Hydro-abrasive erosion on coated Pelton turbines: Nine years of measurements and temporary shutdowns of HPP Fieschertal

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Abstract

Hydro-abrasive erosion in turbines of hydropower plants (HPPs) at sediment-laden rivers is still a concern despite the application of hard-coatings. To further investigate the problem and support HPP operators to better cope with the fine sediment load and its consequences, a long-term research study was conducted at the high-head run-of-river HPP Fieschertal in the Swiss Alps. From 2012 to 2020, the sediment load, erosion and efficiency differences of the two 32 MW-Pelton turbines of the HPP were measured. To do so, a real-time sediment monitoring system was installed and procedures to monitor the efficiency of the turbines were implemented. In parallel, the costs of the refurbishment and replacement of the main turbine parts were tracked. The nine years of detailed data were used to optimize the HPP operation and the turbine maintenance. A key element of this optimization is to shut down the HPP in periods of exceptionally high suspended sediment concentrations (*SSC*). The threshold value above which the operation of this HPP becomes unprofitable, the so-called shutdown-*SSC*, was determined as 15 g/l (15 000 ppm). For reliable real-time measurements up to such high *SSC*, a Coriolis Flow and Density Meter (CFDM) has been installed at the intake in addition to a turbidimeter whose measuring range is limited to 6 g/l. The findings of this project, such as a combination of instruments for real-time *SSC* measurements and the procedure to determine the shutdown-*SSC*, can be applied to other medium- and high-head run-of-river HPPs at sediment laden waters to improve their economic and energetic efficiency.

1 Introduction

Pelton turbines in hydropower plants (HPPs) operated with sediment-laden water are affected by hydro-abrasive erosion [1] [2] [3]. Hard-coating (WC-CoCr) is generally a good protection for the inner bucket surfaces against sliding wear of fine particles (typically up to medium silt). However, at the splitters and cut-outs, particles impact at angles close to 90°. Brittle materials such as hard coatings have limited resistance to such impact wear. Hence, the loss of coating and the subsequent erosion of base material in these zones cannot be completely avoided in many HPPs. Mainly the erosion of the base material leads to reduced turbine efficiencies. To limit the efficiency depletion and the corresponding production losses, turbine parts need to be refurbished and eventually replaced. In most HPPs affected by hydro-abrasive erosion, there is a need for more reliable and up-to-date information on the sediment load and the efficiency of the turbines.

To further investigate the problem and support HPP operators to better cope with the fine sediment load, a research project was conducted at the high-head run-of-river HPP Fieschertal in the canton of Valais, Switzerland, from 2012 to 2020. The sediment load, runner erosion and efficiency changes of two large, hard-coated Pelton turbines were comprehensively measured over nine years. The methods and results of the first three years have been described in detail in [4]. The measuring techniques and selected results of the first five years were presented in [5]. The main results from the final report [6] are presented in this paper.

2 HPP Fieschertal

The HPP Fieschertal, its longitudinal profile as well as the timeline of the Pelton runners in service, their maintenance and the periodic measurements have been described in [5]. The HPP with a design discharge of 15 m^3/s and a gross head of 520 m is equipped with two Pelton turbines with horizontal axes. Each turbine has two injectors and a nominal power of 32 MW. The river water contains sediment particles mainly in the so-called sediment season, when the catchment is not fully snow-covered and glacier ice melts.

Despite the coating, the base material of the runners is at least locally eroded in the range of several millimetres after most sediment seasons. The damaged zones on the splitters and the cut-outs are grinded and re-coated (on-site in the turbine housing) usually every winter. Approximately every six years, depending on the accumulated erosion, the runners are sent to the factory for a major overhaul.

