Temporary shutdowns of the high-head run-of-river HPP Fieschertal to prevent excessive turbine erosion during floods

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Abstract. Hydro-abrasive erosion on hydraulic turbines is economically and energetically important. To better understand the causes and consequences of turbine erosion and to further develop mitigation measures, the suspended sediment concentration (SSC) and size distribution of mineral particles in the turbine water of the 64 MW high-head run-of-river hydropower plant (HPP) Fieschertal, Switzerland, have been continuously measured since 2012. An innovative combination of measuring techniques is used: turbidimeters, single-frequency acoustics, densitometry, laser diffraction and gravimetric analysis of water samples. Automatic warnings have been defined in the HPP’s control system to allow for systematic HPP shutdowns when the SSC in the valve chamber exceeds the threshold value of 10 g/l for at least 15 minutes. During the flood of July 29 and 30, 2017 with an SSC peak of 110 g/l, the intake was closed and the HPP was shut down for half a day. This prevented about 8000 tons of fine sediment from entering the HPP, which corresponds to 9 % of the turbines’ annual suspended sediment load (SSL) in 2017, or 12 % of the SSL in an average year without a significant flood. If the intake had been closed one hour earlier, the SSL could have been further reduced by about 3000 tons. For an earlier closing of the intake in case of floods, the turbidimeter at the intake shall be complemented by an additional instrument capable of measuring also medium to high SSC. Apart from the described flood event, SSC peaks in the range of 5 to 20 g/l occurring typically in late summer were attributed to re-suspension events in the storage tunnel due to HPP operation.

1. Introduction
Wear of turbine parts due to abrasive particles is an important issue at medium- to high-head hydropower plants (HPPs). Run-of-river schemes and storage HPPs with intermediate intakes along the power waterways in geologically young mountains with high sediment yields like the Alps, the Andes and the Himalaya are particularly affected [1] [2] [3]. Hydro-abrasive erosion reduces turbine efficiency, HPP availability, electricity generation and revenues, and increases costs for repairs and replacements. Hence, turbine erosion is of interest to HPP owners, operators, consultants, turbine manufacturers and authorities for mainly technical and economic reasons. The suspended sediment mass concentration (SSC) and the particle size distribution (PSD) in the turbine water may vary quickly and considerably over time, leading to a large variation in the instantaneous turbine erosion rate and induced actual costs. To prevent disproportionate erosion, temporary HPP shutdowns (or “switch-offs”) in periods of exceptionally high erosion potential are an economically interesting option for operational HPP optimization [2] [4] [5]. To do so, real-time suspended sediment monitoring (SSM) with sufficient reliability is required [6].
Many techniques for SSM are available (e.g. [7] [8]). However, it is not evident how to set up a SSM system capable of reliably measuring SSC (and ideally PSD) also during floods, i.e. rather rare events with high turbidity, increased flow velocities and potentially debris in rivers. Moreover, site-specific requirements or constraints may limit the options in the selection and installation of instruments.

In an on-going research project, SSC and PSD in the turbine water of HPP Fieschertal, Switzerland, have been measured in real-time since 2012. In parallel, hydro-abrasive erosion on the Pelton turbines and turbine efficiency variations have been measured over the years (see companion paper [9]). The present paper deals with SSM, the measured SSC peaks and their causes as well as temporary HPP shutdowns during floods. Firstly, the instrumentation for SSM at the intake and at the sand trap of HPP Fieschertal is described as a complement to the instrumentation in the valve chamber reported in [10]. Secondly, SSC peaks in the turbine water due to HPP operation are treated. Thirdly, the flood event of July 29 and 30, 2017, and the corresponding HPP shutdown are described and analysed as the main part of this paper. To the knowledge of the authors, no detailed analyses of HPP shutdowns during flood events based on comprehensive measurement data have been available in the literature so far. Then, the suspended sediment loads (SSL) during the years 2012 to 2017 are presented, and the situation in the 2017 flood with HPP shutdown is compared to the 2012 flood without shutdown [5]. Finally, recommendations for improved instrumentation and HPP operation in case of floods are given.

2. Set-up

2.1. General

The HPP Fieschertal is a high-head scheme (Fig. 1) at a tributary of the Rhone River in the Canton of Valais, Switzerland [2] [10]. The intake of this HPP is located a few hundred metres downstream of the end of Fieschergletscher, the second longest glacier in the Alps. Through underground gravel and sand traps, the water is diverted into a 2 km long free-surface flow tunnel whose water level may vary to serve as a daily compensation basin. From the valve chamber at the end of the tunnel, the water flows down a penstock and through two Pelton turbines back to the river. Because the active volume of the storage tunnel (64 000 m³) is relatively small, this HPP is practically a run-of-river scheme. Given its layout and its location downstream of a major glacier, the SSC in the river and in the turbine water are relatively high, causing considerable turbine erosion despite the use of coated turbine parts.

