Continuous turbine efficiency and suspended sediment monitoring

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Abstract

Continuous monitoring of turbine efficiency is essential to ensure optimal performance and to determine the need and timing for maintenance actions in hydroelectric power plants (HPPs). Combined with continuous sediment monitoring, this enables the detection of problems related to hydro-abrasive erosion, allowing for proactive countermeasures.

Additionally, an effective monitoring system allows economic analyses to optimize the timing of major runner overhauls. This balances potential revenue losses caused by efficiency deficits against refurbishment costs, ensuring cost-effective maintenance strategies. As sediment load, and therefore turbine erosion (or cavitation erosion), varies from year to year, the optimal time between overhauls is not constant. In order to determine the optimal time for a specific runner's major overhaul, the efficiency history of the corresponding turbine is an indispensable basis.

Suspended sediment concentration (SSC) at the intake and, consequently, in the turbine water can vary significantly and rapidly over time. This leads to large variations in the instantaneous erosion rate of the turbine and the associated costs. To prevent disproportionate erosion, the economically interesting option for operational HPP optimisation is to temporarily close the intake or shutdown the HPP during periods of exceptionally high erosion potential. This requires continuous, real-time monitoring of SSC and a limit value of the SSC to close intakes or shutdown HPPs temporarily. A literature review on such limit SSC is provided together with options for instrumentation.

It is essential to ensure that operational data from the various sensors in a HPP is uncompressed, centrally stored, easily accessible and validated for meaningful efficiency tracking and SSC assessment. Various methods are demonstrated to check the long-term stability and consistency of the measurement data for efficiency monitoring. Physical and statistical approaches are particularly important to validate the input data.

The continuous monitoring of both turbine efficiency and suspended sediment concentration and its application to optimize maintenance and operation is discussed based on examples from the HPPs Filisur and Tiefencastel in Switzerland. The two HPPs comprise several water intakes, compensation basins and two Francis turbines each.

1 Introduction

The water used in hydroelectric power plants (HPP) may contain suspended mineral sediments, which can cause hydro-abrasive erosion (wear) on exposed components. Turbine components in high- and medium-head HPPs are particularly affected, as they are exposed to high flow velocities. The influencing factors, such as the flow velocity and the properties of the particles and turbine components, are described in the IEC Guideline 62364 [1] and in the underlaying literature. Such wear reduces the efficiency of the turbines and thus electricity production (e.g. [2]). It also leads to increased operating costs due to the need for more frequent and extensive overhauls as well as premature replacement investments. In addition, production losses can occur if turbine units are unavailable due to hydro-abrasive erosion. Therefore, wear on turbines affects the energy efficiency and economic viability of such HPPs (e.g. [3], [4] and [5]). Particularly affected are HPPs:

- in catchment areas with a high fine sediment yield (e.g. due to current or former glaciation),
- if the water for turbine operation is not taken from a reservoir, i.e. run-of-river HPPs, or
- if intermediate intakes exist along the power waterways of storage HPPs.

The issue of turbine wear is becoming increasingly important for the following reasons:

- As a result of the retreat of glaciers and permafrost in mountain regions and the increasing variability of precipitation, more sediment is carried into waterways.
- Long-standing cost in the hydropower industry are driving the implementation of further economic optimization measures, such as automatic monitoring of suspended sediments and efficiency, and condition-based

maintenance programs.

- For dams with sedimentation problems in regions with advanced environmental policies, the possibility of continuously transferring fine sediments via HPP waterways is being increasingly investigated to reduce peaks in suspended sediment concentration (SSC) which would e.g. occur during conventional flushing [6].

To mitigate reductions in turbine efficiency and ensure operational safety, regular inspections and replacements of turbine components are necessary. Hard coatings are increasingly applied to enhance abrasion resistance, but these can also suffer damage from excessive fine sediments, cavitation, or high local stress caused by stones occasionally contained in the water. Since the SSC varies greatly depending on rainfall and natural hazards events (such as landslides) in the catchment area, another option is to temporarily close the intake or shutdown such HPPs in periods of particularly high SSC [7].

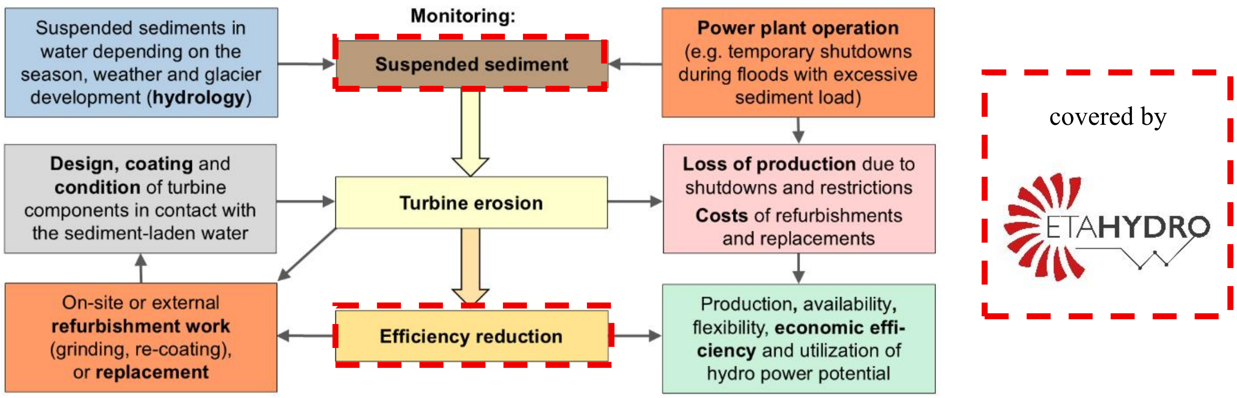

Fig. 1. Influencing factors, effects, monitoring and possible actions regarding hydro-abrasive erosion on hydraulic machines (modified from [3])

Fig. 1 schematically illustrates the factors influencing hydro-abrasive erosion, its consequences, and typical strategies for optimizing the operation and maintenance of affected HPPs. While the qualitative relationships between these factors are well understood, additional practical measurement methods and a better quantitative understanding of these relationships are required to optimize operations and planning. Although general principles apply across all HPPs, measurement setups and mitigation strategies must often be tailored to the specific conditions of each HPP. The "etahydro" monitoring platform was developed to address suspended sediment monitoring ("the cause") and turbine efficiency monitoring ("the consequence" of erosion and other modifications on the turbines).

