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Optimization of hydropower plants with respect to fine sediment focusing on turbine switch-offs during floods

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Abstract. At medium- and high-head hydropower plants (HPPs) on sediment-laden rivers, hydro-abrasive erosion in turbines is an important economic issue. In HPPs with headwater storage, reservoir sedimentation is another problem related to fine sediment. On the one hand, turbine erosion is mitigated by reducing the sediment load in power waterways. On the other hand, reservoir sedimentation may be mitigated by conveying more fine sediment through power waterways to downstream river reaches. To optimize the operation of HPP schemes on the long-term, it is recommended to find a balance between these options based on real-time data using available monitoring techniques.

An operational measure to mitigate turbine erosion is to close intakes and switch-off turbines in periods of high suspended sediment concentration (SSC) and coarse particles, typically during floods. Prerequisites for such operation are (i) there is no obligation to generate electricity, (ii) real-time SSC measurements are available, and (iii) the value of the 'switch-off SSC' is known. In a case study at the high-head HPP Fieschertal, a switch-off SSC of 10 g/l was estimated. The economic analysis showed that it would have been clearly profitable to practice such a switch-off during the major flood in 2012 which had an SSC peak of 50 g/l.

1. Introduction

In the design and operation of hydropower plants (HPPs), handling of sediments is a major challenge. At medium- and high-head HPPs on sediment-laden rivers, hydro-abrasive erosion on hydraulic turbines is an important economic issue because it increases maintenance costs, and reduces turbine efficiency, electricity generation and hence revenues [1] [2] [3].

In HPPs with headwater storages, reservoir sedimentation is another problem related to sediments. The percentage of sediment which settles in a reservoir, i.e. the trap efficiency, depends mainly on the reservoir's storage volume compared to the mean volume of annual inflows, i.e. the capacity-inflow-ratio (CIR) [4]. The CIR reflects the mean residence time of the stored water. With high CIR, finer sediment particles settle. Reservoir sedimentation may have the following negative effects [4] [5]:

- Loss of active storage volume, and thus reduced ability to compensate in- and outflows for hydropower, irrigation, drinking water and flood retention;
- Increased turbine erosion because of higher SSCs and coarser particles in power waterways due to reduced trap efficiency of the reservoir;
- Reduced operational safety due to blockage of water intakes and dam outlets;

- Sediment deposits at the dam may compromise dam stability if not considered in the design;
- Lack of sediment in downstream river reaches, affecting the stability of river beds, banks and nearby infrastructures, as well as river morphology, ecology and habitats.

The loss of reservoir capacity due to sedimentation is estimated to be 0.8 % per year on worldwide average [6]. Because this is more than the increase of capacity due the construction of new reservoirs in recent years, the usable storage volume in reservoirs decreases worldwide [6] [7]. On the medium- and long-term, reservoir sedimentation may become economically more important than turbine erosion in some HPP schemes. Both turbine erosion and reservoir sedimentation are becoming more important for the following reasons:

- More sediment tends to be transported in rivers due to more intense precipitations as well as retreat of glaciers and permafrost (climate change);
- Additional HPPs are constructed on rivers with relatively high sediment loads;
- Public awareness and legal regulations regarding ecology and sustainability are increasing;
- Market situations may demand further economic and energetic optimization of HPPs.

This paper deals with measures to optimize the design and operation of HPPs at sediment-laden rivers. First, measures to cope with hydro-abrasive erosion and reservoir sedimentation are reviewed. The option of conveying fine sediment from reservoirs of low- or medium-head HPPs through the power waterways to downstream river reaches is highlighted. Then it is proposed to economically balance turbine erosion and reservoir sedimentation based on real-time sediment monitoring. In the second part of the paper, the option of temporary closing of intakes and pausing of turbine operation during floods is treated based on a case study at HPP Fieschertal, Switzerland, which was conducted in the scope of a research project [3] [8]. In particular, a relatively simple approach to estimate the so-called switch-off concentration is presented, i.e. the limit of suspended sediment concentration (SSC) above which the operation of a HPP is unprofitable. Finally, the economic benefit from such an operation regime is demonstrated in a scenario referring to a past major flood event.