3 Methods

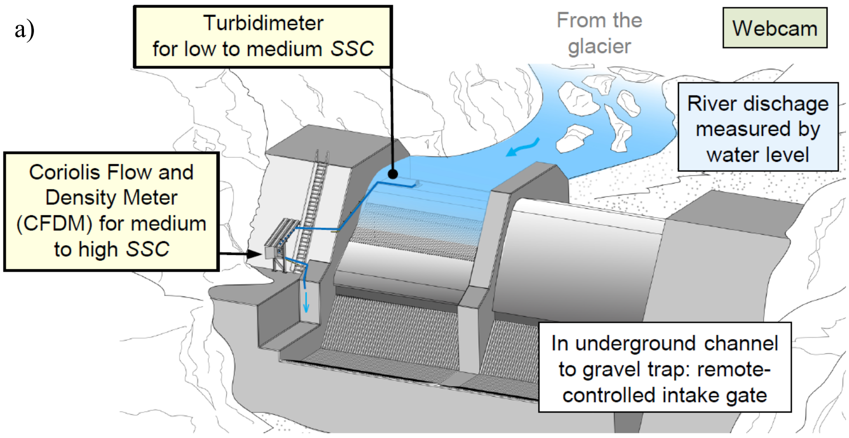
3.1 Suspended sediment monitoring

The setup for the real-time suspended sediment monitoring in the valve chamber has been described in [5]. This measuring location was the most important to quantify the sediment load in the penstock and hence for both turbines.

During the project, a turbidimeter was added at the intake (Fig. 1a) and another one at the end of the sand trap [6]. For several years, automatic water samplers were operated at these locations. From the water samples, suspended sediment concentrations (*SSC*) were determined in the laboratory by weighing of the dried residues. These gravimetric *SSC* served as the reference to convert the recorded turbidities to *SSC* time series.

In 2018, a Coriolis Flow and Density Meter (CFDM, Figs. 1a and 1b) was installed at the intake to measure medium to high *SSC*. With this type of instrument, positive experience was gained in previous years in the valve chamber. To avoid the installation of a pump with associated future maintenance, the CFDM was set below the overfall crest and fed with river water via a ¾-inch-pipe. To reduce temperature fluctuations due to solar radiation and avoid damage by rockfall from the valley flanks, the CFDM was installed in a shelter made of steel. The turbidimeter and the CFDM at the intake serve to warn the HPP operator of exceptionally high *SSC* at the entry to the power waterway in real-time.

a)



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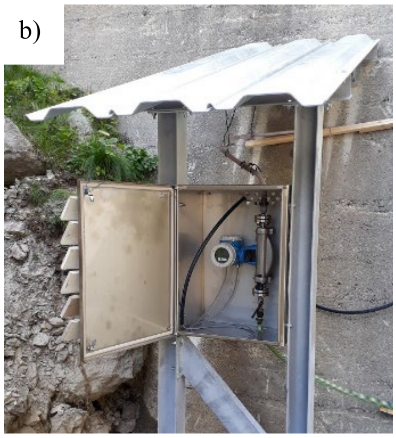

Figure 1: a) Combined instrumentation for real-time suspended sediment monitoring at the intake of HPP Fieschertal and b) detail of the CFDM installed in a shelter and fed with river water [6].

3.2 Turbine erosion and efficiency monitoring

The erosion on two buckets per runner was monitored by photos, optical 3D-surveys, and coating thickness measurements usually before and after the sediment seasons [5].

The changes in turbine efficiency due to (i) hydro-abrasive erosion and (ii) refurbishment or replacement of turbine parts were quantified by sliding needle index efficiency measurements (SNM) and by continuous efficiency monitoring [5]. For the latter, operation data from the SCADA system of the HPP are evaluated.

4 Selected results and discussion

4.1 Sediment properties

On average, the sediment particles in the turbine water consisted of 31 % quartz (Mohs hardness MH = 7), 37 % feldspar (MH = 6), 7 % other hard minerals (MH > 4.5), 18 % mica (MH = 3) and 6 % other soft minerals ($MH \leq 3$) [4]. Hence 31 % of the particle mass is abrasive for the hard-coating and 31 + 37 +7 = 75 % is abrasive for the base material. According to microscope images, the abrasive particles had angular shapes [2], as expected for the short transport distance in the river between the end of glacier and the intake of the HPP in the present case.

The median particle diameter d_{50}, exceeded by 50 % of the particle mass, was on average 11 µm, which lies in the range of medium silt. Occasionally the d_{50} increased up to 120 µm (fine sand), mainly when particles were resuspended at low water levels in the storage tunnel. The sand trap is designed to exclude particles larger than 300 µm.

4.2 Performance of instruments for SSC measurements

Figure 2 shows the *SSC* time series measured at the intake and at the end of the sand trap by various techniques during a sediment transport event in early October 2020. According to the CFDM, the *SSC* reached 17 g/l. High values measured by the CFDM were confirmed by two water samples of approx. 12 g/l during decreasing *SSC*. For *SSC* below approximately 6 g/l, that is before and after the *SSC* peak, all techniques yielded similar values. But in the period when the *SSC* exceeded 6 g/l according to the CFDM, the turbidimeters showed much lower values, which were classified as invalid (dashed line sections). Such implausibly low values occur when turbidimeters are overloaded due to multiple scattering [7]. This was the reason to add the CFDM described in Section 3.1. During the event in Figure 2, the CFDM allowed to continuously measure high *SSC* for the first time at this location.

