The Rhône is one of the major river systems of Europe. Originating in the Swiss Alps, it flows mainly through France to the Mediterranean Sea. At the catchment outlet, the mean annual discharge is approximately 1,700 m³/s for a basin area of 95,500 km². Compared to similar catchments, the Rhône River is quite steep and its flow discharge is significant. A powerful waterway, the Rhône River is not only a source for hydropower generation but also a carrier of sediment.

The Rhône River cascade: background and challenges

The French State entrusted the concession of the Rhône River in 1934 to Compagnie Nationale du Rhône (CNR) to fulfil three objectives for the benefits of the national community: hydroelectricity production, navigation development and management, and irrigation. CNR is France’s leading producer of 100% renewable energy (water, wind, sun), with a total installed capacity of approximately 3,700 MW including a cascade of nineteen (19) dams and hydropower plants from the Swiss border to the Mediterranean Sea (Figure 1). The company produces 25% of France’s hydroelectricity, and manages a concession covering 27,000 hectares in the Rhône Valley and 330 km of wide-gauge navigable waterways. CNR has conceived a redistributive business model based on the River Rhône management whereby green electricity production is combined with territorial development[1].

Except for three dams including the Génissiat dam on the French Upper Rhône (i.e. between Swiss border and the city of Lyon), all hydropower developments operated by CNR are run of-the-river short-circuiting the natural river course through a side canal[2] (Figure 2). Typically, run of the river facilities include a barrage built across the river mainstream that diverts the major portion of the flow through a headrace canal towards the power plant. To maintain suitable conditions for aquatic life, an ecological flow discharge is released into the natural river course through one of the dam outlets. The reservoir storage capacity of run-of-the-river dams is negligible compared to river flow volumes, especially during flood conditions. Neither inter-annual nor seasonal regulation is thus possible because the water outflow is very close to the water inflow.

On the Rhône River cascade, CNR has to cope with several sedimentation-related constraints, among them the facilitation of sediment routing loads arriving at inlets of reservoirs. Significant quantities of sediments are supplied to reservoirs during flood periods or flushing events.
initiated by dam operators in the upper Swiss Rhône and the French Rhône tributaries. At the same time, it is crucial to keep the fine suspended sediment concentrations downstream of the dams low enough for several river uses, such as supporting aquatic life, and the operation of intakes for cooling water supply and bathing areas. Moreover, floodwater routing must be ensured by guaranteeing adequate hydraulic capacity of channels and by avoiding adverse obstructions of dam spillways, possibly resulting from sediment deposits. Good navigation conditions have also to be maintained through regular monitoring and maintenance of the riverbed. To deal with these requirements, CNR has adopted an overall sediment management program established under the supervision of the French authorities. Complementary to this masterplan, “environmentally friendly flushing” operations are also regularly conducted at the Génissiat dam as a result of the historical transboundary issues of the Rhône River.

“Environmentally friendly flushing” concept from the Génissiat Dam

Since the completion of the Verbois dam (located near Geneva, upstream of the Génissiat dam) in 1942, the Swiss operator SIG has been initiating full drawdown flushing events every three years to prevent increased-flood hazards that may be caused by sedimentation in the Verbois reservoir. Before 2016, Swiss reservoirs had used to be completely emptied during these operations, leading to very efficient remobilization rates but also to lethal effects on the aquatic fauna due to suspended sediment concentrations reaching up 40 g/l.