2. Options to cope with hydro-abrasive erosion

2.1. Increasing the erosion resistance

One way to reduce hydro-abrasive erosion is to increase the erosion resistance of exposed parts. For hydraulic turbines, a martensitic stainless steel with 13 % chrome and 4 % nickel is mainly used [9]. Such steel has a Mohs hardness of 4.5 to 5, i.e. it can be eroded by harder mineral particles such as quartz and feldspar. Other steel grades and alloys with higher erosion resistance are used for e.g. welded hard-facing layers in Pelton buckets [10] or needles of Pelton injectors (e.g. steel-cobalt-alloys such as ‘stellite’).

Another option is to apply coatings on steel surfaces exposed to sediment-laden flow. Soft-coatings (based on polyurethane/epoxy resin) have been used in turbines at lower heads (e.g. Kaplan) [11]. In medium- and high-head turbines, thermally sprayed hard-coatings made of tungsten carbide, cobalt and chrome (WC-CoCr) have become state-of the art [1] [2] [11]. Such coatings are approximately as hard as quartz. They reduce the extent of erosion and increase the times between overhauls, but can still be damaged. Coated runners have generally a smaller initial efficiency than uncoated ones due to higher roughness and potentially different hydraulic profiles, but the loss of turbine efficiency is slower, resulting in higher revenues depending on site conditions [1].

2.2. Reduction of the sediment loading

Another approach to reduce hydro-abrasive erosion on turbines is to reduce the factors contributing to the sediment “loading”, i.e. the number of particles, their impact energy and angle of attack (mode of erosion). In the planning phase, a turbine can be designed to be less prone to hydro-abrasive erosion [9] [12]. To find a suitable combination of measures and a specific turbine design, turbine erosion needs to be addressed in an early stage of planning and meaningful sediment data are required [1] [2].

For existing HPPs, the head and the velocity inside the turbines cannot be generally reduced; and the hardness and shape of particles are properties of the river catchment.

The SSC and the median particle size can be reduced by investments in the design and construction of civil works and by suitable operation of HPPs. When the turbine water is not taken from a reservoir, one or several of the following facilities may serve for partial sediment exclusion:

- Sand traps [13], mostly in the form of long, open-air or subsurface settling basins, possibly preceded by a gravel trap. Various flushing systems are available. Typically, sediment particles with diameter > 0.3 mm are excluded; a smaller design particle size can be economically justified at high-head HPPs with hard and angular particles;
- Flushable intake areas, compensation basins/chambers or storage tunnels;
- Coanda-effect screens for intakes with low discharges (typically below a few m^3/s) and when typically grains with diameters > 0.5 or 1 mm are to be excluded;
- Hydro-cyclones in penstocks with moderate discharges (under development): according to numerical simulations, particles larger than 60 μm and some > 20 μm can be excluded [14].
- Additional sediment traps (often called 'rock traps') should be provided at HPPs with unlined waterways or with water adductions from simple intake structures into the power waterway.

The sediment load in power waterways and turbines can also be limited by temporary closing of intakes and pausing of turbine operation during floods or other events with high sediment load [1] [2] [15] [16] [17]. This operational measure is treated in detail in section 5. Hydro-abrasive erosion can also be reduced by avoiding part-load operation, because the amount of erosion per kWh is higher at part load than at full load [2].

Moreover, highly sediment-laden water may be released through Pelton turbines without erosion on the runner and without electricity generation when the jet deflectors are activated (as during an emergency closure). Such operation is an option for rare situations with very high SSCs, e.g. due to re-suspension of settled sediment, as may occur during the emptying of upstream storage facilities or dewatering of the power waterway.