![Figure 1. Schematic longitudinal profile of HPP Fieschertal with installations for suspended sediment monitoring (modified from [10]).](image)
2.2. Installations for suspended sediment monitoring in the valve chamber
For real-time SSM and to quantify the SSL of the turbines, the following set of instruments described in [10], [11] and [12] is in operation in the valve chamber (Fig. 1):

1a) several types of turbidimeters,
2) a Coriolis Flow and Density Meter (CFDM),
3) a laser diffractometer (Laser In-Situ Scattering and Transmissometry LISST) without dilution,
4) a single-frequency (1 MHz) acoustic system based on a pre-existing Acoustic Discharge Measurement (ADM) installation, and
5) an automatic water sampler with a peristaltic pump and 24 one-litre bottles.

The optical and acoustic instruments serve for measuring low to medium SSC, whereas the CFDM is suitable for higher SSC. LISST provides detailed PSD between 2 and 380 µm in addition to SSC.

To prevent excessive turbine erosion in periods of high SSC, automatic warnings based on the signals of the mentioned instruments in the valve chamber have been implemented in the HPP’s control system to allow for systematic HPP shutdowns when the SSC exceeds 10 g/l for at least 15 minutes [5].

2.3. Installations for suspended sediment monitoring at the intake
To quantify the sediment input into the HPP’s waterway and to increase the pre-warning time until heavily sediment-laden water reaches the turbines, two turbidimeters were additionally installed in the headworks area of HPP Fieschertal in 2013 and 2014 (Fig. 2):

- in the river, at the right abutment just upstream of the intake (Figs. 2a and 2b, item 1b in Fig. 1, initially CUS41 from Endress+Hauser, replaced by CUS52D),
- in the underground sand trap, at the right wall close to the end of the basin (Fig. 2c, item 1c in Fig. 1, CUS51D from Endress+Hauser).

At both locations, automatic water samplers (items 5b and 5c in Fig. 1) were operated for several years. Through suction hoses with inlets close to the turbidimeters, water samples were pumped into bottles.

Figure 2. a) River Wysswasser at the intake of HPP Fieschertal in summer with location of the first turbidimeter at the right abutment, b) close-up view on the right abutment, and c) second turbidimeter on the wall of the sand trap (sand trap dewatered during maintenance works) (pictures: VAW).
3. Methods

3.1. Data acquisition
Operational data such as discharges were obtained from the HPP’s control system. The data of the SSM instruments shown in Fig. 1 have been recorded generally at 1 Hz from spring to late autumn in every year since 2012, i.e. during the sediment transport seasons [10]. The SSM system was checked and maintained regularly (e.g. automatic cleaning of turbidimeters, manual cleaning of LISST).

The three water samplers were programmed to take samples at fixed time intervals (every three, five or ten days depending on the season and location) and more frequently if the turbidity or density measured in their vicinity exceeded certain threshold values (external triggering). The bottles with the water samples were then transported to the laboratory and stored in a refrigerator.

3.2. Data evaluation
From the water samples, the SSC were determined by the gravimetrical method, i.e. evaporation of the water in an oven, weighing of the dried residues and accounting for the concentration of the formerly dissolved minerals [10]. The outputs of the instruments for continuous and indirect SSM were converted to SSC based on the gravimetrically determined SSC (reference) [10]. These ‘conversions’ can also be called ‘field calibrations’ in the wider sense of the word.

From the SSC time series of the instruments in the valve chamber, the best-estimate SSC time series was compiled considering the data availability and the uncertainty depending on the measuring ranges [13]. Based on the best-estimate SSC and the discharge time series from the valve chamber, the mass flux rate of sediment was calculated for each minute [13]. The cumulative annual suspended sediment loads (SSL) were obtained by integrating the sediment flux over time from the beginning of each year.

4. Results and Discussion

4.1. Overview
In the period 2012 to 2014, SSC in the turbine water was on average 0.5 g/l and the median particle size $d_{50}$ was on average 10 µm, i.e. in the range of medium silt [2]. SSC and particle size varied considerably over time: SSC was almost zero during the winter months, ≥1 g/l during on average 12 days per year (mainly in summer), and ≥10 g/l during on average 4 hours per year (during a few peaks per year). During on average 13 days per year, coarser-than-usual particles with $d_{50}$ in the range of coarse silt (20 to 60 µm) were transported. Occasionally, $d_{50}$ ranged up to 100 µm (fine sand).