2 Continuous turbine efficiency monitoring

The changes in turbine efficiency due to hydro-abrasive erosion, refurbishment or replacement of turbine parts can be quantified through continuous efficiency monitoring [8]. To accomplish this, all relevant data from the control system are securely transferred into the monitoring platform "etahydro". Due to the unsteady operation of the HPPs and the delayed response behaviour of some measurement quantities (e.g. flow rate measured directly upstream of the turbine), detecting steady-state sequences is necessary to reduce data scatter. The following routines are applied to calculate and visualize the turbine efficiency history of each unit, updated day by day:

- Preparation of raw data, including adjustments and calibrations (e.g., supported and advantageous by an absolute efficiency measurement campaign)
- Input data validation (IDV) to establish a quality system for the measurement data and the corresponding sensors (more in section 2.1)
- Detection of quasi-steady operating conditions (steady-state detection SSD) for measurement data that have passed the quality system (more in section 2.2)
- Determination of the current turbine efficiency under these operating conditions
- Reading of the reference efficiency in the real hill chart considering all possible operating points, while respecting the entire hill chart from partial to full load with various units in operation (more in section 2.3)
- Based on the above, continuous updating of the efficiency history (more in section 2.4)
- Continuous visualization for the operator (and possibly the trading)

2.1 Rule-based input data validation and sensor monitoring system

A comprehensive input data validation (IDV) must be established for every HPP. The simplest and most effective way is to compare two physically correlated measurement quantities (e.g. two flow rate measurements, of which one directly upstream of a unit and one for example at the top of the penstock, in single unit operation). Then, define acceptable deviation limits that should not be exceeded. The advantage of this “rule-based IDV” method is that the limits can be set based on experience and are easy to understand. The disadvantage is that engineering effort is necessary for each individual HPP because for example each flow rate measurement is affected by specific flow conditions resulting in different behaviour regarding fluctuations and hence standard deviations. Furthermore, every HPP has a unique waterway, and a different number of installed measurement devices. Therefore, the possibilities for “rule-based IDV” differ from HPP to HPP.

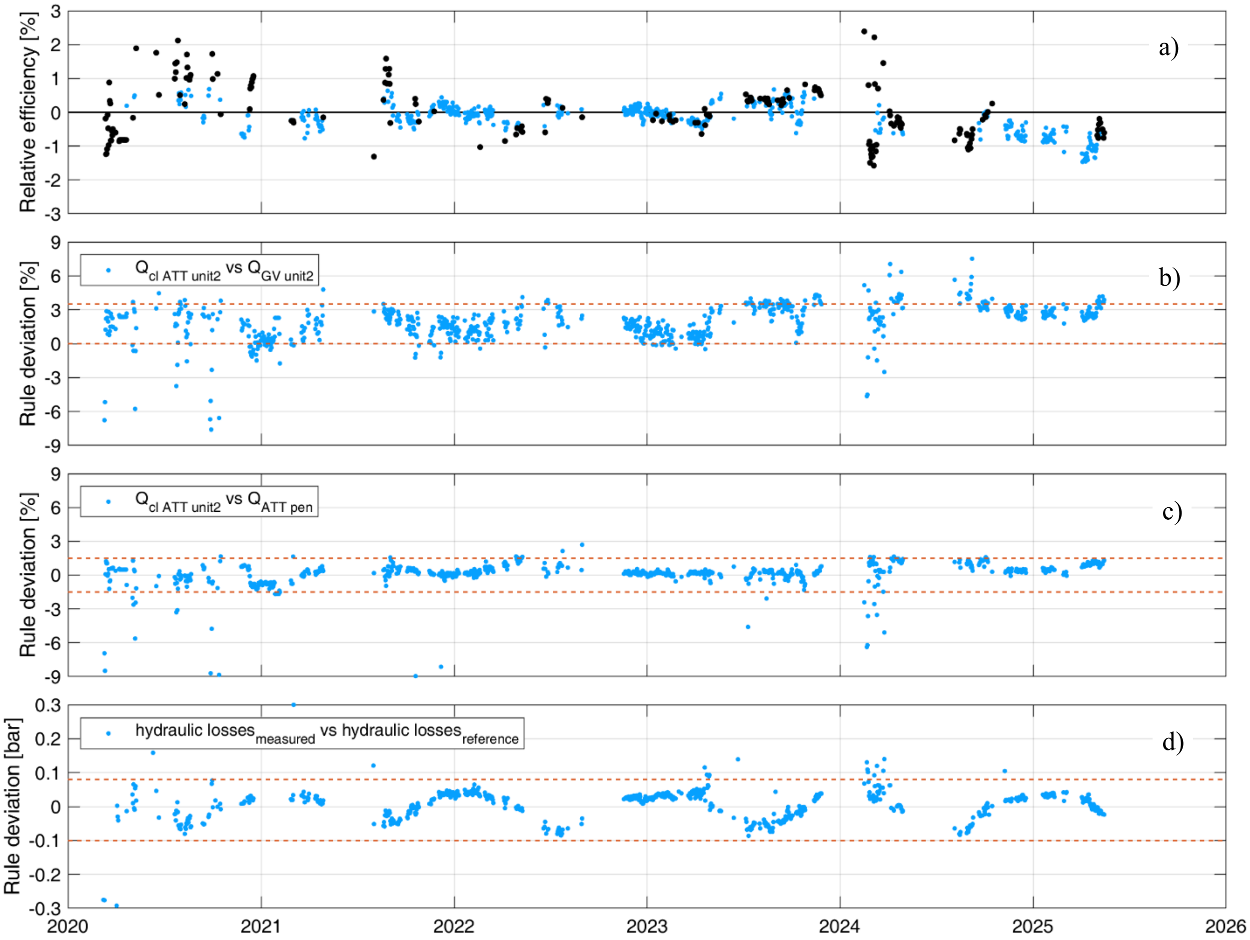

Fig. 2. Examples of IDV for unit 2 at HPP Filisur, a) efficiency history with blue points (valid) and black points (invalid) which are discarded if the rules on the following comparisons are not fulfilled, b) between a direct and an indirect flow rate measurement, c) between two direct flow rate measurements and d) between the hydraulic losses based on the current measurements and those in the reference model.