3. Options to cope with reservoir sedimentation

3.1. Overview on countermeasures

There are many measures to mitigate reservoir sedimentation [4] [5] [6] [18] [19] [20] [21]. An overview of these measures is given in figure 1. Feasible measures depend also on the CIR. Because sediment input into reservoirs cannot be fully prevented, sediments have to be evacuated at the latest when the active storage volume is reduced to an unacceptable extent. Occasional restitution of sediment-laden water into the river at the dam toe (via dam outlets or by hydro-suction) may lead to high SSCs downstream of the dam [19]. To limit negative environmental impact, flushing operations are mostly combined with higher discharges and accompanying measures, and admissible SSCs have to be respected, depending on site conditions (e.g. [22]).

3.2. Sediment conveyance from reservoirs through power waterways

To mitigate reservoir sedimentation and to re-establish sediment continuity without causing high SSCs in the river downstream of the dam, fine sediments from reservoirs can be conveyed through power waterways and hence turbines to downstream river reaches [23]. Sediment particles from reservoirs can be transported into power waterways by (figure 1):

- Sluicing of sediment-laden water, possibly with the aid of jet-induced turbulence to hinder settling [23];
- Venting of turbidity currents, possibly requiring modifications of the intake and/or waterway [24];
- Re-mobilisation of settled fine sediment (often cohesive) by hydro-suction/pumping [25] [26], with the possibilities to control the area of sediment removal, the sediment transport rate and to exclude larger particles; or possibly by using air-bubbles [21].

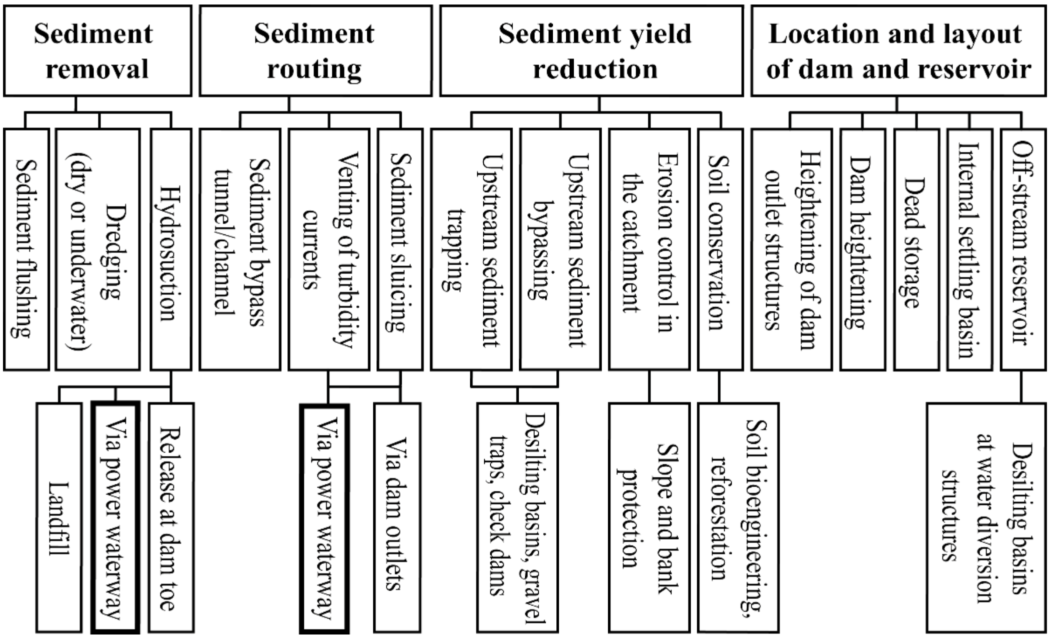

Figure 1. Overview on options to reduce reservoir sedimentation (modified from [5]).

