Measuring Suspended Sediment: Results of the first Year of the Case Study at HPP Fieschertal in the Swiss Alps

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Abstract

Rivers and waterways may transport large quantities of suspended sediment that can cause severe damages to turbines of hydropower plants (HPP) and lead to reservoir sedimentation. To mitigate these negative effects, continuous and real-time suspended sediment monitoring (SSM) is required. In a research study at the HPP Fieschertal, a high-head scheme in the Swiss Alps with a strongly glaciated catchment area and without storage lake, suspended sediment mass concentration (SSC) and particle size distribution (PSD) are measured since summer 2012 using a portable laser diffractometer (LD). PSD is an important parameter for hydro-abrasive erosion and sediment transport or deposition. For comparison, also devices based in simpler measurement principles, such as turbidimeters and an acoustic method based on existing installations for acoustic discharge measurement (ADM) are employed to obtain SSC estimates. Based on the data recorded at the study HPP, prior laboratory tests of the devices and site-specific time-invariant SSC-calibrations obtained from laboratory analysis of automatically taken bottle samples, time series of SSC and PSD in the turbine water were calculated. The calibration factor for SSC from LD accounts for strongly non-spherical shape of the particles. The results show that not only SSC but also PSD may vary considerably in time. In an example period of ten summer days, with SSC ranging between 0.2 and approx. 10 g/l, the median particle size $d_{50}$ increased occasionally from 12 to approx. 100 µm. Although the transport of coarser particles was observed to be mostly associated with increased SSC, there is a wide scatter in the correlation between SSC and PSD due to a different temporal behavior of SSC and PSD. SSC and PSD depend on meteorological and hydrological processes and also on the operation of the free-surface-flow storage tunnel of HPP Fieschertal. The turbidimeters, and to a smaller extent also the acoustic method, underestimate SSC if particles are greater than assumed in the time-averaged calibration. At HPPs with existing ADM installation, no additional hardware is required to get estimates of SSC in the penstock by means of the acoustic method. The accuracy of SSC estimates from the acoustic method and turbidimeters decreases as the variability in PSD increases and the PSD variations are not well correlated with SSC. In such environments, LD is recommended for SSM, since actual particle sizes are considered in SSC-estimates and information on PSD with high temporal resolution is provided. Further acoustic systems to measure SSC together with PSD are under development. The measurements of suspended sediment at HPP Fieschertal will be continued and SSC and PSD data will be further evaluated. The particle load passing the turbines in time intervals between turbine inspections or efficiency measurements will be calculated in order to find correlations between particle load, turbine wear and efficiency which contribute to optimized design and operation of HPPs. This paper focuses on measurements of suspended sediment, whereas the corresponding paper by Abgottspon et al. (2013b) treats measurements of wear at Pelton buckets and turbine efficiency changes at the same HPP.

1 Introduction

In the design and operation of hydropower plants (HPPs) handling of sediment transported in river water is a major challenge. Siltation of reservoirs and hydro-abrasive erosion at turbines can be economically important issues. In order to improve the understanding of the processes related to hydro-abrasive erosion and to contribute to an appropriate design and operation of HPPs, suspended sediment mass concentration (SSC) and particle size distribution (PSD) have to be measured continuously and in real-time at intakes and/or waterways of HPPs in combination with regular turbine inspections and monitoring of turbine efficiency decrease.
The Laboratory of Hydraulics, Hydrology and Glaciology (VAW) of ETH Zurich in cooperation with Hochschule Luzern (HSLU) initiated an interdisciplinary research project to investigate the problem of hydro-abrasive erosion on turbines mainly by means of a case study at the existing HPP Fieschertal. It is a high-head scheme located at a tributary of the upper Rhone River, in the Canton of Valais, in the Swiss Alps. Since the first operation in 1976 severe hydro-abrasive erosion at needles, nozzles and runners of the two 32 MW-Pelton units has been observed. Although coating of turbines parts reduced the extent of annual on-site revision works and increases the time between factory overhauls, sediment handling as well as optimized operation and maintenance of the HPP have remained important economic issues. In the past decades an increased yield of fine sediment has been observed due to glacier retreat and increased variation in precipitation. One operational option studied in this project is to systematically switch-off turbines during suspended sediment peaks if the costs caused by turbine wear exceed the benefits from power sales.

In a first part of this research project various devices for SSM as described in section 2 were tested in a mixing tank in the hydraulic laboratory of HSLU using suspensions made of mineral particles. This allowed establishing calibration curves for various types of particles and to investigate effects of particles size and shape (Felix et al. 2012). Particle size is a relevant parameter for turbine wear since the hydro-abrasive erosion potential is higher for coarser grains at given SSC (e.g. Winkler et al. 2011). In a second part of this on-going project, these devices were installed in the case study HPP (Fig. 1) for continuous SSM. In parallel periodical turbine inspections are made and turbine efficiency is monitored.