An example of such a “rule-based IDV” is shown in Fig. 2 for unit 2 of HPP Filisur. In all four time series, each point represents a mean value for one day. The first time series shows the efficiency history with all points. The black points were detected by the IDV as invalid. The remaining points (blue) were used for the efficiency history of the second diagram in Fig. 6 in periods when only one unit was in operation. The second time series in Fig. 2 shows the history of the relative deviations between two flow rate measurements. One is provided by a two-path clamp-on acoustic transit time flow meter directly upstream of the turbine ($Q_{cl\_ATT\_unit2}$). The other one is not a direct flow rate measurement, but it is based on the measurement of the guide vane position from which the flow rate is calculated (Q_{GV_unit2}). The dotted limits are defined by experience. If a one-day average value lies outside the limits, this point is not considered in the efficiency history (black point in the first time series in Fig. 2).

The third time series in Fig. 2 shows the history of the relative deviations between two available flow rate measurements at the waterway of unit 2. As mentioned above, $Q_{cl\_ATT\_unit2}$ is measured directly upstream of the turbine. Q_{ATT_pen} is measured on the top of the penstock by a four-path acoustic transit time flow meter. The checking principle and the consequence are the same as for the signals in the second time series.

The fourth time series in Fig. 2 shows a comparison of actual vs. the expected hydraulic losses in the waterway. The actual losses are calculated using measurements of the pressure upstream of the turbine, the headwater level and a flow rate (here $Q_{cl\_ATT\_unit2}$). The expected hydraulic losses for the actual operation conditions, i.e. the reference, result from a model established at the beginning of the project (hydraulic losses$_{reference}$). It is assumed that the relation between the hydraulic losses and the flow rate does not change significantly over the investigated period. Hence, a deviation between the actual and expected head loss beyond the defined limits indicates that something happened to the involved signals. Because pressure and flow rate are two main quantities besides power output for efficiency evaluation, this is a practical check to see if the pressure or the flow rate measurement shows short- or long-term deviations.

A total of fourteen rules are analyzed, all of which contribute to eliminating invalid daily points from the efficiency history and reducing its scatter. The more important rules were shown in Fig. 2. The more rules involve the measurement quantity, the clearer it becomes which measurement device has a long-term deviation and needs to be adjusted or maintained.

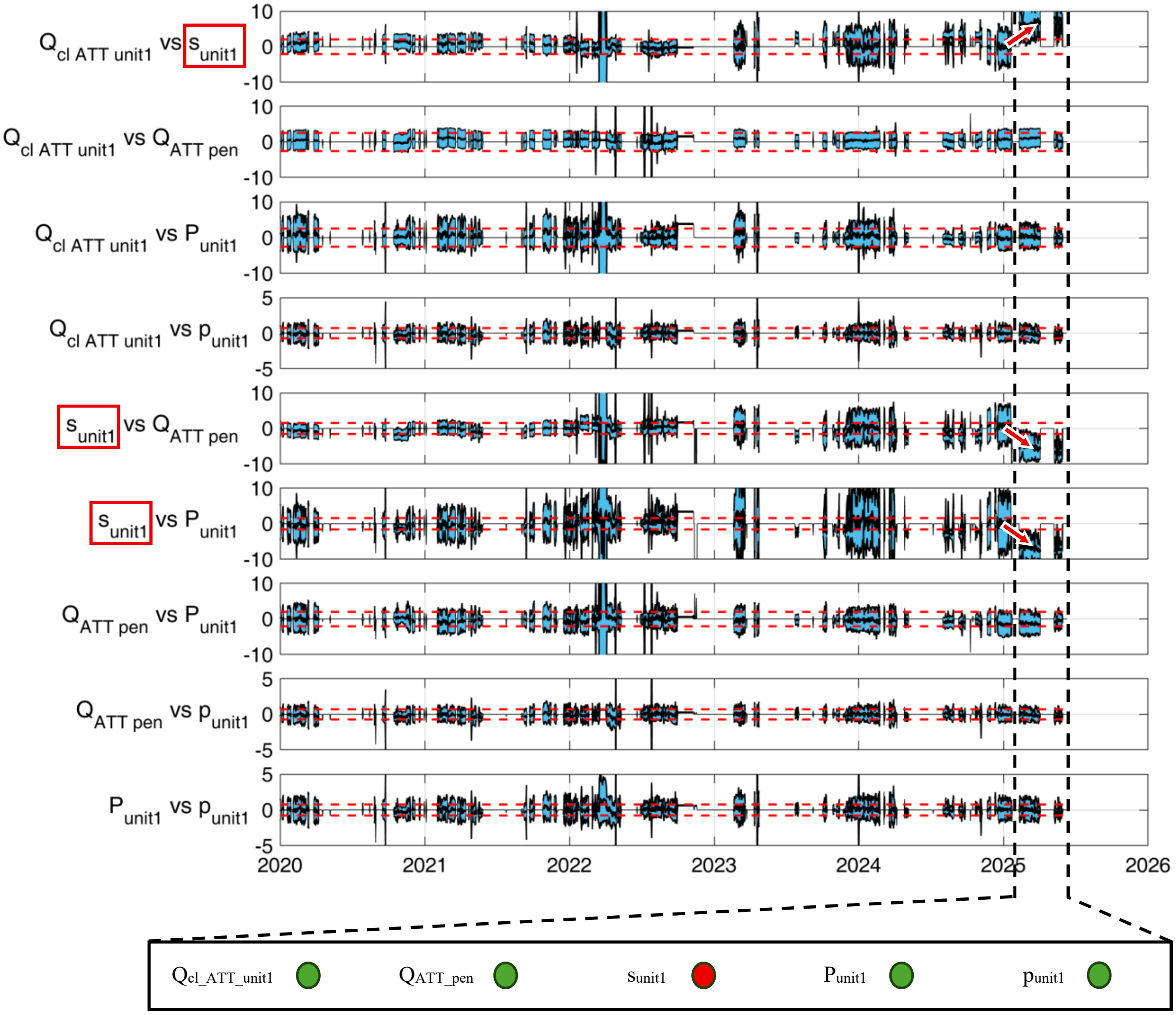

Fig. 3. Sensor monitoring system for unit 1 at HPP Filisur. The time series show various relative comparisons of two signals (with deviations in percent); below a warning system is displayed, indicating in this example a problem with the signal of the guide vane position, due to anomalies indicated by the red arrows in the corresponding time series.

A further approach is to extend the “rule-based IDV” into a “sensor monitoring system”. The goal of this system is to detect long-term variations in individual measurement devices.

An example of this system is provided in Fig. 3. Several measurement quantities are compared to each other over time, though not all comparisons are shown. Furthermore, the extended standard deviation of the comparisons, with a confidence interval of 99.7 % (3 σ) is shown by blue areas. The zero value, or zero deviation of the comparison, is defined at the beginning of the project under defined steady-state conditions over the course of several hours (reference). The extended standard deviation of the comparisons (again with 3 σ) during the initial reference period are plotted as red dotted lines.