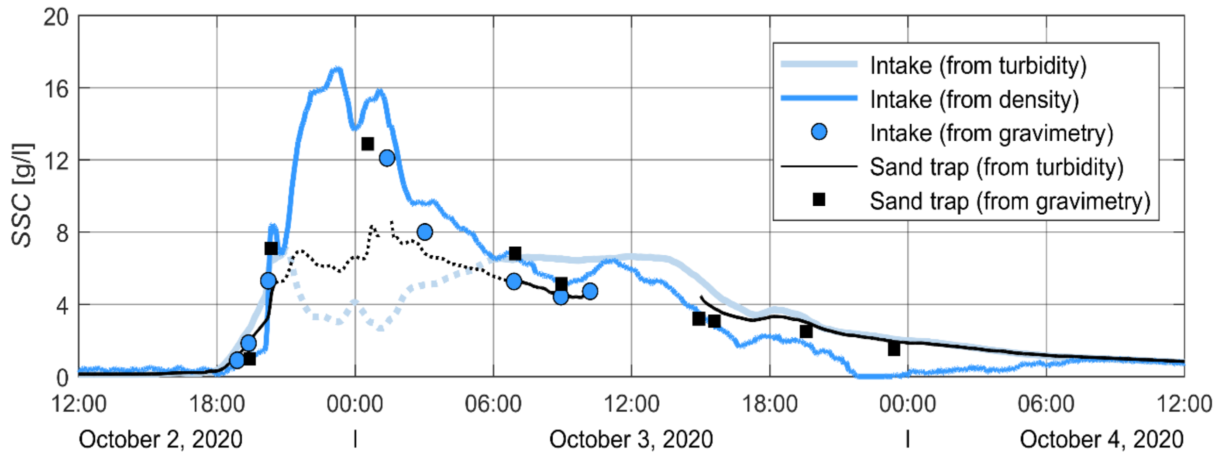

Figure 2: Suspended sediment transport event in early October 2020: *SSC* at the intake and sand trap measured by several methods (dashed lines = invalid *SSC* from overloaded turbidimeters) [6].

4.3 Suspended sediment concentrations (SSC)

The *SSC* in the penstock was on average 0.53 g/l over the nine years and had many peaks of several g/l during the sediment seasons from mid-April to the end of October (Fig. 3). Four sediment transport events with outstanding *SSC* due to rain, thunderstroms or glacier-related processes are marked by circles. Further *SSC* peaks in the penstock, marked by stars, occurred due to HPP operation. In such events, sediment particles which previously settled in the storage tunnel were resuspended when the bottom shear stress was high because of a high turbine discharge at a low tunnel water level.
In July and August, the river discharge usually exceeds the design discharge of the HPP, which is hence mostly operated at full load. During these two summer months, about 50 % of the annual electric energy is produced (clear blue bars with percentages on the right axis). High *SSC* occurred mostly as expected when the river discharge was higher than in winter.

