# Operating Experience from intentional transit of fine sediment through hydraulic turbines

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**Abstract**

Within the framework of securing the bottom outlet valve of the Chambon Dam (France, Romanche), EDF HYDRO succeeded in removing a volume of approximately 32,000 $m^3$ of sediment without interrupting production while complying with environmental regulations. The solution used was to perform a sediment dilution and pumping operation along with injection at the intake and transit through the hydraulic turbines of St Guillerme II.

After presenting the general procedure that was used and the preliminary studies, this article details the main characteristics of the power plant and sediment, then partly describes the dredging work performed to remove sediment and perform injection and finally describes the real-time monitoring required to enable the project to be completed without incident (human or environmental) and without excessive wear on the turbines.

## 1. Introduction

In order to guarantee its volume of water storage and hydro-electrical generation capacity in the long term, EDF is working to find sustainable solutions to remove the sediment build-up in its dam reservoirs without interrupting hydropower generation and while complying with environmental regulations.

Of the various solutions available, the easiest is to intentionally and continually inject the sediment through the turbines. The main advantage of such a solution is that there is no loss in generation while generating capacity increases.

However, since EDF's power stations were not designed in accordance with [1] for long-term exposure to sediment, a complete method was developed [2] to:

- Analyse and prevent the risks induced by sediment erosion and clogging.
- Control the average concentration of injected sediment in real time.
- Monitor turbine behaviour while sediment is flowing through it.
- Measure and evaluate the impact on the whole power station.

After presenting the global methodology that was developed and some specific characteristics of the Chambon dam and St Guillerme II power station, the article briefly describes how injection was performed.

## 2. General Process

Injecting sediment continuously through hydraulic turbines can be an advantageous solution for managing the silting-up of water reservoirs. However, before considering a sustainable operating process that aims to intentionally increase the natural concentration of sediment flowing through the turbines, many issues need to be addressed. The scope covers a wide range of engineering aspects: environmental, civil, mechanical, measurement & instrumentation and operational. To prevent a catastrophic situation where the turbines are completely eroded, some steps must be validated, requiring comprehensive risk analyses and real-time monitoring from where dredging is being carried out to the behaviour of the turbine.

Typically, these steps consist of defining and validating:

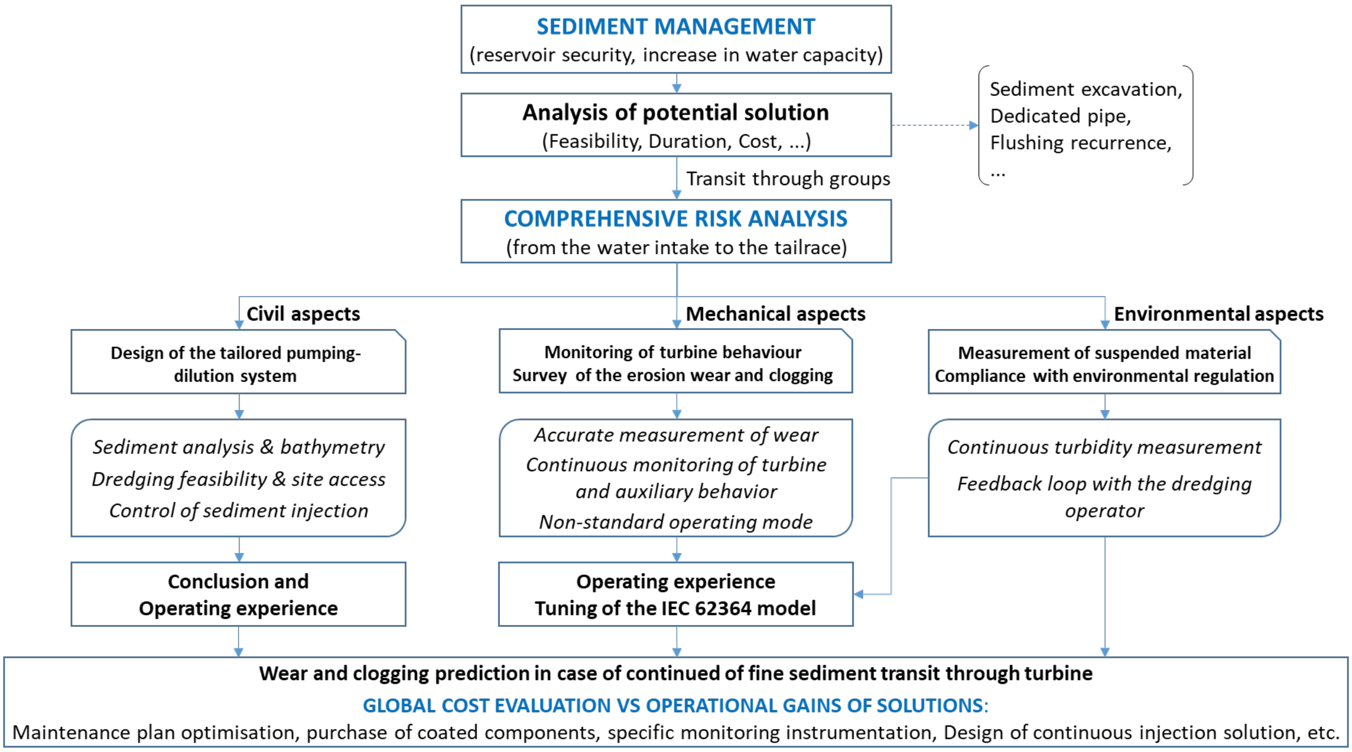
I. The capability of the dredging operator to design an adequate pumping-dilution system which will control the sediment concentration at the injection inlet in real time. To reduce the impact of erosion wear, it is necessary (but challenging) to keep the concentration of suspended material in the turbines as constant as possible.