If the blue areas exceed the red borders, the fluctuations of the comparisons increased compared to the reference period. This could indicate a sensor malfunction or disturbance. If the mean value of the blue area exceeds the red limits, then one of the measurements experienced a significant alteration over time (shift or drift). If such deviations are observed for several comparisons, it can be confirmed that a specific measured value is faulty or has drifted. At the beginning of 2025 this happened to the position measurement (stroke “s”) of the servomotor regulating the guide vane position. The position sensor was replaced by the operator, and the newly installed sensor showed different measurement values (which will be considered in a new reference status for this unit).

As for Figure 2, an intuitive, graphical comparative time series analysis with defined alarm levels, which are checked continuously in the background, allowed to identify a problem with a specific sensor. This enables the operator and the monitoring expert team to judge the problem and take actions to prevent disturbances of a faulty signal on the turbine efficiency history.

2.2 Steady-state detection

A steady-state detector (SSD) is important to exclude data points from the efficiency history which have been calculated during transient conditions. While short term temporal variations in the efficiency history, which do not result from real alterations of the turbine, are unavoidable due to the measurement uncertainty and standard deviations in the underlaying signals, such fluctuations can be minimized to an acceptable level.

Pressure measurements directly upstream of a turbine have proven to be the most effective way to determine periods of steady-state operation. Pressure measurements react immediately to power changes. Furthermore, they provide information of the surge tank oscillations.

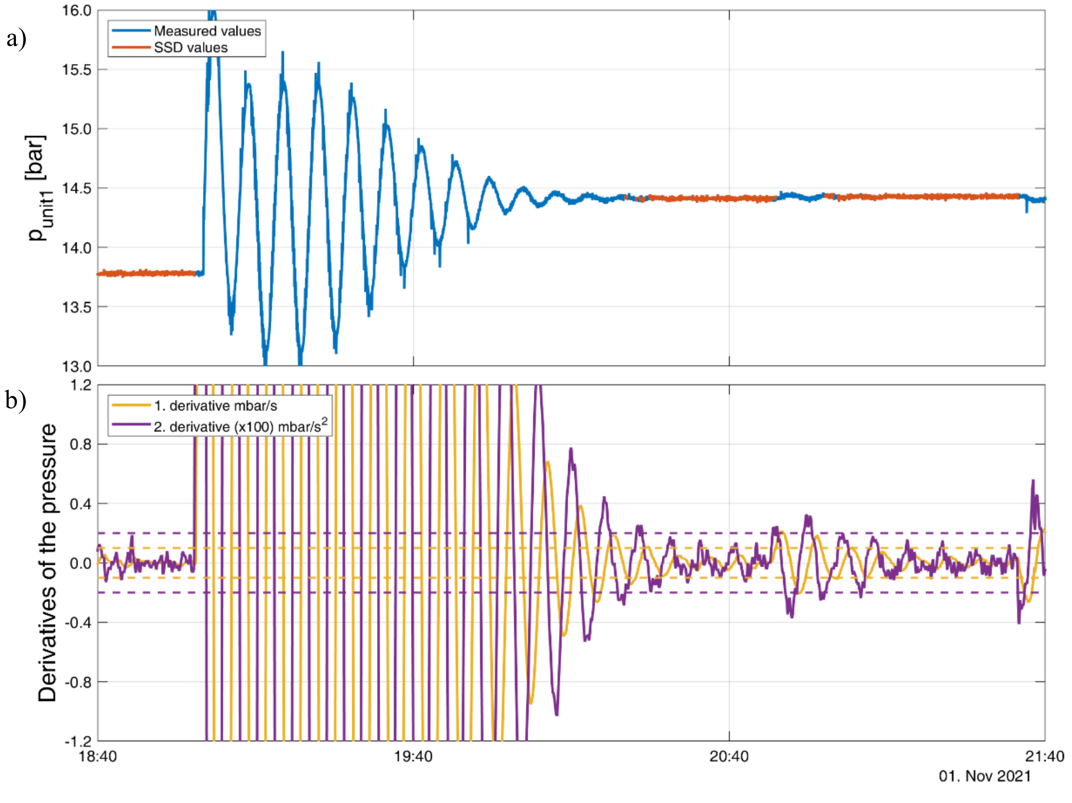

Fig. 4. Steady-state detection SSD before and after a significant power change at unit 1 in HPP Tiefencastel, based on a) the pressure measured upstream of this unit and b) monitoring of the first and second derivatives of this signal.

Fig. 4 shows an example of such an SSD over three hours. The power of unit 1 of HPP Tiefencastel was reduced from 15 to 8 MW. The first time series shows the pressure directly upstream of the unit, measured before, during and after the load reduction. While the headwater level remained practically constant, the mean value of the pressure increased due to the smaller hydraulic losses at the lower flow rate. Additionally, the water oscillation in the surge tank is visible, which declines due to damping over about an hour.

The first step is to calculate the first derivative, i.e. the slope (yellow line in Fig. 4b). Where the gradient is within defined limits (in this example less than 0.1 mbar/s), the values are considered as steady state. However, during a surge tank oscillation, which happens many times throughout the day, the gradient is several times within these limits, but there is obviously no steady-state operation. Hence, the first derivative is insufficient. Therefore, also the second derivative, i.e. the concavity (purple line in Fig. 4b) is calculated and monitored. For steady-state operation, the second derivative must also be within defined limits (in this example smaller than 0.002 mbar/s^2). Since the first and second derivative of an oscillating signal are phase-shifted, the zero crossings never occur at the same instant in time. Using the first and the second derivative, transient conditions are captured correctly, because not both derivatives are simultaneously within the limits. Therefore, steady-state operation is detected reliably, as shown by the orange line segments in Fig. 4a.

2.3 Measurement of reference efficiency hill chart

Fig. 5 provides an efficiency hill chart established by a comprehensive reference measurement campaign with the thermodynamic method for one unit in the HPP Filisur, Switzerland. This HPP is equipped with two Francis turbines with a gross head of 415 m and a rated output 33 MW each. The turbines are affected by hydro-abrasive erosion. The hill chart was created using three measured efficiency curves (dotted black lines in the left and right subfigure) for a) one unit operation, b) mixed unit operation and c) two unit operation. It is important to create such a reference hill chart based on HPP measurements, because the real efficiencies may deviate considerably from those expected based on model tests or numerical simulations.