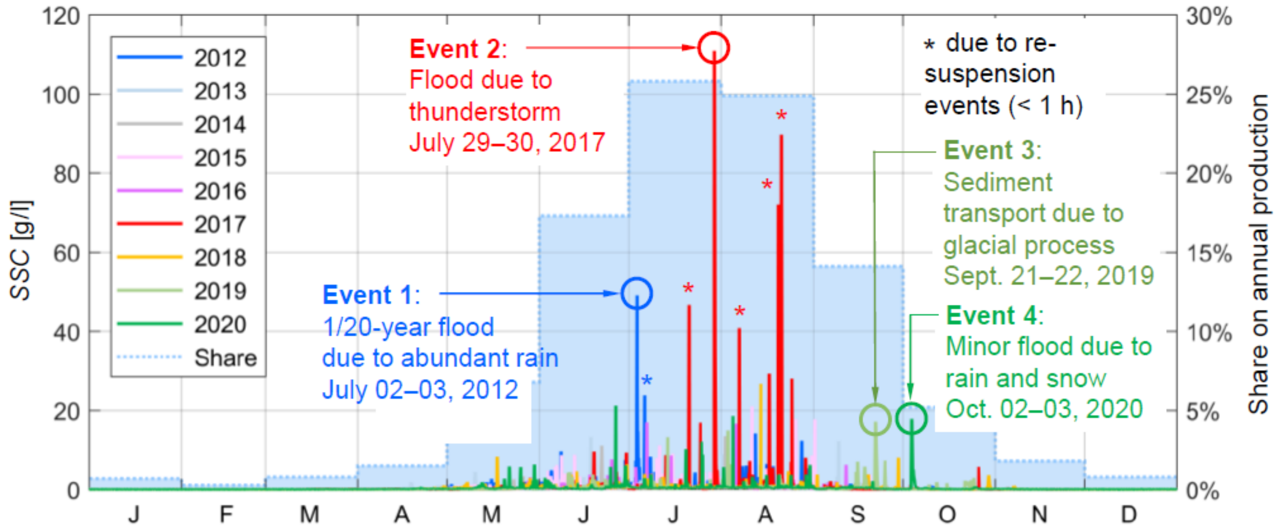

Figure 3: Suspended sediment concentration (*SSC*) measured in the penstock (valve chamber) as well as average monthly shares of the annual production of HPP Fieschertal [6].

4.4 Suspended sediment loads (SSL)

Suspended sediment loads (*SSL*) were obtained by integrating the product of *SSC* and discharge over time. Over the nine investigated years, the annual *SSL* in the penstock was on average 75 000 tons with a standard deviation of 18 000 tons (= 25 % of average). In the year 2014 with no flood events, the *SSL* was only 43 000 tons (42 % below the average). However, in the year 2012, in which the HPP was operated during a flood with an estimated return period of 20 years, the *SSL* reached 107 000 tons (43 % above the average).
The annual flow through the penstock was on average 141 Mio. m^3 with a standard deviation of 10 Mio. m^3 (= 7 % of average). Hence, the *SSL* varied more over the years than the turbined volumes. This means that higher *SSL* did not only result from higher water volumes, but also from higher annual average *SSC*. The annual average *SSC* and annual *SSL* can be highly affected by single rain events leading to floods.

4.5 *Efficiency histories*

Figure 4 shows the efficiency history of machine group (MG) 1 over the investigated nine years. The values are differences in absolute efficiencies and refer to the first sliding needle index efficiency measurement (SNM) of that MG. Negative differences show an efficiency deficit. The uncertainty of the SNM was estimated as 0.2 %.

With the continuous efficiency monitoring, the uncertainty (scatter) is higher than with SNM, but the temporal resolution is higher. This is particularly interesting during the full load operation period (summer), when the main efficiency reductions occur and SNM cannot be performed to avoid production losses (e.g. in summers 2016 and 2017). A higher temporal resolution in the order of weeks or days is valuable to initiate inspections and refurbishment in case of an anomaly [8].

In the years 2012 (with HPP operation during a major flood) as well as in 2016 and 2017 (fifth and sixth year of operation since the last major runner overhaul), the efficiency dropped by 1.1 to 1.3 %. In the other years, the efficiency was reduced less or remained practically constant. For runner 2, a slight increase in efficiency was measured. Potential reasons are:

- In a first phase, hydro-abrasive erosion in the buckets may slightly reduce their roughness (polishing of coating).
- The grinding on the splitters and cut-outs during the winters may lead to slightly improved hydraulic profiles in some years before the efficiency is reduced pronouncedly due to accumulated deviations from the planned profile.