With sediment conveyance from reservoirs through power waterways, the SSC in the river downstream of the HPP's water restitution point is relatively low, because the sediment is transported during long periods in a large volume of water. In the river reach between the dam and the HPP's water restitution point, i.e. in the residual flow reach, SSC is not increased. Other advantages are that no further transport, dewatering and land-based disposal of the sediment are required and no flushing water is lost for electricity generation. To limit turbine erosion, the following factors are favourable for this option of sediment handling:

- Low to medium head HPP, thus smaller flow velocities in the turbines;
- Relatively small particles (clay as well as fine and medium silt, ≤ 20 µm [21]);
- Low particle hardness (typically in catchment areas with sedimentary rocks);
- Suitable turbine design (e.g. seals, trunnions, cooling water system adapted to high SSCs).

Generally, sediment deposits close to intakes and dams are to be removed. In medium and large reservoirs, deposits in these zones consist typically of fine particles, because coarser sediment particles settle typically more upstream, in delta zones close to inflows. Because small particles cause less turbine erosion than larger particles at a given SSC [12] [27] [28], less erosion damage is expected from such fine sediment.

Sediment conveyance from reservoirs through power waterways was practiced e.g. in the three Francis HPPs listed in table 1. These HPPs have moderate heads and rather small reservoirs. Sediment particles (mainly silt) were transported by hydro-suction from the bottom of reservoirs in front of the intakes, where they were entrained into the power waterway and passed through the turbines. The admissible increases of SSC in the downstream river reaches were defined by environmental authorities as a function of the season and on the SSC in the rivers upstream of the restitution points (SSC_{us}). The hydro-suction units were controlled in function of the measured SSC_{us} or corresponding turbidity. In the second example in table 1, a more dynamic sediment mobilization regime was selected for environmental reasons. When the hydro-suction installation was operating at full capacity, i.e. removing 200 m^3 of sediment deposits per hour, the SSC in the turbine water was 1.4 g/l at design discharge. This is considerably lower than typical SSCs during reservoir flushing operations. The resulting downstream SSCs are similar to natural conditions before the construction of the HPPs on this river.

Table 1. Examples of HPPs, where fine sediments were removed from reservoirs by hydro-suction and conveyed through the power waterway to the downstream river reach.

HPP (river) and reservoir names, country	Gross head	Design discharge of turbines Q_d	Admissible increase of SSC in the downstream river reach	Admissible sediment return at Q_d
HPP Kubel (Sitter), Gübsensee, Switzerland [29]	97 m	16 m³/s	0 in winter, 0.2 g/l otherwise	270 t/day
HPP Walgauwerk (Ill), Compensation basins Rodund, Austria [30]	162 m	68 m³/s	0 if $SSC_{us} \leq 0.05$ g/l, 0.2 g/l if $0.05 < SSC_{us} < 0.2$ g/l, 1.5* SSC_{us} if $SSC_{us} \geq 0.2$ g/l	1170 t/day ≤ 4800 t/day
HPP Langenegg, Reservoir Bolgenach, Austria [21]	280 m	approx. 30 m³/s	practiced restitutions of 0.02 g/l to 0.2 g/l (mainly at high natural Q) were below admissible SSCs	practiced ≤ 500 t/day (80 000 t/year)

4. Optimization of HPPs with respect to fine sediment

4.1. Balancing turbine erosion and reservoir sedimentation

It is proposed to balance the negative effects of fine sediments on HPPs, i.e. turbine erosion and reservoir sedimentation, by economical optimization considering the whole HPP scheme (civil structures and electro-mechanical equipment) over its lifetime.

The SSC in the power waterway can be partly controlled by operational decisions: The SSC can be increased to reduce reservoir sedimentation or can be limited to reduce turbine erosion (figure 2). The former can be achieved by transporting fine sediments in front of the power water intake as described in the previous section. The latter can be achieved by temporary closing of intakes and pausing of turbine operation during floods, as mentioned in section 2.2 and treated more in detail in section 5.