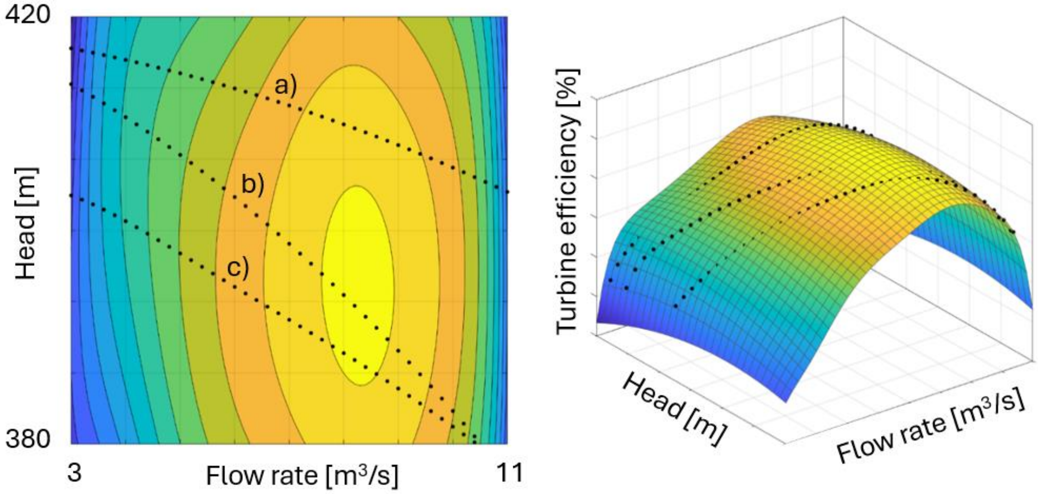

Fig. 5. Efficiency hill chart of one unit at HPP Filisur resulting from a comprehensive reference measurement campaign.

2.4 Histories of turbine efficiency

Fig. 6 shows the efficiency histories for the two units at HPP Filisur. The efficiency history for unit 1 is available since 2016. For unit 2, the efficiency history begins in 2020. Each point represents the mean value over one day. The resulting relative efficiency is the difference between the efficiencies in the current and the reference status. Negative differences indicate an efficiency deficit while positive differences mean that the current status is better than during the reference measurement. Normally, the refence real hill chart is determined after a major turbine refurbishment, after commissioning of a new runner with a new design, or after commissioning of a newly installed turbine in rehabilitation or greenfield HPP projects. However, the reference real hill chart can be determined at any point in time since the efficiency history is relative.

Based on such an efficiency history over years, the consequences of events related to the turbine, refurbishment actions, and ongoing hydro-abrasive erosion can be analysed [5] [8] [9].

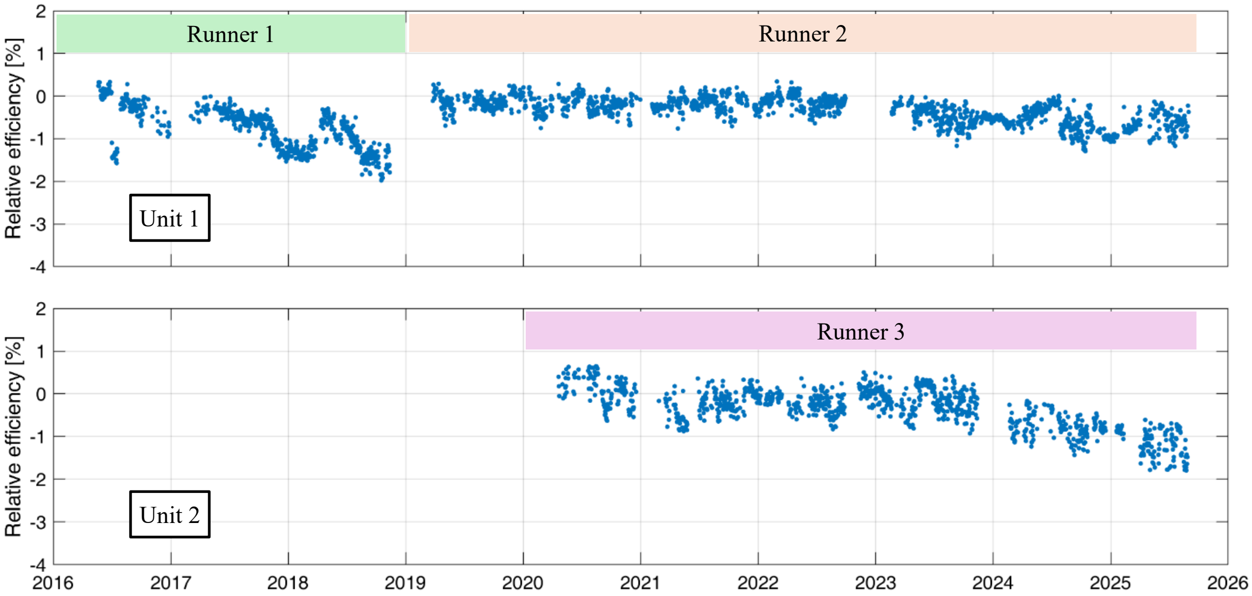

Fig. 6. Turbine efficiency history of unit 1 (above) and 2 (below) at HPP Filisur (as it is visible in "etahydro" for the operator).

3 Continuous suspended sediment monitoring

To quantify the cause of turbine erosion, the suspended sediment concentration (SSC) and particle properties such as size, shape and hardness are relevant [1]. Some of these parameters change less over time than the others. Hence, the following monitoring strategy is usually adopted:

- The shape and hardness of the particles primarily depend on the catchment area, which can be assumed to remain constant. Particle shape and hardness are usually investigated based on laboratory analyses (microscope images and mineralogical composition by X-ray diffraction or elemental analysis) of a few samples.
- It is widely accepted that coarser particles cause more abrasion, particularly on coated components. The sizes of sediment particles transported in a river and the turbine water may vary on the hydrological and hydraulic conditions as well as the HPP operation. Hence, particle size distributions (PSD) should be measured continuously. This has been done in research projects using laser in-situ scattering and transmissometry (LISST) [10]. However, such advanced optical instrumentation is limited to moderate SSC, requires an engineering follow-up, and is rarely affordable. Acoustic multi-frequency methods are less sensitive to fouling, measure up to higher SSC and can be more suitable for coarser particles. Such techniques are under development, but the inversion of their signals remains challenging, resulting in less precise PSDs. In absence of a suitable and affordably technology, PSDs are usually not measured continuously at HPPs.
- The SSC in the turbine water varies quickly and considerably over time, from clear water in the low-flow season to very turbid water after heavy rainfall or natural hazard events. Obviously, this leads to a large variation of the turbine erosion rate and induced actual costs. The SSC is the most important parameter to measure continuously, ideally at every major river water intake of HPPs where turbine erosion is a concern. To use SSC measurements for operational decisions (Section 3.3), real-time monitoring is essential