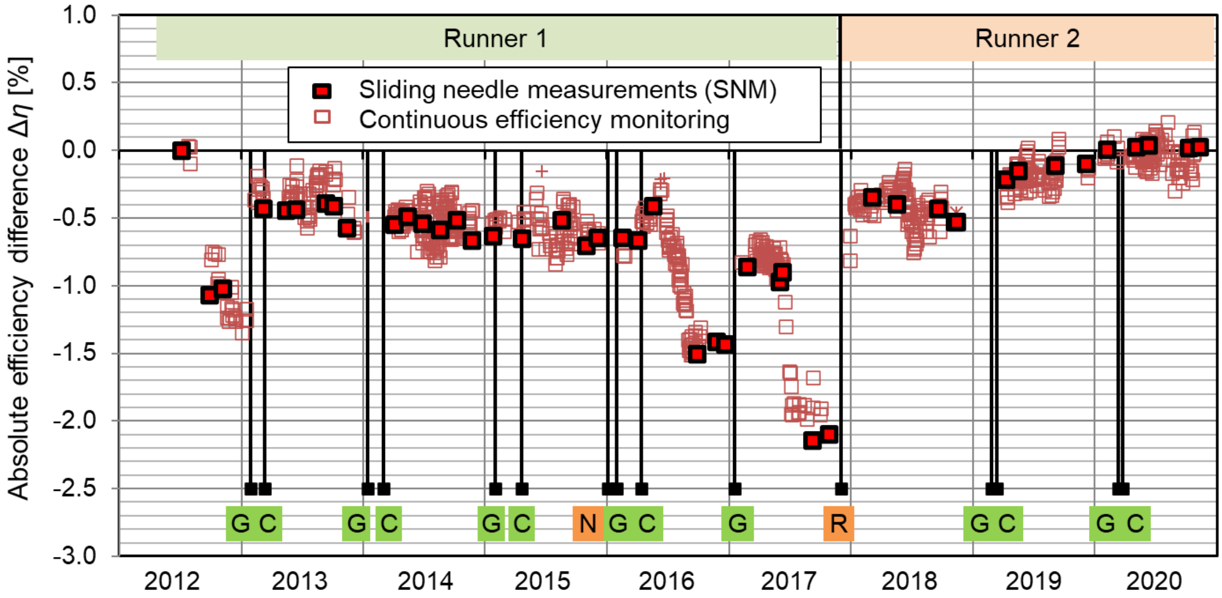

Figure 4: Efficiency history of MG 1 in HPP Fieschertal over nine years with grinding (G), on-site re-coating (C), replacement of nozzle parts (N) and change of runners (R) [6].

4.6 *Efficiency differences*

As a basis for economic considerations, the following efficiency differences were evaluated from the efficiency histories of both MG (extended from [9]):

- The efficiency reduction per sediment season ranged from 0 to 1.3 % (17 observations), with an average of 0.35 % and an expanded uncertainty (2σ) of ±0.22 %, depending on the *SSL* and the runner condition (geometry of splitters and cut-outs prior to the suspended sediment season).
- The efficiency increase due to an on-site refurbishment (grinding and recoating) was on average +0.12 % in 8 cases. In other three cases with blunter splitters, grinding alone led to an efficiency increase of +0.43 % on average. The refurbishment had a more beneficial effect on the efficiency when the efficiency had been clearly reduced during the previous sediment season.

Because of the low number of observations so far, the expanded uncertainty is as high as the average or even higher. Hence, the numerical values of the average efficiency differences need to be interpreted with care. With measurements over further years and a refined evaluation, the uncertainty is expected to decrease.

4.7 *Efficiency differences vs. annual sediment loads*

Figure 5 shows efficiency differences per sediment season of each MG as a function of the corresponding *SSL* (again 17 observations). With an average *SSL* of 75 000 tons/year in the penstock (Section 4.4), the average *SSL* for each turbine was 37 500 tons/year.

At an *SSL* in the range of ±20 % around the average *SSL*, the efficiency can remain or drop by 1 %, depending mainly on the status of the runner before the sediment season. This effect of the accumulated pre-damage led to unexpected combinations, such as a 50 % smaller efficiency reduction with a 40 % higher *SSL*. Hence, efficiency reductions of coated Pelton turbines cannot be predicted with reasonably low uncertainty based on *SSL* only. In the following section, efficiency reductions are related to an indicator of turbine wear instead of *SSL*.