In this paper, methods and selected results of suspended sediment measurements of the year 2012 at this HPP are presented. Project components related to SSM are highlighted in Figure 1. The corresponding paper by Abgottspon et al. (2013b) describes methods to quantify wear at buckets of Pelton turbines and efficiency changes, and first results from the same case study HPP. Further results of this study were presented by Abgottspon et al. (2013a).

Fig. 1: Schematic longitudinal profile of the Case Study HPP Fieschertal

2 Devices used for Suspended Sediment Monitoring

As particle size is an important parameter for turbine wear, a portable laser diffractometer (LD), which provides not only information on SSC but also on PSD was employed (item 6 in Table 1). For the use in HPPs specific models of LD devices were developed (Agrawal et al. 2012). In this project a multi-purpose model, as used in marine science and limnology, was used. In order to extend the range of measurable SSC the optical path length of the LD was reduced from 50 mm to 5 mm by insertion of a glass cylinder (90 percent path reduction module). The used LD has a nominal particle size measuring range from 2 to 380 μm in the calculation mode for so called ‘random shaped’ particles, which are according to Agrawal et al. (2008) particles with an irregular surface and no preferred axes (no elongated or platy particles). The working principle of LD is based on the inversion of a scattering pattern, which, in the portable LD device used here, is measured at small angles (up to approx. 10 degrees, Agrawal et al. 2008). Similar LD devices are used for SSM at a few HPPs so far (Boes 2009, Agrawal et al. 2012). For comparison and in view of the acquisition costs, also devices for SSC estimates based on simpler measurement principles, such as turbidimeters and an acoustic system, were included in the study. Two models of submerged turbidimeter probes as mainly used in waste water treatment plants (items 1 and 2 in Table 1), two in-line turbidimeters measuring in flow-cells on a pipe as mainly used in the process industry (items 3 and 4 in Table 1) and one
Turbidimeter measuring at a free falling jet are employed (item 5 in Table 1). Turbidimeters measure either the backscattering of light from suspended particles (e.g. at 90 degrees) or the attenuation of light through the suspension (optical transmission). Turbidimeter data are usually converted to SSC with a linear and time-invariant calibration curve. Turbidimeters are inexpensive and widely used. The major drawback thereby is that their calibration depends strongly on particle properties, mainly particle size (e.g. Gippel 1995, Wren et al. 2000).

The acoustic method for SSM used in this project (item 7 in Table 1) is based on existing acoustic discharge measurements (ADM) installations. ADM is widely used at waterways of HPPs. In ADM, ultrasonic pulses are sent from one transducer through the water and are received by a transducer at the other end of the path (Fig. 2). For the basic task of an ADM, i.e. the calculation of discharge based on flow velocity, differences in transit time of acoustic pulses travelling in and counter flow direction are measured. For SSM, one possibility is to use the additional attenuation of the received signals caused by suspended sediment particles. The correlation of attenuation of forward scattered ultrasonic signals and SSC has been investigated in recent laboratory tests at HSLU using transducers that are similar to those in ADM installations (Costa et al. 2012, Felix et al. 2012). At HPP Fieschertal a 4 path arrangement (2 crossed path of 2.27 m length in two horizontal layers) operated at 1 MHz is available at the top of the penstock. In the software of the ADM controller the amplitudes of the received signals at the four paths were defined as additional output parameters and no additional hardware had to be installed for SSM.

Table 1: Devices used for continuous suspended sediment monitoring (SSM)