3.1 Measuring techniques for suspended sediment concentration monitoring

For continuous SSC measurement in real-time, various indirect measurement methods, such as turbidity, acoustics and density measurements, are available [10] [11]. All sensors have their advantages and disadvantages regarding measurement ranges, calibration, ease of installation, need for sampling pipes, cleaning and maintenance, and signal quality (representativeness, misleading outputs in case of saturation or error, signal drift, outliers which would cause too many false alarms etc.). For the three mentioned types of instruments, there is a main difference regarding the range of measurable SSC:

- Turbidity probes and acoustic methods are suitable for low to medium SSC. The maximum measurable SSC depends on the specific instruments and the particle properties. For silt particles typically found in alpine catchment areas, we experienced that usual turbidity probes (up to 4000 FNU) can be used up to 6 or 10 g/l, and acoustic methods up to approximately 20 g/l (depending on the ultrasound frequency and setup).

- SSC in rivers can exceed 50 or 100 g/l e.g. after heavy rain. Because such SSC are particularly relevant for preventing excessive turbine erosion, there is a need for measuring medium to high SSC. This can be done with a Coriolis flow and density meter (CFDM). Such an instrument has also the advantage that the conversion of the measured density to SSC relies on the factory calibration of the instrument, whereas turbidimeters and acoustic methods cannot be fully factory calibrated, because the conversion of their outputs to SSC depend on the particle properties, which are site-specific and not known in advance or in real-time. However, a CFDM is not suitable to measure low SSC, but these are less relevant for turbine erosion.

At the water intake "Tuors" of the HPP Filisur, a CFDM is operated. The mountain torrent emerges from a valley with some steep bare-land areas prone to erosion. The CFDM is placed on the riverbank above the intake and fed with river water by a submerged pump installed at a steel column in front of the intake rack (Fig. 7a). The pump can be moved vertically along the steel column. The pump is usually positioned downstream of the bed-load guiding wall to reduce its exposure to natural hazards. For inspection and replacement, the pump can be pulled up manually.

The pumped water containing suspended sediments is fed to the mobile CFDM measurement installation (Fig. 7b). Thanks to its mobile design, the CFDM installation is stored in a garage during winter, when there is no need for SSC monitoring and to prevent it from freezing. Furthermore, the CFDM installation can be moved to other sites for test measurements or temporary monitoring e.g. during flushing operations. At this site with a partly vegetated catchment area, the river water contains not only sediment, but also organic material such as parts of plants, which occasionally lead to the clogging of the CFDM. To reduce the need for manual maintenance on site, an automatic backflushing for a few minutes every day was implemented. To this end, the installation comprises three motorized valves controlled from a programmable logic controller, which can be also accessed from remote. The CFDM installation is thoroughly cleaned at the end of every sediment season.

The weak point of the SSC measurement installation at this site is the pump, which can become clogged and requires intense maintenance. Ideally, the CFDM would be installed at a pipe with gravity-driven flow, but the required elevation difference was not available at this site.

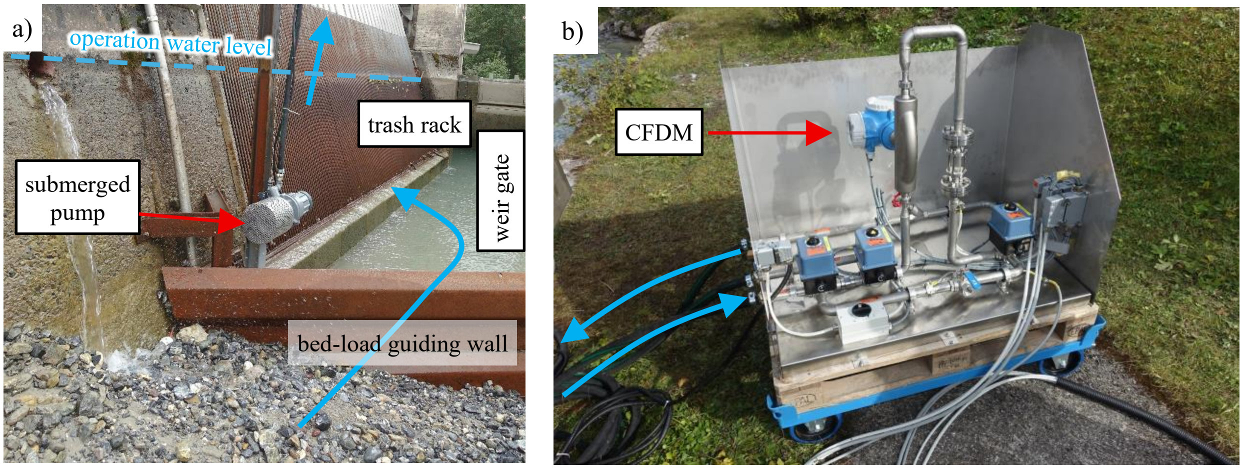

Fig. 7. CFDM at intake Tuors of HPP Filisur: a) the vertically movable suction pump at the beginning of the sampling pipe (with lowered water level for picture) and b) the mobile measurement installation.

3.2 Histories of suspended sediment concentration

Fig. 8 shows the SSC time series measured at the intake Tuors with the CFDM during three full sediment transport seasons (April to November), as well as during the current year up to the beginning of September. The first diagram has been scaled up to 50 g/l to show high SSC which occurred and would not have been measurable with a turbidimeter or most acoustic techniques. The second diagram is scaled up to 10 g/l to reveal additional details at lower SSC. The SSC was usually well below 0.2 g/l. It exceeded 10 g/l about three times per year, and 50 g/l about once a year, for some hours (typically due to thunderstorms) or for maximum a few days (period of intense and abundant rain).

As detailed in Section 3.3, the Tuors intake is closed whenever the SSC exceeds 6 g/l (indicated by the horizontal lines in Fig. 8). In 2022 and 2023, this threshold was reached or exceeded during seven events each year. In 2024, it occurred twice, and so far in 2025, three such events have been recorded. On average, this results in four to five events per year. Since 2024, the intake has been closed semi-automatically, with an alarm message sent to the operating staff. The SSC measurements with the CFDM are robust as long as the submerged pump remains operational.