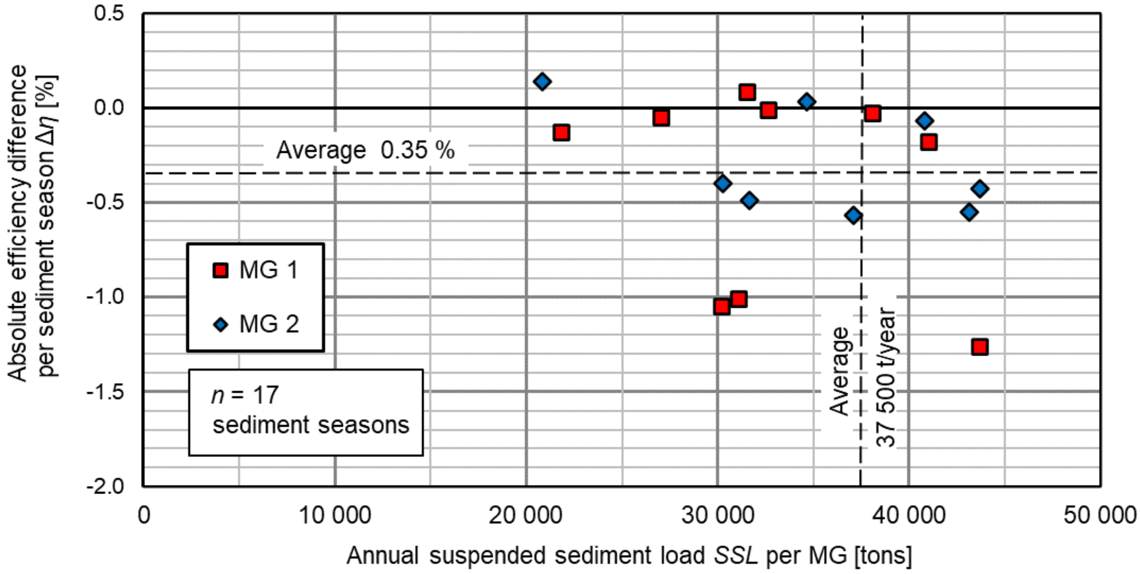

Figure 5: Turbine efficiency reductions as a function of the sediment loads per sediment season [6].

4.8 Efficiency differences vs. relative splitter width

The splitter width *s* is a typical indicator of wear on Pelton runners [1] [10]. Regarding hydrodynamics, the splitter width in relation to the jet diameter is relevant. The latter is typically one third of the bucket width. To get a comparable indicator of wear for various bucket sizes, *s* is normalized with the inner bucket width *B*. Brekke *et al.* (2002) [1] indicated as a typical order of magnitude that the efficiency of a Pelton turbine (with an uncoated runner) is reduced by about 1 % at full load when the relative splitter width s/*B* reaches 1 % as well.

Figure 6 shows the efficiency changes of the turbines in HPP Fieschertal as a function of s/*B*. For runner 4, no 3D surveys are available during the nine years. For runner 2, there were no or only minimal changes in the splitter width and no clear dependency on the efficiency deficit can be seen. For runner 5 with a more recent hydraulic design, the splitter was initially wider than in the earlier design (runners 1 to 4). In the recent design, robustness against hydro-abrasive erosion was apparently given preference over high initial efficiency. Over the four years that this runner was in use during the study, the widening of the splitter began while the efficiency decreased only slightly. For runners 1 and 3, however, clear trends with a slope of about −2 resulted. Note that the initial relative spitter width is >0, because a minimum radius on the splitter crest is required for the application of the coating.

For the runners of HPP Fieschertal with the earlier design, the gradient of efficiency reduction was hence about twice the value expected according to Brekke if the initial spitter width was neglected (black dotted line with a slope of −1).

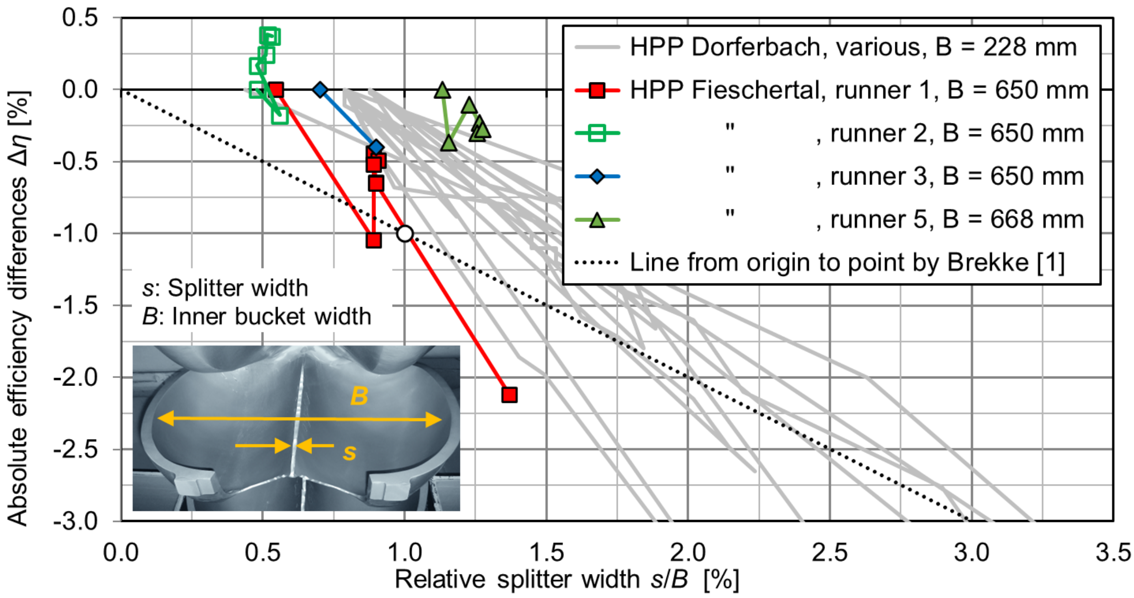

Figure 6: Efficiency differences of Pelton turbines as a function of their relative splitter width [6].