II. The instrumentation system in the hydraulic circuit used to measure the concentration of sediment passing though the turbines. A feedback loop must be created to inform the dredging operator of what is happening inside the turbines (notwithstanding the time required for the sediment to travel from the water intake to the turbines).

III. A comprehensive risk analysis related to erosion and clogging of each component in the hydraulic circuit to prevent any issues. Since each risk evaluation is site dependent, the analysis must take into account the natural transition history of the sediment (routine and extraordinary events) and the operator's feedback. The results of the analysis will be used to identify protective measures that need to be implemented.

IV. Detailed measurement of wear on mechanical components which are exposed to the sediment. This requires assessing the condition of the component (which will be used as the reference) as closely as possible to the beginning of the test.

The overall process is illustrated in the following diagram:




One of the most value-added features of this approach is that not only is turbine wear controlled but important parameters are measured and recorded. This enables EDF to build up a comprehensive database including sediment characteristics (size, shape and mineralogy), variation in sediment concentration over time and associated turbine erosion/ wear.

IEC 62364 wear rate models can then be fine-tuned and used for predicting early turbine deterioration and maintenance requirements or whether other sediment removing operations can be performed safely.

## 3. Initial Operating Experience

The first of EDF's experiments involving intentional sediment injection are described fully in [2]. Two different facilities were selected for these experimental tests.

To recap, some of the main conclusions of these tests were that:

- Dredging capabilities have to be prepared to meet EDF specifications. Measurement of sediment concentrations in production units showed noticeable variations (+/- 50%) around the targeted concentration of sediment going into the turbines.
- Continuous transit of even fine sediment accelerates turbine ageing. This implies that this type of operation must be prepared methodically and monitored to provide the operator with the benefit of increased hydro-storage capacity without having to carry out costly turbine repairs afterwards.

## 4. Dredging operation at Le Chambon Dam

Based on the experience acquired, a dredging operation at Le Chambon Dam was initiated. This was the first industrial scale application of removing sediment by injecting it through the generating turbines.
The aim of the operation was to remove an estimated volume of 35,000 $m^3$ of sediment from in front of the bottom outlet valve to create a stable clearance area. This would increase the safety of the valve and protect it from potential future progression of the sediment front on the dam bed.
Numerous issues had to be addressed before the operation could start since this type of operation is different from what dredgers normally do: discharge of sediment must be controlled at the same time as managing the effect of the high tidal range (+/- 27 m).
The solution proposed was based on a pendulum dredge pump operated by a crane with a double winch installed on a pontoon (Figure 1). The submerged sediment is dislodged using a pressurised water injection system (8 bar jetting) and then pumped before being released in front of the water intake.