<table>
<thead>
<tr>
<th>Device type</th>
<th>Item No.</th>
<th>Device model and manufacturer</th>
<th>Device output and measuring principle</th>
<th>Derived parameters</th>
<th>Installed at</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbidimeter, submerged, with wipers</td>
<td>1)</td>
<td>Turbimax W CUS41 Endress-Hauser</td>
<td>Turbidity [FNU] from backscatter</td>
<td>SSC</td>
<td>Intake</td>
</tr>
<tr>
<td></td>
<td>2)</td>
<td>Solitax ts-line sc Hach-Lange</td>
<td>Turbidity [FNU] from backscatter</td>
<td>SSC</td>
<td>Tailrace channels</td>
</tr>
<tr>
<td>Turbidimeter, in-line Pressure flow</td>
<td>3)</td>
<td>TurbiScat (90°, 25°) Sigrist Photometer</td>
<td>Turbidity [FNU] from backscatter</td>
<td>SSC</td>
<td>Valve chamber, at the inlet to the penstock</td>
</tr>
<tr>
<td>(in flow-cells without wipers)</td>
<td>4)</td>
<td>TF16-N with F20 Optek Danulat</td>
<td>Turbidity [CU] from transmission</td>
<td>SSC</td>
<td></td>
</tr>
<tr>
<td>Free falling jet</td>
<td>5)</td>
<td>AquaScat Sigrist Photometer</td>
<td>Turbidity [FNU] from backscatter</td>
<td>SSC</td>
<td></td>
</tr>
<tr>
<td>Portable laser diffractometer (LD)</td>
<td>6)</td>
<td>LISST-100X, Type C Sequoia Scientific</td>
<td>Volume concentrations in 32 size classes [ppm]</td>
<td>SSC and PSD</td>
<td></td>
</tr>
<tr>
<td>Acoustic method (based on existing ADM installation)</td>
<td>7)</td>
<td>Risonic Modular Rittmeyer</td>
<td>Received amplitude [V] forward scattering</td>
<td>SSC</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2: Schematic of penstock with an acoustic path of an ADM installation, which can also be used for estimating suspended sediment concentration

Fig. 3: Optical devices for continuous suspended sediment monitoring installed in the valve chamber of HPP Fieschertal; numbers 3 - 6 refer to items in Table 1
The devices for SSM were installed at the study HPP in summer 2012 (locations see Tab. 1 and Fig. 1), except items 1 and 5, which were added in 2013. Most of the devices are placed in the valve chamber at the top of the penstock (Fig. 3). The turbidimeters are installed at a sampling pipe fed from the penstock, which leads to a bucket with overfall and bottom outlet. The measuring head of the LD is inserted laterally into the bucket and the optical path of the LD is arranged below the end of the pipe. Further information on the devices, the laboratory tests as well as the installation at the study HPP and previous results are described by Felix et al. (2012) and Abgottspon (2011).

3 Method

The LD was programmed to take a measurement every minute whereas the signals of the other devices were recorded every second. The devices and the sampling pipes were checked and flushed regularly.

In addition to the devices for continuous SSM, automatic water samplers are operated in the valve chamber and at the intake, respectively. They are programmed to take samples every three days. In addition to that, the samplers are triggered by signals of turbidimeters at the respective sampler locations in order to increase sampling frequency in case of increased turbidity. The samplers contain each 24 one-litre bottles. The bottles are filled by means of a peristaltic pump. The transparent suction hose of the sampler in the valve chamber can be seen on Figure 3 (item 1 and 5, which were added in 2013). From each bottle sample the SSC (g/l) was determined in the laboratory by weighing before and after drying in an oven, deducting dissolved minerals.

From selected samples the quantitative mineralogical composition was determined using x-ray diffraction (XRD). The samples contain mainly quartz, feldspar and mica, i.e. the main components of granite rock. The solid density of selected samples of mineral particles was determined by means of a gas pycnometer and was found to be close to the density of quartz (2.65 g/cm³).

The volume concentrations obtained from LD in the three smallest size classes (approx. 2-3 μm, not relevant for turbine wear) were discarded, since these contributions were considered to be overestimated with the prevailing particle mix (compare Andrews et al. 2011, Felix et al. 2013). Since the particle mix at the study site contains angular (not yet rounded by fluvial transport) and flaky (mica) particles, which differ considerably from the particle shape assumed in the LD inversion software (Agrawal et al. 2008), SSC obtained from LD was calibrated based on bottle samples using a constant factor.

The time series from turbidimeters and the acoustic method were also converted to SSC based on time-averaged calibrations from bottle samples. The calibration curves obtained from field data were compared to those from laboratory tests and were found to be within a plausible range.

4 Results and Discussion

4.1 Time series of suspended sediment concentration and particle size

From the time series of SSC and median particle size d₅₀ in the turbine water of HPP Fieschertal obtained from LD, an extract of ten days during the sediment season is presented in Figure 4. The median particle size d₅₀ stands for the diameter of graded particles of which 50 percent by mass are smaller. Whereas the average SSC during this period was 0.5 g/l, periods of increased SSC ranging up to several g/l for some hours occurred (Fig. 4b). Strong SSC increases occur within less than a few hours, decreases however are generally slower; similarly to typical flood hydrographs. Calibrated SSC is in overall good agreement with reference SSCs (circular markers in Fig. 4b).