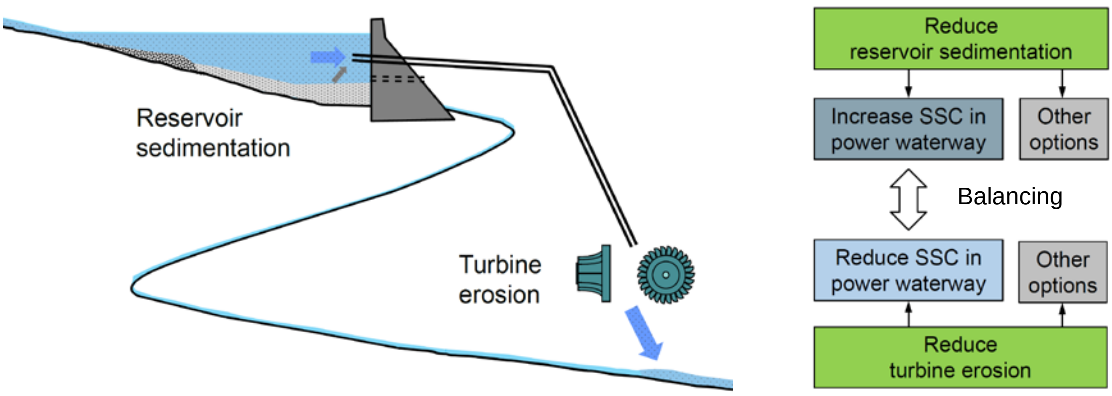

Figure 2. Economical balancing of reservoir sedimentation and turbine erosion at medium- and high-head storage HPPs by increasing or limiting the SSC in the power waterway.

4.2. Decision-making based on real-time data

For a few decades or years, various techniques and instruments (sensors) have been available for the continuous real-time monitoring of (i) sediment levels, SSCs and particle size distributions (PSD) as well as (ii) turbine efficiency ([31] [32] [33] [34] [35] [36] and [3]). It is recommended to make use of such monitoring data to optimize the operation of HPPs with respect to sediment and its consequences. In addition to real-time data, also hydro-meteorological forecasts may be considered in short-term operational decisions.

5. Option of turbine switch-offs at high SSCs

5.1. Temporary turbine switch-offs

SSC and PSD in the turbine water may vary considerably [8]. In a period with high SSC and potentially relatively coarse particles, the direct and consequential damages on turbines and other elements of HPPs may exceed the revenues from electricity sales in these periods. These damages include (i) the costs of repair works and replacement investments due to hydro-abrasive erosion, and (ii) losses of revenue due to reduced turbine efficiency or due to downtimes during revision works. If possible from the regulatory framework and production obligations, it is thus economical to close water intakes and to pause turbine operation when SSC and particle sizes exceed limit values. Since the effect of PSD on turbine erosion is not yet fully known, switch-off decisions are so far based on SSC. Engineers are thus faced to the task to determine the value of the so-called switch-off SSC.

5.2. Basic data and annual sediment-induced costs at HPP Fieschertal

To determine the switch-off SSC, data on the sediment load, turbine erosion, efficiency reductions, as well as the sediment-induced costs and electricity prices are required. In the frame of an interdisciplinary research project, such data were obtained for the high-head HPP Fieschertal in Valais, Switzerland. This HPP has a design discharge of 15 m^3/s, a gross head of 520 m and is equipped with two horizontal 32 MW Pelton turbines [1]. A storage tunnel (64 000 m^3) serves to compensate interdaily variations of inflow and turbine discharge (no storage lake). Since the headwater storage is relatively small, the HPP is practically a run-of-river scheme.

The sediment load, turbine erosion and efficiency reductions in the years 2012 to 2014 are reported in [8] [3]. The average annual costs which are induced by the fine-sediment load transported through the turbines were estimated in table 2. For simplicity, the electricity price was assumed to be constant at 0.05 €/kWh (50 €/MWh). The annual costs in table 2 resulted from data on executed repair works and purchased turbine replacement parts as well as the estimated average annual probabilities of the individual cost elements. The annual costs induced by fine-sediment correspond to some percent of the value of the annual electricity generation and are thus economically relevant.

Table 2. Average annual costs induced by fine-sediment load at HPP Fieschertal (for whole HPP with two turbines, estimate based on data from 2012 to 2014).