Moreover, corresponding results from several uncoated and coated runners of HPP Dorferbach ([10] and further data from TIWAG in [4]) are shown in grey in Figure 6. In that HPP, the runners are significantly smaller and the buckets only about one third as wide as in HPP Fieschertal. Due to the normalisation of *s* by *B*, the slopes of the trend lines can still be compared. For the earlier generation of runners of HPP Fieschertal, the gradient of efficiency reduction was higher than on average at HPP Dorferbach.
The comparisons among the data sets show that there are considerable differences. To make a forecast model more reliable and generally applicable, further investigations in the concerned HPP, other HPPs and in the laboratory are required in parallel with an additional classification and a more detailed parameterisation of the problem. To gather information over the years and to know the actual efficiency level of each MG in a HPP, continuous efficiency monitoring is highly recommended.

4.9 Temporary HPP shutdowns during sediment transport events

As presented in Section 4.3, the *SSC* varies greatly over time. Hence, the actual sediment-induced costs vary considerably too. If they exceed the actual revenue from the power sale, it is economic to temporarily pause the HPP operation [4] [11]. Over the nine investigated years, the costs induced by the fine sediments passing through the HPP (both MG) amounted to 290 kCHF/year. With an average *SSL* of 75 000 tons/year (Section 4.4), this corresponds to 3.90 CHF/ton.
With such average values and an electricity price of 50 CHF/MWh, which was a typical assumption before and during the project, it was determined that the HPP shall be shut down if the *SSC* exceeds 15 g/l (= 15 000 ppm by mass). This threshold, called the shutdown-*SSC,* would be accordingly higher if the electricity price rises. The 15 g/l are 50 % higher than previously estimated based on data from the first three project years [11] and higher than for other Pelton HPPs with uncoated and coated runners (1.1 to 6.5 g/l) reported in literature so far [4] [12] [13]. The high value for HPP Fieschertal is attributed to the usually quite fine sediment particles (d_{50} in the range of medium silt), the low number of injectors per turbine (z_0 = 2), and the refurbishment strategy with on-site and factory overhauls of the quite large, hard-coated runners optimized over decades.
The shutdown-*SSC* is 30 times higher than the average *SSC* and was exceeded during only 3 h/year on average. During the nine years, there were as few as four events during which the HPP should have been shut down to avoid extensive turbine erosion. Using the warnings from the CFDM at the intake, and assuming that the HPP operation would have resumed when the *SSC* fell below half of the shutdown-*SSC*, the downtime of the MGs would have been only 2.5 to 7.3 h per event. In two flood events (2012 and 2017) with *SSC* peaks of 50 and 110 g/l respectively, the shutdowns would have led to economic advantages of several ten thousand CHF. In the other two events, in which the *SSC* did not largely exceed the shutdown-*SSC*, the shutdowns were less advantageous but still slightly profitable.

5 Conclusion

The sediment load, the erosion on runner buckets and efficiency changes of two large, hard-coated Pelton turbines were measured in detail over nine years. To do so, a system to measure *SSC* in real-time was installed and procedures for continuous efficiency monitoring were implemented. In parallel, the costs of turbine refurbishments were tracked.
The *SSC* was on average 0.53 g/l, increased several times per year to 10 g/l and reached 110 g/l in the flood 2017 due to a thunderstorm. The turbidimeter at the intake is capable of measuring *SSC* up to 6 g/l with the typically prevailing silt particles. To measure also higher *SSC* in real-time at the entrance to the power waterway, a CFDM was added.
From the efficiency histories of the two MG, average efficiency differences per sediment season and due to refurbishment actions were evaluated. However, these quantities vary considerably from year to year and show no clear correlation with the annual suspended sediment loads, because they depend also on the wear status of the runners before the sediment seasons. Hence, continuous efficiency monitoring beyond the duration of the research project is recommended to plan economically optimized refurbishment activities based on actual physical evidence (condition-based maintenance).
Another important element for economical optimization of a HPP is to shut it down in periods of particularly high *SSC*. With an assumed electricity price of 50 CHF/MWh and average values, a shutdown-*SSC* of 15 g/l (15 000 ppm) was determined. With elevated electricity prices, the shutdown-*SSC* is accordingly higher. Because the rather high value of 15 g/l is beyond the measuring range of usual turbidimeters, another instrument such as a CFDM is required to provide warnings for HPP shutdowns.
The findings of this research project, such as the combined instrumentation for real-time *SSC* measurements, the continuous efficiency monitoring, and the procedure to determine the shutdown-*SSC*, can be applied to other medium- and high-head run-of-river HPPs at sediment laden waters to improve their economic and energetic efficiency.