The SSC varies much more than the river flow rate, and there is no strong correlation. Warnings of intense rain from the weather service are not reliable enough to plan the closing of the intake in advance. Hence, SSC measurements proved to be required for a fact-based and economically justified temporary closing of the intake. To obtain some pre-warning time, options for additional real-time SSC measurements further upstream are investigated.

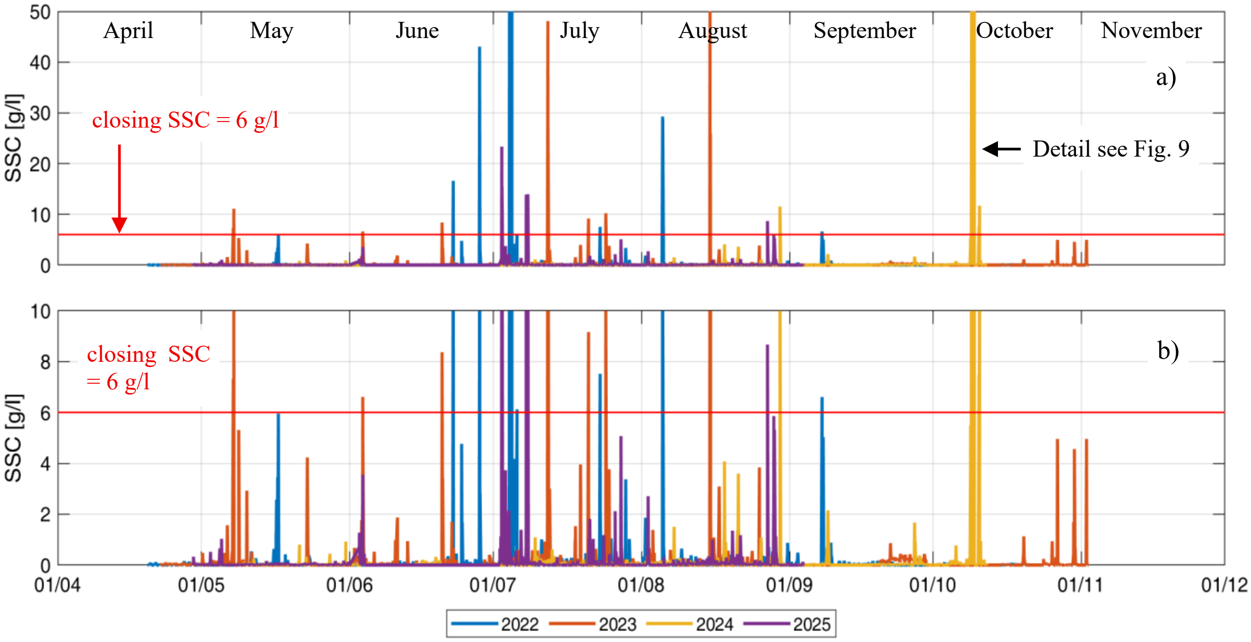

Fig. 8. Suspended sediment concentration (SSC) during the sediment transport seasons (April to November) of almost 4 years a) up to 50 g/l and b) up to 10 g/l. The horizontal red lines represent the limit, at which the intake shall be temporarily closed.

3.3 Temporary intake closing or HPP shutdown

To prevent disproportionate turbine erosion and other negative impacts of sediment in run-of-river or storge HPPs with intakes along the waterways, temporary closing of intakes and subsequent turbine shutdowns (or “switch-offs”) in periods of exceptionally high SSC are a cost-effective approach for optimizing HPP operations [7] [10]. For HPPs with several intakes, a particular intake at a river with currently high SSC can be closed while other intakes at rivers not affected by a sediment transport event, and all or some turbines, may remain in (partial) operation.

The SSC threshold at which operating an intake or turbine becomes unprofitable is referred to as the "closing SSC" in this paper. So far, only a few studies on this topic have been reported in the literature. Table 1 summarises the available data on the closing SSC of HPPs with Pelton and Francis turbines, which range between 1.1 and 15 g/l, mostly between a few and <10 g/l. In some regions of the world, SSC is reported in ppm (by mass), corresponding to mg/l. Hence, SSC-values in g/l are to be multiplied by 1000 to obtain values in ppm.

For the systematic implementation of temporary closing of intakes during periods of exceptionally high SSC and subsequent HPP shutdowns, the following elements are required (adapted from [13]):

- Technical and contractual possibilities for the HPP operator and energy utilities to tolerate or compensate for temporary production reductions or outages within the overarching boundary conditions (e.g. production obligations or compensation by other HPPs within an electricity balance group).
- Reliable measurements of increased SSC in the headwater as early as possible. This means a measuring system for real-time SSC monitoring in the relevant SSC range, ideally also operational in case of closed intake, and if possible, with redundant sensors relying on different operation principles.
- Criteria for the closing of the intake (i.e. closing SSC) and for resuming the intake operation (opening SSC, usually lower than the closing SSC).
- Corresponding alarms in the monitoring system and defined procedures for the involved parties.

The closing SSC is specific to each site. As shown in Table 1, it depends on more than just the hydraulic head of the HPP. It is determined by balancing the economic trade-off between erosion-related costs and the revenue generated from electricity sales. This involves sediment and turbine properties, the cost of maintenance works and electricity prices [3] [13]. For the intake Tours of HPP Filisur, a closing SSC of 6 g/l was obtained from an economic analysis.

Table 1: Closing SSC of HPPs with Pelton (P) and Francis (F) turbines and their key features (sorted by decreasing head); with z_2 = number of nozzles and B = inner bucket width for Pelton turbines (extended from [13]).