Since the beginning of this research project in spring 2012, two major flood events occurred. The flood on July 2 and 3, 2012, with an SSC peak of about 50 g/l measured in the valve chamber [13], was due to heavy rain from the South over several days. The second flood, about five years later, on July 29 and 30, 2017, was the consequence of a local thunderstorm in the evening of a hot summer day.

The causes for temporarily elevated SSC in the penstock, i.e. sediment transport events leading to higher than average turbine erosion rates for some time, can be classified as follows:

i) Operation of the HPP, affecting the settling, transport and re-suspension of sediment particles in the HPP system, mainly in the storage tunnel, and

ii) Natural events (external forcing), i.e. mainly intense or abundant rain leading to increased river discharge (floods), or glacier-related processes.

In the following section, sediment transport events occurring several times a year due to i) are treated. Then the 2017 flood is described as an example of a major sediment transport event due to ii).

4.2. Temporarily high SSC due to HPP operation
In the storage tunnel between the sand trap and the valve chamber, free surface flow prevails (Fig. 1). The water level varies by up to 4 m depending on the HPP operation [2]:

- In warm and sunny periods in summer, the river discharge is high due to glacier melt and exceeds the design discharge $Q_d = 15$ m³/s of the HPP. Hence both turbines are continuously operated at full load while the water level, $Z$ is at its nominal maximum (1643 m a.s.l., Fig. 3a).

4
- If the river discharge falls below $Q_d$ during some hours of the day (usually after midnight), the water level in the storage tunnel is drawn down (Fig. 3b) to use the stored water until the inflow increases again.

- If the inflow is low and no stored water left, only one or two turbines are operated at partial load. The measured SSC- and $d_{50}$-peaks in the penstock occurred typically when the tunnel water level was low during turbine operation [2]. These peaks are explained by the hydraulic conditions in the storage tunnel, which were investigated by backwater calculations. At high $Z$ and no (or low) turbine discharge, mainly the coarser sediment particles settle in the tunnel. When the water level is drawn down, the average flow velocity $v$ and the bottom shear stress $\tau_b$ in the storage tunnel at the highest point of the invert were estimated to increase by factors of 4 and 40, respectively (Fig. 3). With high bottom shear stress, settled particles are eroded and re-suspended. This has been observed and described earlier by the HPP operator, the responsible engineer and [14].

Figure 3. Schematic longitudinal sections of the storage tunnel of HPP Fieschertal with turbine operation at design discharge $Q_d$ and a) high or b) low water level $Z$ leading to settling or re-suspension of particles, respectively [2].

Figure 4 shows SSC and $d_{50}$ as a function of the tunnel water level $Z$. The purple and green dots indicate measurements during falling and rising water levels, respectively, on August 11, 2012 as an example of a re-suspension event. At this time, probably a high volume of deposited fine sediment was in the storage tunnel as a consequence of the major flood in the beginning of July 2012. The grey dots summarize many re-suspension events over three years (2012 to 2014). All points in Figure 4 represent measurements in periods of turbine discharge $Q > 0$ and when precipitation was $< 5$ mm/day on the current and the previous day (i.e. no events due to intense rains). More and larger particles were transported when the tunnel water level approached its nominal minimum (1639 m a.s.l.) or occasionally fell below it. During the pronounced re-suspension events, “washed” fine sand, mainly from the second half of the storage tunnel, which cannot be flushed via the gate at mid-length of the tunnel (Figs. 1 and 3), was transported into the penstock and through the turbines.

Figure 4. a) Suspended sediment concentration SSC and b) median particle size $d_{50}$ in the turbine water of HPP Fieschertal as a function of the tunnel water level $Z$ (modified from [2]).
If the turbines were not operated at low tunnel water levels, sediment deposits affecting the active storage volume would build up mainly in the second half of the storage tunnel. Without structural measures like additional flushing facilities, SSC- and $d_{50}$-peaks in the turbine water due to HPP operation can hence not be avoided by operation restrictions in this HPP.

4.3. Flood event of July 29 and 30, 2017

At 19:00 on July 29, 2017, the river discharge increased due to a local thunderstorm. Figure 5 shows the high turbidity of the river and of water samples from the penstock in the valve chamber during the flood. The peak in river discharge at about 20:00 was not extreme (2.5 times the design discharge $Q_d$ of the HPP). After the peak, the discharge decreased within a few hours (Fig. 6a).