The median particle size d₅₀ had a base level of 12 μm and rose occasionally up to approx. 100 μm (Fig 4a). Periods of increased SSC are mostly associated with the occurrence of coarser particles. The time series of SSC and d₅₀ are, however, not synchronous and time shifts among peaks in SSC and d₅₀ were observed.

Figure 5 shows a detail with one selected period of increased SSC (suspended sediment transport event), as indicated by the shaded areas in Figure 4. SSC obtained from LD rose from 0.2 g/l to several g/l and fell back to 0.4 g/l (Fig. 5b). The SSC-estimate from LD is supported by one bottle sample. With the particle sizes in this event, LD measurements were possible until approx. 10 g/l and resumed when SSC was falling below approx. 7 g/l.

In Figure 5a, d₁₆ and d₄₄, i.e. the sizes of particles of which 16 or 84 percent by mass are smaller, are plotted in addition to d₅₀. The diameters d₁₆ and d₄₄ are often used in geotechnical and river engineering to characterize the “width”, i.e. the so called spreading, of a PSD. d₁₆ of up to approx. 200 μm was measured, this is smaller than the classical design grain size for sand traps of 250 to 300 μm. Whereas SSC decayed rather continually after the peak, d₅₀ remained at an elevated level until SSC fell back to the base level.

In addition to LD, SSC estimates from the other SSM devices in the valve chamber are displayed in Figure 5b. The turbidimeter signals were de-trended in order to compensate signal drift caused by accumulating contamination of the optical windows in the flow-cells. It turned out that the flow in the flow-cells is not strong enough for self-cleaning and that occasional flushing of the sampling pipe without manual cleaning of the windows in the flow-cells was insufficient to prevent signal drift (Abgottspon et al. 2013a).
Fig. 4: Time series of (a) $d_{50}$ and (b) SSC in the turbine water obtained from LD after calibration to reference SSCs from bottled samples (circular markers); example of ten days in summer (from August 10 to August 19, 2012)

Fig. 5: Detail of half a day out of the time series in Figure 4, additionally including SSC-estimates from the other devices installed in the valve chamber and particle sizes $d_{16}$ and $d_{84}$ (from LD)
Before and after the period of increased SSC all devices yielded similar SSC estimates. During the period of increased SSC, however, the acoustic method and the turbidimeters underestimated SSC, because their calibration is based on the usually prevailing relatively fine particles \( (d_{50} \approx 15 \mu m) \) and these devices do not recognize the variation in particle size in contrast to LD. At given SSC, turbidity and attenuation are smaller with coarser particles. The acoustic method is less sensitive to changes in particle size than the used turbidimeters, what was also observed in laboratory experiments (Abgottsporn 2011, Felix et al. 2012).

4.2 Correlation of suspended sediment concentration and particle size

As observed from Figures 4 and 5, coarser particles tend to be associated with higher SSC. Figure 6 shows an example of pairs of SSC and \( d_{50} \) values obtained from LD during ten summer days from August 10 to 19, 2012 (as in Fig. 4). A positive correlation with a wide scatter can be seen. In that period, SSC above approx. \( 1.5 \) g/l were associated with \( d_{50} \geq 30 \mu m \). SSC and \( d_{50} \) may be quite independent variables, depending on sediment availability and the processes which govern suspended sediment transport in a specific system.

SSC and PSD depend generally on meteorological and hydrological factors, such as glacier melt, precipitation in form of rain or snow, extent of snow cover in the catchment area, changes of flow paths in the glacier, etc. In the present case, SSC and PSD depend also on the operation of the turbines and the free-surface-flow storage tunnel (Fig. 1) upstream of the measurement location; as observed earlier by the HPP operator and described by Abcottsporn (2011). Depending on the turbine discharge and the water level in the storage tunnel, sediment particles settle or are re-suspended, according to the prevailing turbulence and bottom shear stress. If the river flow exceeds the design discharge of the HPP, turbines are run at full load with filled storage tunnel, whereas in other periods the water level and the discharge in the storage tunnel fluctuate due to intermittent part-load operation of the turbines.

![Fig. 6: Correlation of concentration (SSC) and median diameter \( (d_{50}) \) of suspended sediment in the turbine water of HPP Fieschertal, example from August 10 to 19, 2012, obtained from LD (SSC calibrated with bottle samples)](image)

5 Conclusions and Recommendations

Selected results of concentration and PSD of suspended sediment measured in summer 2012 in the power waterway of HPP Fieschertal, which has a strongly glaciated catchment area and no storage lake, were presented. This gives information on site-specific SSC and PSD ranges of an example period of 10 days in the sediment season (without rare events) and allows also a cross-comparison of the measuring capabilities of the instruments used for SSC-estimates.