HPP, country Literature source	Turbine Type	Installed capacity [MW]	**Head [m]**	z_2 [-]	*B* [mm]	Hard-coating of Runner(s)	**Closing SSC [g/l]**
Tala, Bhutan [14]	P	6 x 170	**819**	5	747	Yes	**5.5**
Dorferbach, Austria [15]	P	1 x 10	**686**	4	228	first No, then Yes	**1.1**
El Platanal, Peru [16]	P	2 x 110	**627**	-	-	-	**4**
Cheves, Peru [17]	P	2 x 84	**602**	-	-	-	**2.5**
Yuncan, Peru [16]	P	3 x 43	**525**	-	-	-	**2**
Fieschertal, Switzerland [13]	P	2 x 32	**500**	2	650	Yes	**15**
Basochhu Lower, Bhutan [14]	P	2 x 20	**459**	4	580	No	**1.7**
Chhukha, Bhutan [14]	P	4 x 84	**435**	6	786	Yes	**6.5**
Filisur, Switzerland [this study]	F	2 x 33	**415**	-	-	Partially	**6**
Machupicchu, Peru [16]	P F	3 x 30 1 x 98	**356**	-	-	-	**2**
Basochhu Upper, Bhutan [14]	P	2 x 12	**337**	2	570	No	**1.4**
Dharasu, India [18]	F	4 x 76	**248**	-	-	first No, then Yes	**3**
Cahua, Peru [19]	F	2 x 22	**215**	-	-	first No	**3**
						then Yes	**10**
Jhimruk, Nepal [20]	F	3 x 4	**202**	-	-	No	**3**
Amaime, Colombia [21]	F	2 x 10	**198**	-	-	No	**≈ 3 to 7**

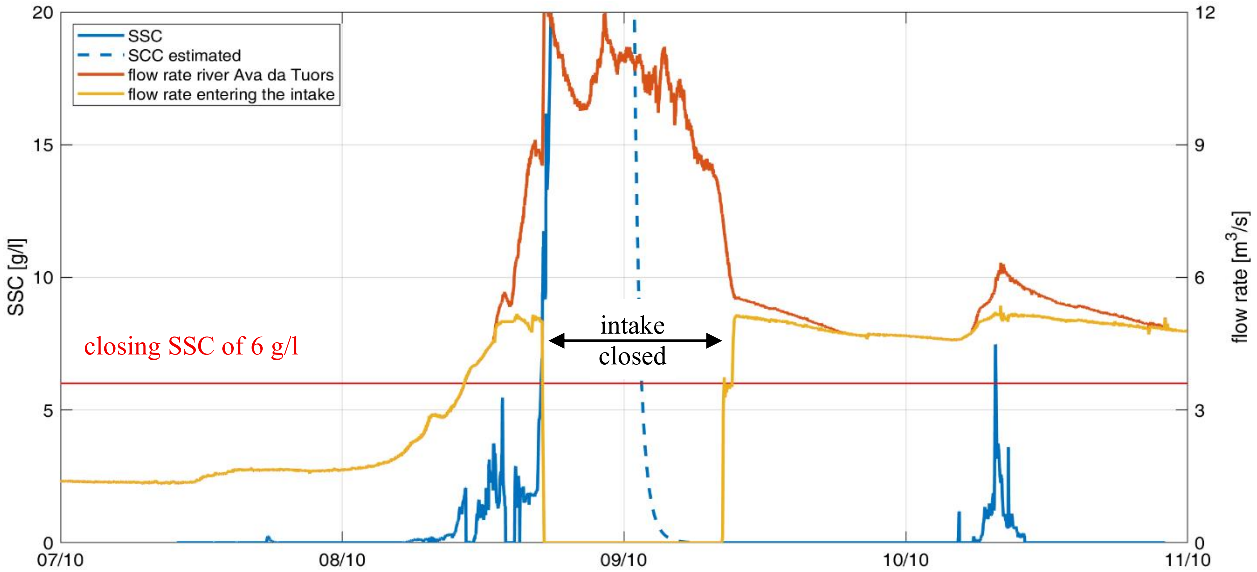

Fig. 9. Example of an automatic closure of the intake Tuors of the HPP Filisur during a major flood in October 2024, with time series of suspended sediment concentration (SSC) as well as the flow rates in the river and of the intake over four days.

Figure 9 illustrates a temporary closure of the Tuors intake at the HPP Filisur during a major rainfall event in 2024. The graph shows the SSC, river flow rate, and intake flow rate over a four-day period.

The SSC rose within minutes, later and much sharper than the river flow rate. Once it reached 6 g/l for five consecutive minutes, the intake gate closed automatically (intake flow rate = 0) while the weir gates opened to let the flood discharge pass. The graph shows SSC up to 20 g/l, whereas the SSC rose to over 100 g/l. A very high SSC > 100 g/l was present for approximately six hours (estimated based on experience and interpretation). At a design flow rate of the intake of 5 m^3/s, this would have resulted in > 500 kg/s, i.e.> 1'800 t/h of suspended sediments entering the waterway and later flowing through the turbines. During the six hours, a fine sediment load of more than 10'000 t was prevented from passing the turbines in this event.

4 Conclusions and Recommendations

Over fifteen years of experience with turbine efficiency monitoring have shown that just installing AI and implementing the relatively simple calculation of turbine efficiency is not sufficient. While machine learning algorithms for continuous efficiency monitoring can potentially be transferred between HPPs with identical setups, significant adjustments and adaptations are often required. These include customising rule-based input data validation and steady-state detection. A comprehensive simulation toolbox complete with practical insights and best practices tailored to individual cases can only be developed through iterative refinement and the accumulation of sufficient case studies.

The benefit of an efficiency history lies in long-term observation. The efficiency history shows that there is certain degree of temporal variation that cannot be reduced by any amount of effort. For this reason, short-term changes in efficiency should not be overinterpreted, but rather be viewed in the context of the established efficiency history. The examples of efficiency histories given in this paper demonstrate the effectiveness of our approach. It is particularly useful for identifying the optimal time to perform a major turbine refurbishment. Furthermore, knowing the absolute efficiency reveals the efficiency differences across the units installed in a particular HPP. This enables the operator to optimize unit dispatching.

Given the highly variable nature of suspended sediment concentration (SSC) in rivers, temporarily closing intakes or shutting down turbines during periods of exceptionally high SSC offers an economically viable strategy for medium and high-head run-of-river or storage HPPs with intakes along their waterways. To do so, a reliable SSC monitoring system is required at the main river intake(s). To obtain some pre-warning time, additional SSC sensors upstream - or collaboration with upstream HPP operators if available - are an advantage. The selection of SSC monitoring instruments, their implementation, calibration and integration into a HPP's control system, and the limit-SSC for the closing of intakes, are site-specific. The optimization of HPP operation with respect to sediment takes usually several years, during which a monitoring system and a data treatment workflow are established and stepwise improved building on the growing experience with sediment transport events.

Continuous efficiency monitoring for each unit and real-time SSC monitoring together form the foundation for fact-based decision-making in HPP operations. These tools enable operators to plan refurbishments, manage sediment-related risks, and optimize both economic and energetic performance.

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