![Figure 5. a) Upstream view from the intake of HPP Fieschertal during the flood of July 29, 2017 (19:43 MEST, picture courtesy of Gommerkraftwerke AG); and samples of turbine water from the penstock in the valve chamber b) before vs. c) during and after the flood (pictures: VAW).](image)

SSC in the river water at the intake started to rise at 18:40 (Fig. 6b), i.e. some 15 minutes before the sharp increase in discharge (Fig. 6a). After a bit more than one hour (19:40), the water with high SSC arrived in the valve chamber at the end of the storage tunnel (Fig. 6c). SSC obtained from turbidity measurements at the intake and in the sand trap (black and grey lines in Fig. 6b) are implausibly low during the main period of the flood compared to those of the bottle samples from the sand trap and the valve chamber (dots in Figs. 6b and 6c). This is explained by the fact that the turbidity of the water exceeded the upper limit of the measuring range of the turbidimeters during the main period of the flood. At $SSC > 20$ g/l, only the CFDM provided plausible SSC in accordance with the results from the bottle samples (Fig. 6c). $SSC$ reached approximately 110 g/l both in the sand trap and in the valve chamber.

In contrast to the 2012 flood, the HPP was taken out of service during the 2017 flood. The intake was closed towards 20:00 (drop in the black $Q_1$-line in Fig. 6d) after the staff member on duty had noticed the high turbidity at the intake (Fig. 5a) via the webcam in the control room. Since the beginning of the flood less than 1.5 hours before, a SSL of about 4600 tons was transported into the HPP (brown area in Fig. 6b). Closing the intake prevented approximately 8000 tons of fine sediment from entering the intake (purple area in Fig. 6b). If the intake had not been closed, a sum of 12 600 tons of fine sediment would have entered the HPP during the flood.

Without knowing how the flood event would evolve, both turbines were operated at half load during a bit more than one hour (Fig. 6e) after the intake was closed. In this period, water from the storage tunnel with high $SSC$ of 50 to 110 g/l passed the turbines, resulting in a SSL of about 3100 tons (red area on the left in Fig. 6c). The operator informed the dispatch center about the ongoing flood. Based on a conservative estimate of the flood duration, a shutdown until the next morning was agreed.

At about 21:00, both turbines were taken out of service (Fig. 6e). During the night, the storage tunnel...
remained about half filled (Fig. 6d) and $SSC$ in the stagnant water, measured at the beginning of the penstock, declined only slowly from about 60 to 25 g/l (Fig. 6c). $SSC$ in the river declined below 20 g/l already well before midnight (Fig. 6b).

Figure 6. Time series during the flood event on July 29 and 30, 2017 (MEST) at HPP Fieschertal: a) natural discharge at the intake, b) suspended sediment concentrations ($SSC$) at the intake and in the sand trap, c) $SSC$ in the valve chamber, d) discharge from the sand trap to the storage tunnel and water level at the end of the storage tunnel, as well as e) electric power of both machine groups (MG).
At 06:00 on the following day, the intake was opened again (rise of $Q_1$ in Fig. 6d). Considering the relatively low electricity prices on an early Sunday morning in summer in Switzerland, the turbines were taken back in full load operation only towards 08:00. By that time, SSC in the river at the intake declined below a few g/l and additional staff was available to de-clog the cooling water systems of both machine groups. SSC in the turbine water was about 25 g/l at the restart of the turbines and declined to a few g/l by 09:00, resulting in a SSL of about 700 tons (red area on the right in Fig. 6c).

The production loss during the HPP shutdown was approximately 750 MWh (filled area in Fig. 6e), corresponding to about 0.5 percent (%) of the nominal annual production. With an assumed relatively low wholesale electricity price of 20 to 40 €/MWh during that night, the lost revenue due to the shutdown is estimated as 15 000 to 30 000 €.

The average specific cost induced by fine sediment (for repairs and replacement parts of both MG and the sand trap, including generation losses due to reduced turbine efficiency) was estimated as 6 €/t, assuming linear damage progression and average values [13]. With 8000 tons of sediment kept out of the HPP due to the temporary closing of the intake, costs of about 48 000 € have been avoided. This means that the shutdown as practiced in 2017 was profitable (estimated benefit of 18 000 to 33 000 €).

4.4. Optimized shutdown scenario for the flood event of July 29 and 30, 2017

The sediment input into the HPP during the flood 2017, and thus the SSL of the turbines, could have been further reduced by about 3000 tons, if the intake had been closed as soon as the shutdown criterion, i.e. $SSC \geq 10$ g/l during at least 15 minutes, was met at the intake. This would have been the case at 19:00, i.e. about one hour earlier than the intake was closed in reality (based on visual judgement of the situation at the intake via the webcam, and after the shutdown criterion was met in the valve chamber). Preventing additionally 3000 tons of fine sediment from entering the intake would have kept 11 000 tons of fine sediment out of the HPP, corresponding to 87 % of the turbines’ SSL during this event in case of no shutdown. This would have further reduced the sediment-induced costs by approximately 18 000 €.