The measurements confirm that not only SSC but also PSD can vary considerably in time. In periods of increased SSC coarser particles were transported compared to the conditions before and after such events (positive correlation of PSD and SSC). However, it was observed that peaks of SSC and PSD do not occur simultaneously and that after a SSC-peak particle size did not decrease as quickly as SSC. This different temporal behaviour of SSC and \( d_{50} \) contributes to a wide scatter in the correlation of SSC and PSD.

In dynamic sediment environments, where SSC and PSD are quite independent variables, the use of portable LD is recommended. With LD, actually prevailing particle size is considered in SSC measurements and PSDs with high temporal resolution can be obtained, what was previously not affordable with laboratory PSD analysis of bottled samples. The portable LD device is suitable for SSM in the power waterway of HPPs since particles greater than the upper limit of the size measuring range are usually excluded by sand traps. An option to extend the limited range of
measureable SSC is to perform LD measurements on suspension samples that are diluted with clear water at a known mixing ratio (Agrawal et al. 2012).

SSC estimates from methods that are based on simpler measurement principles, such as turbidimeters and the described acoustic system, are biased in periods in which the size of the transported particles differs from that assumed in the calibration. Such methods can be used with good accuracy for SSC estimates in situations where (i) particle size is almost constant over time or (ii) a strong correlation of SSC and PSD exists and is known. In the latter case, a calibration curve which accounts for changes in PSD with increasing SSC has to be used. Correlations between SSC and PSD can be investigated using portable LD for some period at a certain measurement location. If turbidimeters and the described acoustic system are used in situations with no clear correlation of SSC and PSD, temporarily biased SSC estimates and less accuracy have to be accepted.

If turbidimeters are used, it is highly recommended to select models which have an automatic cleaning system (wiper or pressurized air) or measure turbidity at a free falling jet, in order to prevent signal drift and the need of frequent manual cleaning, even in cold waters of mountain streams, were little bio-fouling may be expected. In contrast to the acoustic method, turbidimeters are suitable for measuring low SSCs (e.g. < 0.2 g/l).

The acoustic system described here showed less sensitivity to variations of particle size than the investigated turbidimeters. Since the measurements are performed directly in the penstock, no sampling pipe is required that could be clogged or lead to non-representative sampling. Measurements are averaged over the path length and several paths over the cross-section of the penstock can be considered. Using the existing installation at the study HPP measurements up to several 10 g/l were possible. No maintenance (cleaning of the sensors) is required. If no information on actually prevailing PSD is required, this method lends itself particularly for HPPs with an existing ADM installation, since in these cases no additional hardware is required for SSM. The obtainable accuracy in SSC estimates depends on the temporal variability of PSD or its correlation with SSC at a given site.

6 Outlook

The measurements of suspended sediment at HPP Fieschertal will be continued. SSC and PSD will be further evaluated seasonally and event-based. The correlation of SSC and PSD time series will be further investigated and duration curves will be produced.

SSC and PSD time series based on LD will be used to calculate the so called ‘particle load’ that was passing the turbines in time intervals between turbine inspections or efficiency measurements. According to IEC Standard 62364 (2013), particle load is defined as the integral of the product of SSC and weighting factors for particle size, shape and hardness over time.

Regarding SSM using acoustics, methods and systems that allow estimating both SSC and PSD are being investigated and various attempts have been made (e.g. Thorne et al. 2007, Moore 2011, Skripalle et al. 2012). The joint determination of SSC and PSD is physically not possible using one frequency. Therefore, multi-frequency approaches are investigated. With forward scattering (as described above), the use of multiple frequencies is limited due to the small frequency sensitivity of the damping in the particle size and concentration range of interest. If however backscattered signals are used a stronger frequency dependency can be observed, which can be exploited for estimating particle size and SSC simultaneously, although one has to deal with much lower signal levels. The low signal-to-noise ratio of the backscattered signals poses a big challenge for estimating PSD and SSC from the recorded signals (inversion of the backscattering process). HSLU in collaboration with ETH Zurich is currently analysing various analytical models predicting backscattered signals. Having once identified the best suited model for the application range, the ill-posed inversion problem in a noisy environment will be tackled. It is planned to verify the applicability and accuracy of such an approach by experimental investigations at HSLU.

Besides SSM, measurements of turbine wear and efficiency (see Abgottspon et al. 2013b) will be continued. Data on suspended sediment, turbine wear and turbine efficiency will be evaluated to find correlations which contribute to the development of respective prediction formulas and to determine economically balanced criteria for temporary turbine switch-offs during suspended sediment peaks.

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References

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