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Reservoir Sediment Management Using Replenishment: A Numerical Study Of Nunome Dam

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ABSTRACT:
Improving the integration of dams in the natural environment and recovering their storage capacity lost to sedimentation are two topics of growing concern. To address these two issues, the accumulated sediments are being relocated down into the dam's tail water. This process is called sediment replenishment (SR), and has been tested in Japan and other parts of the world. More study is required to enhance its effectiveness, and the present research thus offers a practical method to assess positive outcomes of SR on the downstream ecosystems.
It is shown through a 2-D numerical model of Nunome River that SR positively influences the river's morphology by generating riffle-pool structures and sand bars. These patterns increase the channel's global heterogeneity, and create hydraulically favorable habitats for fish and spawning. The habitat quality was quantified by applying suitability indexes to the computed hydraulic variables, and the SR-induced geomorphologies were designed according to field observations of past SR tests and validated by the 2-D model.

Keywords: reservoir sedimentation management, sediment replenishment, habitat modelling

1. INTRODUCTION

1.1. Context

Given the recent events that occurred in Japan, Fukushima, and their significant impacts in international politics, the future of nuclear energy is not bright. Impacts do not stop at the nuclear energy debate however, and –not even to mention the countless, direct victims of the disaster– the impacts on the ocean near the disaster area are uncertain, but may eventually cause local fisheries to suffer from fishing restrictions, or worse, population boycott (Grossman, 2011).

Within this unstable nuclear situation, elaborating other sources of energy, in particular renewable ones, has thus become more than ever the center of attention. Hydro-power generated by dams could be part of the answer. However, managing these dams with care for the downstream environment is now an integrated part of the deal. Furthermore, this management takes full meaning when it comes to preventing river fish populations which are unaffected by the nuclear spill from declining.

Dam functions are multiple and have already become a necessity to our modern societies. Disaster prevention, flood mitigation, energy production, water storage, so many functions which we could probably not live without. However, their side effects are consequent, as dams induce strong modifications in flow and discontinuity in sediment and river organisms. In the past few years, even before any nuclear event came challenging our relation to energy consumption, dam related issues have become most preoccupying, with raising concerns about environment and increase of sedimentation issues in reservoirs. Not only is this problem becoming critical, as most dams are reaching several decades of age, but it is also accelerating due to climate change (Takeuchi, 2004).

The two principle impacts modern research focuses on are thus the loss of reservoir capacity, and the ecological disturbance in dam tail-water systems. Hereafter, the sediment replenishment (SR) technique is discussed, which offers solutions to both of these issues, and focuses on the case of a specific dam from the Japanese Alps, Nunome Dam.

1.2. Sediment Replenishment

Sediment replenishment basically consists of dredging or excavating the accumulation of sediments in a dam's reservoir and transporting them to the reach just below the dam, where natural or artificial floods will distribute them along the riverbed. A sorting process occurs in most reservoirs, during which coarse particles settle in the upstream area and finer particles reach the hydraulic structure (Schleiss, 2008; Knoblauch, 2006; Okano, 2004). This distribution process can be used to select optimal material for SR, as coarser sediments are more beneficial for river systems than silt, which may impact ecosystems by clogging bed sediments, and causing high turbidity (Hartmann, 2009). Check-dams, located upstream of larger dams, may trap sediments before they enter the functional reservoir and facilitate their removal by land-based excavation, and do not require any water level modification in the larger reservoir (Okano, 2004). Japan is one of the current leaders in SR application, with nearly 25% of its dams resorting to sediment excavation, and a growing use as downstream replenishment. Other worldwide examples illustrate the great diversity of ways to replenish sediments, each contributing to expand the knowledge of sediment replenishment effects.