Hence, it would have been possible to avoid sediment-induced costs of up to 66 000 € in total.

To reliably detect high SSC in the river water in real time, additional instrumentation capable of measuring also high SSC at the intake is required. To gain pre-warning time for HPP shutdowns, additional instrumentation in the de-glaciated area upstream of the intake would be favorable, but requires a high effort due to the absence of upstream infrastructures and natural hazards.

If additional staff had been available during the night for the de-clogging of the cooling water system and if the restart of the HPP did not need to be agreed in advance with the dispatch center, the HPP could have resumed full load operation already at about 02:00, after the SSC in the river fell below 5 g/l. With an earlier and shorter shutdown between 19:00 and 02:00, i.e. 7 hours instead of 11.5 hours, the lost revenue due to the shutdown could have been lower, between 9 000 and 18 000 €. In the best case, after knowing how the flood event passed, an estimated benefit of 48 000 to 57 000 € could have resulted.

4.5. Annual suspended sediment loads (SSL)

Figure 7 shows SSL in the penstock for the years 2012 to 2017 obtained from the best-estimate SSC and the discharge measured in the valve chamber. On average over these six years, the SSL was 75 000 t/year. For the four years without a significant flood (grey lines and grey numbers in Fig. 7), the average SSL was 65 000 t/year.

During the flood event of July 2 and 3, 2012 and the following days, the sediment flux was relatively high (yellow rectangle in Fig. 7). During the flood, 17 000 tons of fine sediment passed the turbines in 39 h, which corresponds to 16 % of the annual SSL in 2012, or 26 % of the average annual SSL in years without a significant flood. Also in the months after the flood 2012 the SSL was relatively high. This is explained by sediments which were transported into the storage tunnel during the flood and were eroded in the following months during re-suspension events (section 4.2).

During the flood event of July 29 and 30, 2017, the SSL in the penstock increased sharply until the turbines were taken out of operation (orange circular marker in Fig. 7). The temporary closing of the intake kept about 8000 tons of fine sediment out of the HPP, which corresponds to 9 % of the annual SSL in 2017, or 12 % of the average annual SSL in years without a significant flood.
5. Conclusions and Recommendations

For continuous measurements of SSC and particle sizes in real time as well as to quantify the SSL of the Pelton turbines at HPP Fieschertal, various instruments were installed and operated at the intake, in the sand trap and in the valve chamber. The analysis of the measurement data revealed a high temporal variability of both SSC and particle sizes in the turbine water, from which a large variation of the instantaneous erosion rate is expected.

Several short SSC peaks per year in the range of 5 to 20 g/l were measured in periods with no significant rain. It was shown that such peaks are due to HPP operation causing occasional re-suspension of particles from the invert of the storage tunnel, as typically occurring in late summer.

Since the beginning of the project in 2012, two significant sediment transport events due to floods with SSC peaks of about 50 and 110 g/l have been recorded in July 2012 and July 2017, respectively. This shows that a monitoring period of several years or even decades is required to capture rare events such as major floods. Whereas the SSC peaks due to operation cannot be avoided in the present configuration of the HPP, the SSL of the turbines is significantly reduced by closing the intake and shutting down the HPP during a flood, as done in 2017. 8000 tons of fine sediment were prevented from entering the HPP, which corresponds to 9 % of the annual SSL in that year, or 12 % of the average annual SSL in years without a significant flood. As a result of the shutdown during 11.5 h, an economic benefit of several 10 000 € was estimated.

The analysis of the event shows that the benefit would have been even larger if the intake had been closed one hour earlier, as soon as the shutdown criterion was met at the intake (instead of later at the valve chamber). To do so, additional instruments to measure reliably also high SSC (approx. 5 to 120 g/l) at the intake are required, because the SSC exceeded the measuring range of the existing turbidimeter. For systematic future HPP shutdowns, it is recommended to implement automatic warnings on the signals of the instruments at the intake in addition to those from the valve chamber.

6. Outlook

In the scope of this research project at HPP Fieschertal, the data acquisition and evaluation are continued. This covers the topics of suspended sediments, turbine erosion, efficiency changes, refurbishment work and replacement of turbine parts as well as operational and economic aspects. The instrumentation for real-time SSM at the intake will be extended by installing a CFDM (as in the valve chamber).
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