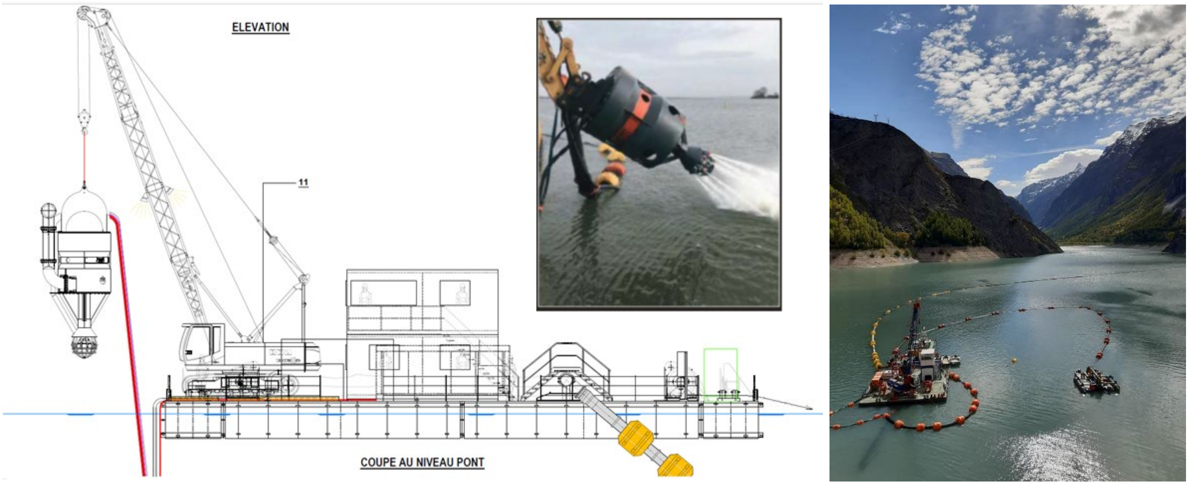



**Figure 1:** Dredging station

Specific monitoring of the injection process was implemented (Figure 2). This aimed to control the concentration of sediment pulp injected into the intake. This pulp is diluted with water at the water intake. Sediment concentration through the turbines was monitored in parallel (taking into account the lag for the time required for the sediment to travel from the injection port to the units). To meet a target concentration of 0.7 g/l through the units at a flow rate of 45 $m^3/s$, the injected sediment pulp should reach a concentration of 135 g/l at a flow rate of 0.2 $m^3/s$.
To secure the operation in the event of the turbines exhibiting significant damage, a second discharge circuit was installed. If this system had to be used, the sediment would be discharged at the tail end of the reservoir (about 1 km from the water intake), in a location where it could be stored without problems.

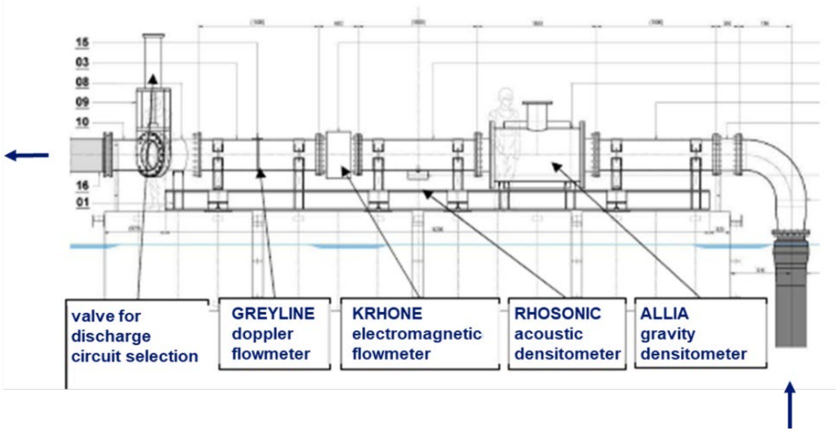



**Figure 2:** Instrumentation system for injected sediment pulp

The last but not least constraint was screening the sediment (max 1 mm) for mechanical reasons (see Section 7). A solution using gravitational screening was implemented. By injecting the sediment pulp a sufficient distance away (approximately 15 m) from the water intake, only fine sediment should be entrained by the water flow at the intake, leaving coarse sediment to fall away naturally under gravity.

The results showed that the approach was effective (Figure 3), though a small amount of coarse sediment was still present in front of the water intake.