Cost or loss item		10^3 €/year	Percentage of the value of the annual electricity
Costs of repairs and replacement parts		270	3.3 %
- Runners	180		
- Injectors and stationary turbine parts	60		
- Flushing system of sand trap	30		
Electricity generation losses		30	0.4 %
- Due to reduced efficiency	10		
- Due to downtime during runner exchange	20		
Total		300	3.7 %

5.3. Estimation of switch-off SSC at HPP Fieschertal

In the following, a simplified approach to estimate the switch-off SSC is proposed and illustrated by the example of HPP Fieschertal.

The long-term average annual load of fine sediment transported through both turbines was estimated as 50 000 tons. This is the average of the annual loads determined from the measurements in the years 2013 and 2014 [8]. For the sake of simplicity, it was assumed that the costs induced by the

fine sediment are proportional to its mass. With this assumption, specific sediment-induced costs resulted in 300 000 € per year / 50 000 tons per year = 6 €/ton = 0.006 €/kg.
With an average SSC of 0.5 g/l = 0.5 kg/m^3, the sediment-induced costs with respect to the water volume are 0.003 €/m^3. If the SSC rises for example to 10 g/l, the fine-sediment induced costs are also 20 times higher, i.e. 0.06 €/m^3.

For HPP Fieschertal, 1 m^3 water is equivalent to 1.2 kWh of electric energy. Thus, the sediment-induced costs with respect to electric energy is 0.003 €/m^3 / 1.2 kWh/m^3 = 0.0025 €/kWh at average SSC. When the SSC increases from 0.5 g/l to 10 g/l, the sediment-induced costs rise to 0.05 €/kWh, corresponding to the assumed electricity selling price. From this it is concluded that the operation of HPP Fieschertal is not profitable when SSC >10 g/l. This switch-off SSC is an approximate value since it resulted from a simplified linear approach and a relatively short data set (3 years). It is recommended to re-evaluate the assumptions and the approach when more data will be available.

5.4. Switch-off and switch-on procedure
The control system of HPP Fieschertal was programmed to issue a warning when the SSC measured at the top of the penstock exceeds 10 g/l for 15 minutes. Preliminary warnings are given from continuous turbidity measurements (i) in the river upstream of the intake and (ii) in the sand trap, offering both a prewarning time of about one hour (cross-section averaged flow time in the storage tunnel at full load at maximum operation level). If the SSC exceeds 10 g/l for 15 minutes, the staff member on duty has the competence to close the intake and to switch-off the HPP, considering the weather forecast and his observations.

Taking the HPP back to operation is associated with some effort, e.g. de-clogging of cooling water systems, flushing operations and checks. Therefore it was proposed to resume operation when SSC is considerably lower than 10 g/l, say 5 g/l, and when the flood is expected to end soon.

5.5. Switch-off scenario during the 2012 flood
These rules for turbine switch-off and restart were hypothetically applied to the situation of a major flood event which occurred in July 2012. This was the only flood event in the years 2012 to 2014, in which the switch-off criterion would have been met. The switch-off duration would have been 16 hours (figure 3).

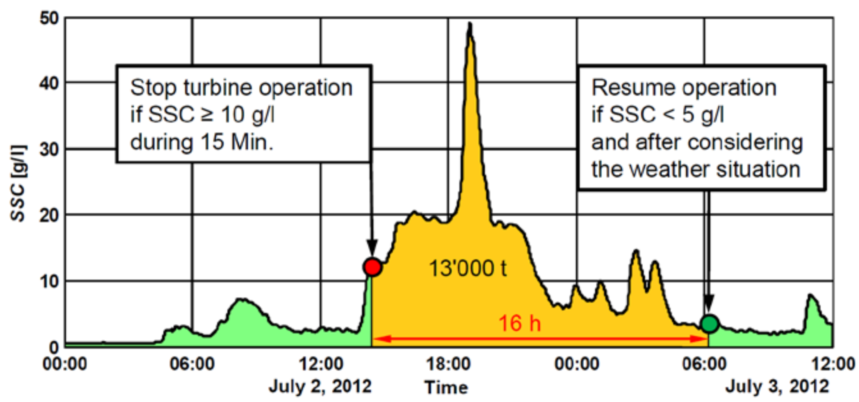

Figure 3. SSC time series in the turbine water of HPP Fieschertal during the major flood event of July 2012 [8] and switch-off scenario with the proposed rules.