1.3. Nunome Dam

This 72 meter high concrete dam is located in the Kizu River system, and is part of a group of five other dams. Constructed in 1990, its two main purposes are flood control and water utilization. It served since 2004 for small-scale SR testing, which were monitored to understand the evolution of bed morphology and ecological effects (Kantoush, 2010). Each year, the selected material was deposited on a flat ledge located on the bank, approximately 600 meters below the dam (Fig. 1). This is done when the discharge is low and the ledge is dry and accessible. When a natural flood occurs, the water elevation rises and submerges the sediments, which are progressively eroded and transported into the channel and downstream.

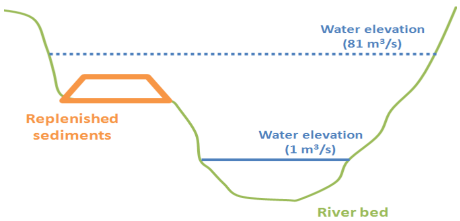

Figure 1. Sediment replenishment concept at Nunome Dam.

2. NUMERICAL MODEL

The reach below Nunome was modeled in RIC-Nays (2009), a two-dimensional pre- and post-processing application for computational flow models. Hydraulic parameters were computed with Morpho2D, a separate numerical solver developed for RIC-Nays. Morpho2D solves the shallow water equations using a TVD-MacCormack scheme. The equations are written in a generalized curvilinear coordinate system and based on the finite volume method, which offers flexibility in designing the mesh. The final reach considered for the simulations was cut down to 500 meters, thus improving computational stability and grid accuracy. Grid cells dimensions were ca. 1.5 m2 in the main channel, and larger in the flood plain to reduce calculation time. The topographic data was mapped to the grid following the Delaunay triangulation method (TIN).

2.1. Model Calibration

Model parameters were calibrated using field and numerical reference values. A 1-D analysis of the reach with HEC-RAS was first performed and calibrated using field observations and water surfaces measured downstream. The water elevations and velocities computed by HEC-RAS were used to calibrate the 2-D model. The grid accuracy, maximum time step and Manning's roughness were adjusted in order for Morpho2D to predict satisfying hydraulic behaviors.

3. SCOPE OF THE WORK

3.1. Objectives

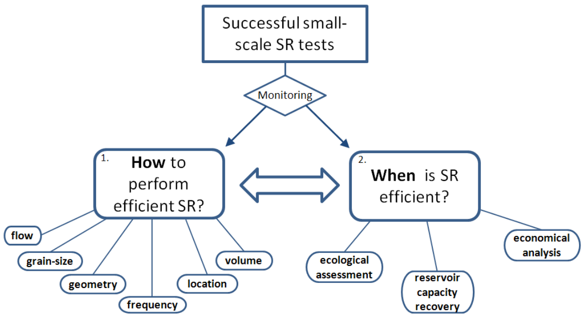

Figure 2. Overview of the remaining goals to enhance SR.

Sediment replenishment is a technique under current development, and two main questions still require further research to improve the method's efficiency (Fig. 2).

The first is how to relocate sediments in the riverbed efficiently. This question needs specific research on the effects of grain size, replenished volumes, frequency of operations and sediment transport. Answering the second question will define when SR is actually effective. In particular, it involves studying how ecological habitats benefit from the contribution of large amounts of material. In term, this question should also balance the environmental benefits with social and economical aspects, by pondering the urgency of reservoir capacity loss. Indeed, these three pillars present somewhat conflicting interests when it comes to planning SR operations.

In the present study, focus will be set on the ecological assessment of dam tailwater systems. The main goal was to evaluate habitat improvement after sediment replenishment operations. Two different bed-morphologies, both induced by SR, were compared to the reference case.

3.2. Scenario Design

Three different bed-morphologies were considered to measure the effects of SR on habitat quality. They were constructed using RIC-Nays' pre-processing module, which allows manual modification of the topographic data (Fig. 3).