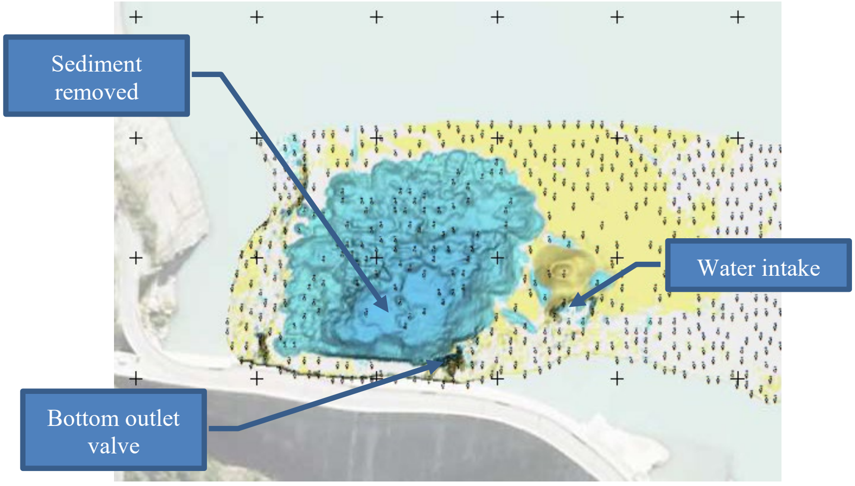



**Figure 3:** Final bathymetry showing the total volume removed

## 5. Sediment composition and concentration measurements

Numerous sediment analyses were performed during the preparatory phase of the work. The results uniformly showed that the sediment mainly consisted of dark grey clayey silt.
The mean diameter $d_{50}$ is estimated at 0.02 mm (i.e., rather fine sediment) and the concentration of quartz and feldspar is 35%.
No data were given regarding the shape of the sediment. It was therefore considered using a semi-angular particle geometry.

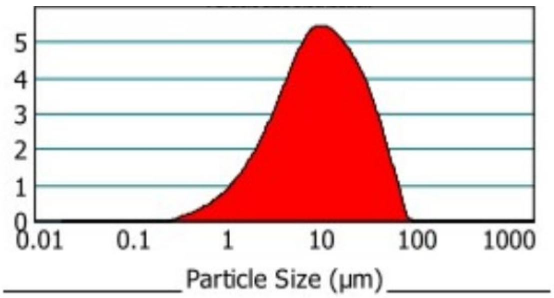



**Figure 4:** Le Chambon particle size distribution

Fortunately, the plant was already equipped with optical sensors for sediment concentration measurement at both tailraces. The correlation law between turbidity and sediment concentration was checked before and during the operation with sampling at regular intervals. Real time measurement results were shared with the dredger (see example in Figure 5).

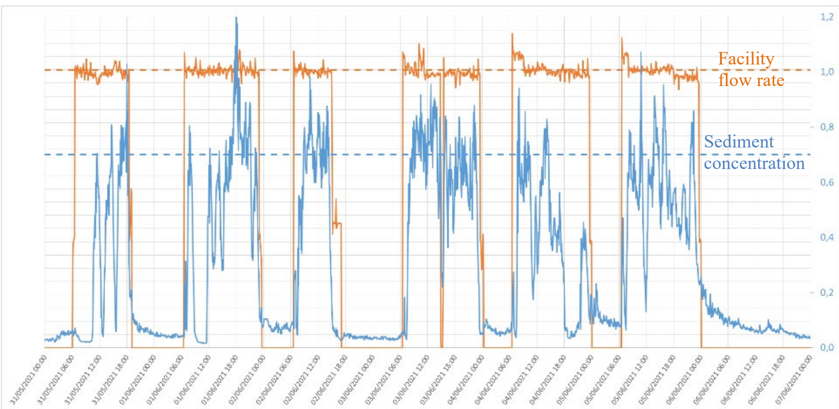



**Figure 5:** Sediment concentration measurement results over one week

## 6. Unit Considerations

### *6.1. Permissible target concentration through the units*

Defining the permissible sediment concentration through the units was one of the biggest challenges. This had to be sufficiently high to limit the length of dredging operations (high daily cost) while not wearing out the turbines. A compromise was established at a mean concentration of 0.7 g/l (+/ 50%) through each unit which represents 1360 tonnes per day (for a 12 hours of turbine operation per day).
With this concentration, the whole volume of sediment could be dredged within approximately 30 days. By incorporating meteorological hazards and potential technical problems, it was thought that the entire operation could be carried out within two months.
By using the wear rate formulation in [1] and all of the above considerations, the wear rate was estimated at 0.22 mm at the outlet of the runner, on the outer diameter side (runner band). The wear rate for other locations (guide vanes, runner leading edge, runner seals and so on) was estimated to be between 0.15 and 0.30 mm. If these results are correct, these relatively small wear rates should not impact the behaviour of the units nor their performance.