During this time, 13 000 t of fine sediment were transported through the turbines (orange fill in figure 3). This corresponds to 12 % of the annual sediment load in 2012 or to 25 % of the sediment load in the other years without a major flood event (average of 2013 and 2014). The amount of sediment which entered the power waterway during these 16 h was higher than the sediment load of the turbines, because a part of the sediment entering the HPP system settled in the storage tunnel. These deposited sediments were occasionally re-suspended and transported through the turbines in the months after the flood. Thus, a sediment load of more than 13 000 t would have been prevented to enter the power waterway and to pass through the turbines if the intake had been closed during these 16 hours.

The economic potential of the switch-off scenario during this flood was evaluated and the result is summarized in table 3. This indicates that switching-off both turbines during the flood in July 2012 would have been clearly profitable, with a net benefit of roughly 200 000 €.

Table 3. Economic analysis (benefits vs. losses and costs) of the switch-off scenario at HPP Fieschertal during the major flood event in 2012 (for whole HPP with two turbines).

Benefits	€	Losses and costs	€
Avoided repair costs because of less erosion (rough estimate)	200 000	Generation loss during switch-off (2 * 32 MW * 16 h ≈ 1 GWh)	− 50 000
Avoided generation loss because of less reduced efficiency	30 000	Potential penalty for non-compliance with the announced generation program	if applicable
Avoided generation loss because of no runner exchange required	30 000		
Total	260 000	Total (without potential penalty)	− 50 000

6. Conclusions

Measures to cope with turbine erosion and reservoir sedimentation were reviewed. To optimize HPP schemes with respect to fine sediment, a combined approach is required. This involves knowledge in engineering sciences (hydraulic, mechanical, material, civil and environmental) in combination with economic analysis.

Adequate solutions to mitigate reservoir sedimentation and turbine erosion depend on the site conditions, the layout and components of HPPs. Long-term measurements and documentation of sediment loads, turbine erosion, efficiency changes, maintenance actions and costs are highly recommended as a basis for economic and power production optimizations. To reduce reservoir sedimentation, conveying fine sediment through power waterways is an option for low- to medium-head storage HPPs if sediment particles are relatively small and soft, and SSCs are low. To mitigate turbine abrasion, temporary closing of intakes and turbine switch-offs in periods of high SSCs and coarse particles are economically interesting measures for medium- to high-head HPPs with no or only small headwater storages, if compliant with the regulatory framework and production obligations.

A relatively simple linear approach for the calculation of the switch-off SSC was proposed and a value of 10 g/l was obtained for HPP Fieschertal. If this switch-off SSC had been applied in the major flood in 2012, the shutdown duration would have been 16 hours and a net benefit of roughly 200 000 € would have resulted.

7. Outlook

As a basis for optimized design, operation and maintenance of HPPs, further knowledge on quantitative relations between sediment and turbine parameters, turbine erosion and efficiency reductions are required. Therefore, further field investigations with detailed measurements at HPPs are highly recommended to enlarge the set of prototype data and to provide a basis for comparison with laboratory investigations, numerical simulations and analytical considerations.

For some HPPs worldwide, a certain SSC-value is taken as switch-off criterion so far. However, a combination of SSC- and PSD-information would better account for the actual erosion potential. The effect of PSD on turbine erosion can be considered by defining a 'modified SSC' = SSC * k_{size}, as proposed by Nozaki [28]. The coefficient k_{size} reflects the relative abrasion potential of particles of various size classes. Then, a switch-off criterion referring to a modified SSC can be formulated and no additional criteria on limit particle sizes are required.

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