investigations prior to the field study by Felix *et al.* (2013c).

4.2 SBT Solis

Since its commissioning in 2012, the Solis SBT was in operation four times during 11 hours on average and diverted sediment volumes between 20’000 and 80’000 m³. The operating conditions varied from event to event and within one single run. Figure 3 shows the normalized spanwise distribution of bed load transport across the eight geophones. It is seen that bed load transport was concentrated on the orographic right side of the tunnel. This is related to a horizontal curve in the tunnel layout located 100 m upstream of the geophones. The bend induces secondary currents transporting bed load at the inner side.

Fehler! Verweisquelle konnte nicht gefunden werden. shows time series of volumetric suspended and bed load transport rates in the tunnel and the reservoir level during the largest flood event since the commissioning of the SBT. Monitoring data show that the lower the reservoir level, the coarser sediment material is transported into and through the tunnel. The geophone data revealed that during the drawdown, three peaks in bed load transport occurred at certain reservoir elevations (see arrows in Fig.4).Turbidity data showed a similar behavior for the suspended sediment transport rate, but the peaks occurred before those of the bed load (Fig. 4). In addition, suspended sediment transport in the tunnel occurred prior to the drawdown of the reservoir level.

Block D1
Saal 5

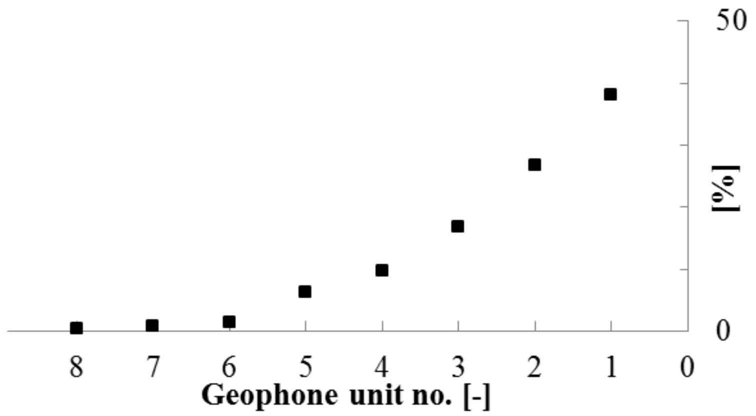

Figure 3: Distribution of the bed load transport in Solis SBT across the tunnel width, registered by the geophone units 1 to 8 at the outlet on 13th of August 2014

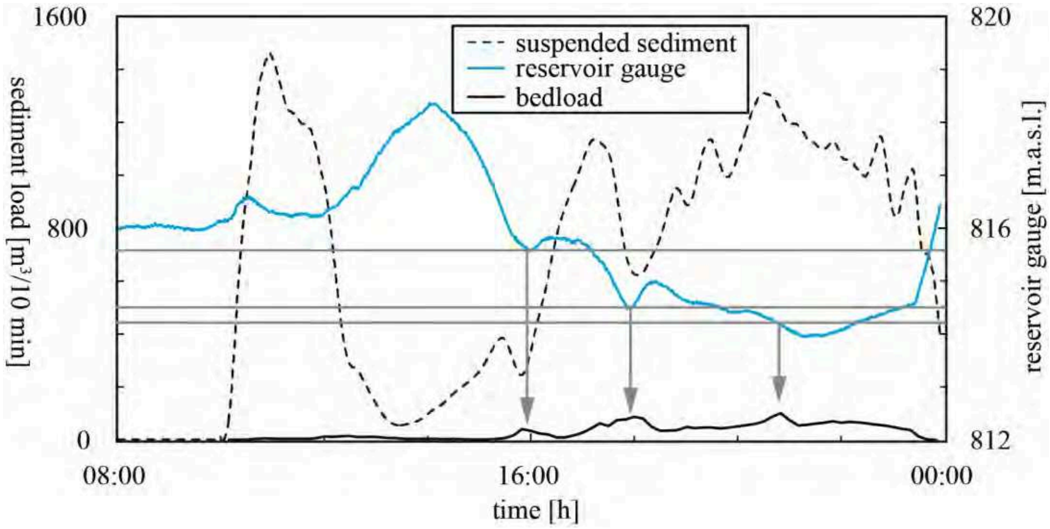

Figure 4: Time series of suspended and bed load transport in the Solis SBT as well as the reservoir level during the flood event on 13th of August 2014

5 Conclusion and Outlook

Selected state-of-the-art monitoring techniques and exemplary field data on suspended and bed load transport measurements were presented. The measuring capabilities of the devices during sediment transport events were evaluated.

In case of temporal variations in PSD, SSCs obtained from turbidimeters or single-frequency acoustic methods are less accurate than those from a calibrated LISST. In dynamic environments it is recommended to measure both SSC and PSD, and to combine continuous indirect measurements with automatic bottle sampling for calibration. In order to extend the SSC measuring range of LISST, devices with automatic dilution are an option (Agrawal *et al.* 2012).

As bed load transport may vary significantly in spanwise channel direction due to secondary currents, it is recommended to measure bed load across the channel width in such situations. Since suspended and bed load transports exhibit different temporal behaviors, it is recommended to measure both suspended and bed load to quantify total sediment transport in rivers and hydraulic schemes.

Measurements and data evaluation at both study sites are continued.

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