### *6.2. Basic Countermeasures*

Both turbines (Francis technology) were commissioned in the 1980s. Their design did not take sediment wear or clogging into account. The general state of the runner did not show severe wear, but negative experience in the past indicated that certain countermeasures against potential damage were required.

EDF decided to operate with both units, in order to:

- Maximise the flow, so that a higher volume of sediment could be passed through and sediment dilution optimised up to the acceptable concentration limit through the turbines.
- Protect the barrel valve seals.

Throughout the dredging operation, operational data such as turbine vibration, runner hub pressure, thrust bearing temperature, penstock pressure change and number of start-ups of the dewatering pumps was monitored to detect any abnormal deviations which could be symptoms of early damage.

In parallel, it was decided to periodically measure the leakage at the shaft seal of both units. This was performed by the operator twice a week with a stopwatch and a 100 litre vessel (see Figure 6). The measurement was of course taken in consultation with the head of the site. Any deviations would be a basis for reviewing continuation of the operation.

**Figure 6:** Dewatering room conditions for shaft seal leakage measurement

### *6.3. Material loss quantification*

Loss of material on the runner was quantified using a pulsed light photogrammetry technique (3D scan, see Figure 7) using System ATOS Compact Scan. The result of this type of measurement is a cloud of millions of points. The first measurement campaign (before injection) was used to compute the reference surface. The same measurement was repeated just after the injection operation. By computing the minimum distance between each measured point and the associated reference surface, a mapping of the difference is obtained which represents the material loss.

This requires precise positioning of each measured cloud compared to the reference surface to obtain representative and physical results. Therefore, a reference plane must initially be identified where possible.

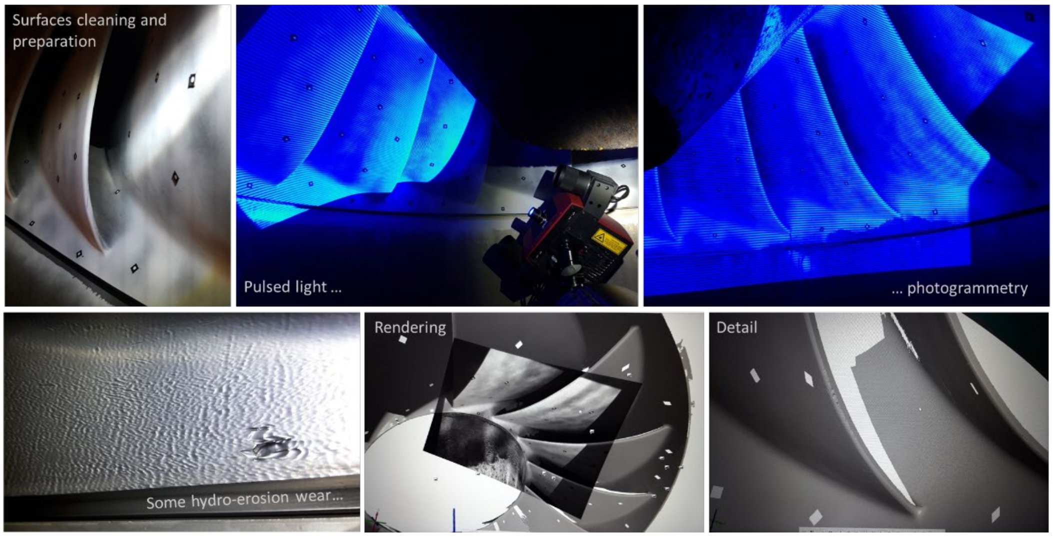



**Figure 7:** 3D photogrammetry scanning with pulsed light

The precision of this type of device is +/- 20µm and repeatability is less than 5 µm. This is sufficiently accurate since the material loss was assumed to be 10 times higher.

Scanned surfaces have to be prepared carefully: all blades must be dried and mattified to prevent reflections during photogrammetry.