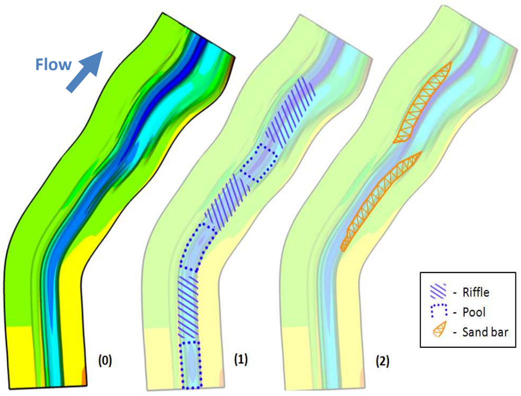

Figure 3. Aerial representation of the reference (0), riffle-pool (1) and sand bar (2) scenarios.

3.2.1. Scenario 0 – Reference channel

The topographical data used for this scenario is based on cross section measurements from 2005. It thus represents the degraded bed affected by 15 years of dam sediment retention. The overall reach in consideration is 530 meters long, and the upstream end of the model is located approximately 600 meters below the dam's outlet, where replenished material was deposited in past operations.

3.2.2. Scenario 1 – Riffle-pool

Riffles and pools are typical features which develop in natural gravel-bed rivers with slopes of 0.001 to 0.02. They are defined as topographic highs and lows along the river's thalweg, and through this alternating pattern, they produce contrasting hydraulic and morphological environments, which can serve a wide range of aquatic species at different life stages (Brown, 2008; Emery, 2003; Ock, 2010). More specifically, they induce water downwelling and promote oxygenation of bed substrate, and are often used by salmonids (Kondolf, 2000). Ock (2010) established the riffle-pool characteristics induced by SR, as well as the key parameters which influenced positively the river's ecology. Following these guidelines, the main channel elevation was either decreased by 0.60-0.65 m to create pools, or increased by 0.30-0.40 m to create riffles. This was done in a fairly asymmetrical way, in order to mimic natural structures. Riffles were systematically designed longer than pools so that the riffle length fraction was of 63%. It appears valid to consider this structure as an effect of SR, as the 2009 field monitoring revealed riffles and pools which were absent before the SR operations.

3.2.3. Scenario 2 – Sand bar

After the 2009 SR operations below the Nunome Dam, field monitoring, and aerial photographs of the river revealed newly formed sand bars (Kantoush, 2010). Two lateral sand bars were implemented in the original mesh based on these observations. In the mesh, cross section data was raised on the river sides to reproduce these bars. Their height goes up to 1.40 m, and the dimensions of the larger bar are 205 m long, and 10 m wide in the center. The shorter bar is 95 m long, has a rougher tip facing the flow, and reaches 6 m into the channel. The equivalent volume of sediments required to build up the bars can be estimated based on their shape. The large bar represents approximately 1000 m^3 of sediments, and the small bar 400 m^3. These amounts seem consistent with typical replenished quantities, which vary from 100 to 700 m^3 and maximum transport capacities during floods calculated with the 1-D model.

3.3. Scenario Comparison

The habitat quality of each bed configuration was compared by applying habitat suitability indexes to the computed hydraulic variables. The first index describes the preferential depths and velocities of salmonids (based on Chinook Salmon observations; USFWS, 1999), and the second describes those most suitable for the spawning of Ayu Plecoglossus altivelis (Nagaya, 2008), a fish which was historically found in Nunome River (Fig. 4). Because of its physiological resemblance with salmonids, the first index was applied as well to this popular and commercially interesting fish, however local suitability observations would be necessary to improve the quality of results. The depth habitat suitability index (DHSI) for the Chinook Salmon at a juvenile stage is optimal at depths between 0.6 and 1.0 m, and optimal VHSI occurs at velocities between 0.1 and 0.2 m/s. For the spawning suitability, depths are not limiting above 3 cm (the approximate body height of Ayu fish), whereas optimal velocities are between 0.6 and 1.0 m/s. The global habitat suitability index was calculated as GHSI = $DHSI^{0.5}$ x $VHSI^{0.5}$ and GSHSI = $DSHSI^{0.5}$ x $VSHSI^{0.5}$ for each life stage respectively. Final GHSI values were classified as poor (0-0.1), low (0.1-0.4), medium (0.4-0.7) and high (0.7-1.0) (Brown, 2008; Pasternack, 2004). The prediction of sediment transport was done by resorting to the analytical equation of shear stress, given by the Einstein log-velocity equation, and the entrainment criteria for the replenished particles was evaluated through the dimensionless Shield's stress τ *.