On the contrary, the sediment release downstream of the Génissiat dam (104 m high, commissioned in 1948) has been conducted under strict restrictions, especially since 1980 as a result of a progressively increasing understanding of sensitive issues on the French Rhône River. In particular, the suspended sediment concentrations released from the Génissiat reservoir have not to exceed 5 g/l on average over the entire operation, 10 g/l on average over any 6 hours period, and 15 g/l over any 30 minutes period. Respecting those limits allows maintaining bearable life conditions for the aquatic fauna and preventing efficiently adverse effects. To achieve this objective, routing and regulation of fine suspended sediment concentrations discharged from the upper Swiss reservoirs are performed by CNR in the Génissiat reservoir (23 km long, storage capacity of 56 Mm³) where the dam is equipped with three outlets (Figure 3): a bottom gate (LLO), an outlet at halfway up the dam (ILO), and a surface spillway (HLO). First, the water surface in the Génissiat reservoir is lowered at specific levels in order to remobilize the sediments previously deposited and to ensure the routing of inflowing sediments discharged from the upper Swiss reservoirs. Inflowing sediments could entirely settle if the water level in the reservoir is too high, while huge sediment concentrations may be released downstream of the dam if the water level is too low. Secondly, an appropriate gate opening program and mixing of the sediment-laden flows released by each of the three outlets (i.e. mixing water with high sediment concentrations from the bottom of the water column with enough “cleaner” water from higher in the water column) are performed to stay within the required concentrations further downstream. The Low Level Outlet (LLO) discharges highly concentrated water, the Intermediate Level Outlet (ILO) releases less concentrated flows and the High Level Outlet (HLO) discharges clear water (Figure 3). The efficiency of such program is controlled with the benefit of real-time sediment concentration monitoring implemented at the dam site and in downstream stations. At other CNR hydropower facilities operated downstream of the Génissiat dam are low head run-of-the-river systems. For normal operating
conditions, the reservoir water level upstream of each dam is more or less horizontal. During high flows or flood conditions, the spillway gates are progressively opened to decrease the water level upstream of the dam and to increase the waterline slope throughout the reservoir. This situation avoids extra-flood hazards for riverine people and allows the recovery of natural-like flow conditions in the whole reservoir. The routing (or sluicing) of inflowing sediments throughout the reservoir is thus facilitated and previously deposited sediments are more easily remobilized. The sediment transport through CNR dams is also eased because the crest of the spillway weir is practically at the same elevation as the river bottom prior to dam construction and because the heights of the spillway gate and dam are very similar.

**Lessons learned**

The efficiency of such a gate arrangement and the operation rules associated with its configuration has been demonstrated for decades and makes possible the sustainable management of sediment fluxes with a very limited impact on the aquatic life and river users. Since the beginning of 1990’s, the operation rules have been continuously optimized. The annual sedimentation rate in the Génissiat reservoir has been consequently reduced by half, and for the 1993-2018 period, the yearly rate of sediments passing through the dam outlets has increased up to 85% on the average, i.e. only 15% of the inflowing suspended sediment flux have been trapped into the reservoir (Figure 4).

Additional gains are expected in the near term as Swiss and French operators have to comply with the same restrictions on suspended sediment concentrations released from dams since 2016. This evolution results from a cooperative work performed between 2012 and 2016 by the operators and the regulatory authorities from both countries with the objective of ensuring a consistent and sustainable management of sediment fluxes throughout the whole river cascade. The benefits of this new operating scheme have been demonstrated during the 2016 event, allowing an adequate balance of the sediment fluxes flowing to the Génissiat reservoir and from the dam outlets. The downstream sediment transfer throughout the CNR run-of-river facilities has been also increased by 50% compared to previous events. Such operation is however costly to CNR, which engages a staff of 400 people 24 hours a day over approximately 10 days, at a cost of about 6 to 8 million euros (based on the 2012 and 2016 flushing).

With the benefit of such design and operation patterns, the impact on sediment fluxes is significantly minimized. Locally, some sediment deposits may, however, occur, especially in areas where the flow velocity is very low, such as navigation lock garages, harbors, and the Rhône-Rhône-Tributary confluence zones. In the Lower Rhône River (downstream of the city of Lyon) the average volume of deposits in the river system represents 0.04% to 5% of the annual inflowing suspended sediment fluxes (Figure 4). These changes have been observed during the continuous monitoring of the river and hydraulic structures performed by CNR with a fleet of hydrographic boats. A comprehensive update of the bathymetric state of the river is carried out with a minimum frequency of 5 years or after significant floods.

In order to keep adequate conditions for navigation, dam operation and hydraulic safety, maintenance works are also performed on sediment deposits and vegetation in the framework of a management plan established under the supervision of the French authorities. This plan is generally updated every 10 years. Ecological restoration works carried out by CNR on oxbows and alluvial margins represent also a noticeable part of these works. Considering dredging operations only, which represent in recent years an annual average volume of 0.54 Mm³, the distribution of works relatively to the issues at stake is as follows: 41% for navigation safety, 41% for ensuring flood passage, 13% for dam operation and 5% for biodiversity restoration. For approximately a decade, extraction of sediment deposits in the channel has ceased. These deposits are instead artificially resuspended in the flow and reinjected in the riverbed further downstream, considering fine and coarse particles respectively. This requirement minimizes the potential disruption of sediment continuity down to the Rhône River Delta and contributes to prevent its erosion.

The management scheme defined and implemented by CNR has demonstrated that achieving a sustainable management of sediment fluxes through hydropower cascades is possible. This program requires that several key factors are respected, namely adequate design and positioning of dam outlets, development of an operation pattern of the reservoir allowing the progressive recovery of natural flow conditions, regular monitoring of the river channel and hydraulic structures, and finally adaptive management of the river depending on a comparison of target states and observed evolutions.

**References**