The main restriction with this scanning device is due to the dimensions of the measurement sensor along with the fixed focal length required (50 to 70 cm), which limit the locations that can be scanned (especially the gap between blades or guide vanes). Extensive proficiency is also required to compute the material loss mapping, especially when positioning the cloud of measured points on the reference surface (the "best fit" option usually used is not recommended).
Because of the extreme precision of the device, it is also crucial that the temperature during each measurement campaign is the same.

## 7. Operational Constraints

To secure operation of the turbines, some special constraints were defined by the operator.
For instance, as mentioned in Section 6, it was decided to operate at maximum power which compelled the operator to run the units at full load notwithstanding the requirement from the grid. This was to maximise water flow to increase sediment dilution and reduce sediment concentration.

The whole hydraulic circuit was also washed every day after each injection phase. This important step was to prevent sediment deposition in the hydraulic circuit and ensure clean water was present to operate valves and to start up the units the next day.

Operations were suspended twice a month to accurately measure the performance of each unit. This severe constraint was required since a performance loss of more than 2% would not have been acceptable. Measurements were performed on each unit in sequence for head, flow rate and active power produced (with limitation of reactive power).

All specific measurements on site (see section 6) were performed by the operator in addition to his usual workload.

Finally, the operator had to take into account specific summer requirements under which the water level has to attain a sufficient level for tourist season activities by the end of June.

## 8. Results

Throughout the operation no readings displayed any particular or alarming changes in any of the parameters.
As shown in Figure 8, no change in the leakage (vs. head) at either shaft seal was noticed.

Throughout the operation, no particular changes in vibration level, temperature (of the metal pads in thrust bearings for instance) or pressure on the runner hub were noticed.
All these findings were confirmed by the fact that yield measurements remained within a band of less than 0.5% (i.e., within measurement error).

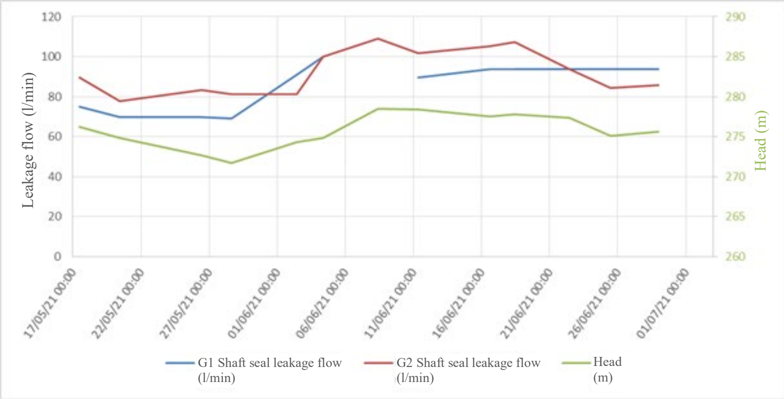



**Figure 8:** Leakage transient change at the shaft seal vs head

By including sediment concentration measurements, it was confirmed that the wash loads were complied with at each end of each day.

Transient records (see Figure 5) showed a high variability in sediment concentration around a mean value that varied from day to day. This variability is intrinsically due to the "plot by plot" dredging principle, the technique of dislodging sediment by jetting and the pumping/dilution process. In total, it was estimated that a volume of 31,500 m$^3$ (bathymetric survey data) of sediment passed through the units.

The data was analysed to graph Sediment concentration against Cumulative hours. The data is shown in Figure 9.

It can be seen that over the 828 hours of turbine operation (between 17/05/2021 and 30/06/021):

- The concentration was lower than 0.2 g/l almost two-thirds of the time (55% with concentration lower than 0.1 g/l and 9% for the range [0.1 to 0.2 g/l]).
- The concentration distribution from [0.2 to 0.4 g/l] and [0.4 to 0.6 g/l] occurred around 12% of the time.
- The concentration around the target value of 0.7 g/l [0.6 to 0.8 g/l] occurred almost 10% of the time.
- A concentration of between 0.8 and 1.0 g/l occurred only 2.4% of the time.
- A concentration above 1 g/l occurred less than 0.5% of the time.