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References

[1] Brekke H, Wu Y L, Cai B Y, "Design of Hydraulic Machinery Working in Sand Laden Water", in Duan C G & Karelin V Y (Eds.), in *Abrasive Erosion & Corrosion of Hydraulic Machinery*, pp. 155–233, Imperial College Press, London, 2002.

[2] IEC 62364: Guide for dealing with hydro-abrasive erosion in Kaplan, Francis, and Pelton turbines, 2nd edition, 2019.

[3] Rai A K, Kumar A, Staubli T, "Hydro-abrasive erosion in Pelton buckets: Classification and field study", *Wear,* 392–393, 8–20, 2017.

[4] Felix D, "Experimental investigation on suspended sediment, hydro-abrasive erosion and efficiency reductions of coated Pelton turbines", *VAW-Mitteilungen* 238 (R Boes, Ed.) and Diss. 24145, ETH Zürich, Switzerland, 2017.

[5] Abgottspon A, Staubli T, Felix D, Albayrak I, Boes R M, "Measuring techniques to cope with hydro-abrasive erosion of turbines", *Proc. 12th Intl. Conf. on Hydr. Efficiency Measurement* (IGHEM 2018), Beijing, China, 2018.

[6] Felix D, Abgottspon A, Staubli T, von Burg M, Kastinger M, Albayrak I, Boes R, "Untersuchung der Schwebstoff-belastung, der hydro-abrasiven Erosion und der Wirkungsgradänderungen an beschichteten Peltonturbinen in der Hochdruckwasserkraftanlage Fieschertal" [Investigation of suspended sediment load, hydro-abrasive erosion and efficiency changes on coated Pelton turbines in the high-head HPP Fieschertal], Schlussbericht vom 19.07.2022 an das BFE, VAW der ETH Zürich und CC Fluidmechanik und Numerische Methoden der Hochschule Luzern, 183 pp., 2022 (in German), https://www.aramis.admin.ch/Texte/?ProjectID=40669

[7] Voichick N, Topping D J, Griffiths R E, "False low turbidity readings from optical probes during high suspended-sediment concentrations", *Hydrology and Earth System Sciences*, 22(3), 1767–1773, 2018.

[8] Staubli T, Abgottspon A, "Efficiency monitoring in the hydropower plant of Filisur". *Proc. 20th Intl. Seminar on Hydropower Plants,* Doujak E (Ed.), Vienna, Austria, 633-639, 2018.

[9] Abgottspon A, von Burg M, Staubli T, Felix D, "Analysis of hydro-abrasive erosion and efficiency changes measured on the coated Pelton turbines of HPP Fieschertal", *IOP Conf. Series: Earth Environ. Sci*., 774, 012030, 2021.

[10] Maldet R, "Pelton runner with high erosion caused by glacier sediment: assessment and measures", *Proc. 15th Intl. Seminar on HPPs*, Doujak E (Ed.), Vienna, 639–646, 2008.

[11] Felix D, Abgottspon A, Albayrak I, Boes R, "Temporary shutdowns of the high-head run-of-river HPP Fieschertal to prevent excessive turbine erosion during floods", *IOP Conf. Series: Earth Environ. Sci.*, 774, 012029, 2021.

[12] Boes R M "Kontinuierliche Messung von Schwebstoffkonzentration und -korngrössen-verteilung im Triebwasser und Quantifizierung der Hydroabrasion an einer Peltonturbine" [Continuous measurements of suspended sediment concentration and particle sizes in the power waterway and quantification of hydro-abrasive erosion in a Pelton turbine], *Wasser Energie Luft*, 102(2), 101–107, 2010 (in German).

[13] Namgyal L, Tandin T, "Hydropower plant operation optimization based on sediment erosion", *Journal of the Bhutan Ecological Society*, 4, 80–95, 2021.