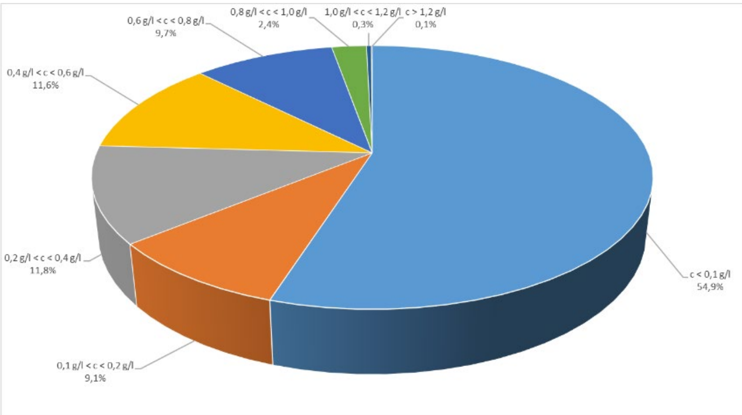



**Figure 9:** Distribution of time duration by sediment concentration

These [Sediment concentration / Cumulative hours] values were plugged into the hydro-erosion wear rate formula proposed by the IEC 62364 standard. The estimated wear rates are summarised in Table 1.

| Location | Wear rate (mm) | *Uncertainty range* |
|---|---|---|
| **Guide vanes** | 0.29 | *[0.2 ; 0.4]* |
| **Wearing plates** | 0.24 | *[0.1 ; 0.3]* |
| **Runner inlet** | 0.25 | *[0.2 ; 0.3]* |
| **Runner outlet** | 0.22 | *[0.1 ; 0.3]* |
| **Labyrinth seal** | 0.16 | *[0.1 ; 0.2]* |

**Table 1:** Estimated wear rates according to IEC 62364 formula

For reasons of accessibility, only the outlet of the runner was scanned. Material loss results are shown in Figure 10 for both runners (outlet side).

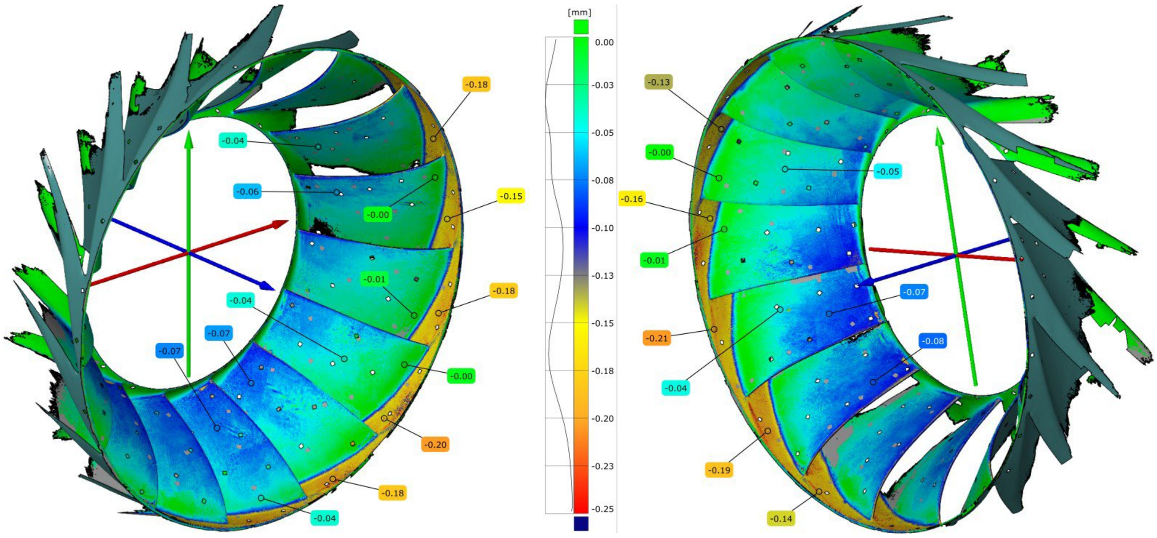



**Figure 10:** Material loss results (left: Unit #1 runner - right: Unit #2 runner)

By considering an average wear rate of between 0.18 and 0.20 mm at the runner band, the results are consistent with estimated wear rates (see orange line in Table 1).

Therefore, quantification of material loss showed that:

- Wear is uniformly distributed on each blade, which confirms their physical representativeness as well as the positioning of the measurements between them.
- On both runners, measurements show similarities in terms of wear rate on the blades (almost no wear at the extrados surface apart from a few rare and faint impact marks) and in water passages (uniformly increasing wear from blade inlet to outlet).
- The order of magnitude of the maximum wear observed is between 0.15 and 0.23 mm; this is located at the runner bands.
  (Note: erosion wear in the labyrinth seals could not be measured).

While the trailing edges of blades appeared to have been "sharpened", they did not seem to have undergone any pronounced wear (loss of material generally less than 0.1 mm). The measured thickness of blades (at the blade outlet) remained consistent with the theoretical values given in the drawings.
Measurements of thickness losses at the runner outlet therefore confirmed the results obtained by the indirect monitoring methods: the total erosion wear measured is low.

To conclude, while ageing was accelerated by the increased (but controlled) flow of sediment during the desilting operation, the runners of both turbines at St Guillerme II did not experience sufficiently high erosion wear to cause a significant loss of performance or mechanical strength.

The same conclusion was reached for the penstock inner wall (which is completely consistent since velocities in the penstock, especially close to the wall, are much slower than in the runner).

## 9. General operation outlines

The paper covers with the work and measurements performed before, during and after the Chambon dam desilting operation. The purpose was to:

- Confirm the absence of negative effects from the hydro-erosion wear identified in the hydraulic circuit (penstock and turbines) of the St Guillerme II power plant, particularly on critical components such as runners and shaft seals.
- Reassure the operator that it would be possible to continue to operate both units safely once the operation had been completed.

The success of the operation depended heavily on the ability of the dredger to meet the average and maximum sediment concentration limits for the turbines. The operating experience shows that over the six weeks of injection, the limits were generally complied with. The high variability measured around the average value of target sediment concentration is intrinsically due to the dredging technique ("plot by plot", dislodging of sediment by "jetting" and the pumping/dilution process). Regarding control of the sediment concentration in the units, the measurements show satisfactory results which meant that the limits defined by EDF were met.

For all the parameters that were monitored, no alerts occurred during the two month period of the operation. Although some minor operating hazards were identified, these did not have any impact on sediment transit through the turbines.

Real-time measurements showed that:

- There was no occurrence of leakage or increase in leakage in the guide vanes.
- There was no increase in leakage at the shaft seals.
- There was no significant change in vibration levels, pressure on the runner hub, pivot temperatures and so on.
- There was no loss in efficiency in either unit.

Quantification of material loss in the runner corroborates these results. Low erosion wear (< 0.25 mm) was measured on the runner band. Other areas (guide vanes, wear plates, runner inlet and labyrinth seals) were not accessible. Therefore, they could not be measured. However, the estimated wear is sufficiently low so as not to be a cause for concern.

Furthermore, these results are consistent with the absence of an increase in leakage rate at the shaft seal and with maintenance of the measured output (no yield loss).

## 10. Conclusion

While transit of sediment through the turbines does necessarily accelerate erosion wear of exposed parts, the results underline that the success of such an operation relies on control of the whole process: from real-time monitoring of sediment concentration at the injection point as well as in the turbines, to real-time monitoring of all possible operating parameters (pressures, temperatures, flow rates, unit efficiency etc.).

Providing that the concentration of sediment during injection is tightly controlled and under certain operating constraints that dilute the concentration of sediment as much as possible, operating experience from this operation shows that it is possible to remove 32,000 $m^3$ of fine relatively abrasive (35% abrasive particles) sediment without accelerating wear too much or significantly damaging the turbines and auxiliaries.

The success of the operation relies on preparation, capabilities and coordination from a large number of stakeholders including technicians, coordinators and managers on the operator's side, dredging and pumping/dilution teams, remote service for unit monitoring, engineering staff for component diagnostics, for performance measurement, environmental monitoring and coordination of the worksite.

All results obtained help to increase understanding and prediction of the phenomena of hydro-abrasion wear and clogging within the units. All the data collected improve the representativeness of a numerical erosion prediction model based on IEC 62364. In the future, these models will enable the acceptability of this type of process to be evaluated, for a situation involving reservoir desilting operations with sediment transit through the turbines.

## References

[1] NF EN IEC 62364, *Hydraulic machines - Guide for dealing with hydro-abrasive erosion in Kaplan, Francis and Pelton turbines*, Edition 2.0, ISSN.0335-3931, AFNOR, 2019

[2] Caffo S., Couzon P.Y., "Characterizing the impact of the transit of fine sediment through hydraulic units", *International Journal on Hydropower & Dams*, HYDRO 2019 Proceedings, 2019