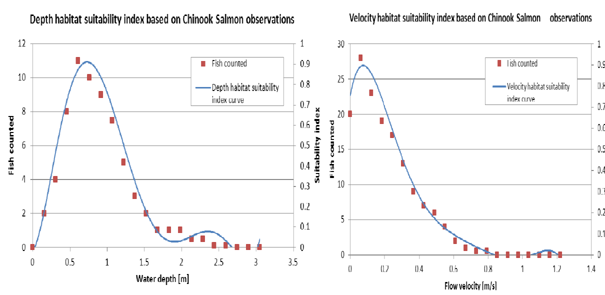

Figure 4. Depth and velocity habitat suitability indexes (DHSI, VHSI) for the juvenile Chinook Salmon.

4. RESULTS

The basic hydraulic parameters were computed with Morpho2D for each scenario grid, and for four different discharges (Q1, Q20, Q50, Q81, discharge units of Q are given in m^3/s). The spatial hydraulic values were converted to the variables of interest, Shield's stress (τ^*), global habitat and spawning habitat indexes (GHSI and GSHI), as well as the intermediate depth and velocity indexes (DHSI and VHSI).

4.1. Habitat Suitability

At low discharge, the reference scenario yielded low depths, up to 0.35 m, and fairly low velocities ranging typically between 0.4 and 0.7 m/s. The corresponding velocity and depth indexes were rather low (Fig. 5). Even for the lowest flow Q1, velocities computed in the reference channel are too high to represent a suitable habitat for the river's maturing fish. Therefore, the GHSI is ultimately poor or low, and thus the reference scenario is, as expected, ecologically unfavorable. This result occurs in fact most of the time, as in the Nunome River, Q1 is the residual flow. The habitat conditions even tend to worsen with increasing discharges.

Conversely, the model predicted a clear improvement with the riffle-pool scenario, in which appeared three large high quality zones, directly correlated to the riffle and pool pattern (Fig. 6). Indeed, the expected effects of the riffle-pool units are accurately represented by Morpho2D, and distinct velocity accelerations can be observed over riffles and slower flows appeared over the deeper sections. This scenario, at Q1 flow, in fact cumulates optimal depths, which now reach 0.7-1 m, and optimal velocities below 0.2 m/s. Moreover, both of these optimal sets of values occur over pools, and this overlapping thus leads to the excellent GHSI reported on Fig. 6.

In the light of these results, the gain of SR is obvious when it is supposed to induce riffles and pools. However, results were not as positive for the second scenario. Indeed, the effects of sand bars are somewhat ambivalent. The first bar did improve slightly the velocities just upstream of it, as it acts like a local obstruction to flow. However, it also acted like a constrictor which reduces the width of the main channel and accelerates the flow to unsuitable velocities. The final GHSI for scenario 2, Q1, was therefore generally low, and locally poor while passing the large bar, due to excessive velocities and shallow water.

For larger discharges, habitat quality was generally lower for all scenarios, despite an increase in terms of DHSI at Q20. Indeed, velocities yielded for large discharges systematically reduced the VHSI. Though for all scenarios velocities offer poor habitat quality, scenario 1 offered the best conditions, because the two downstream pools still managed to reduce velocities towards more favorable values. Ultimately, starting at 20 m^3/s, the velocities become generally too high, and GHSI values remain poor in most areas of the channel. This tends only to worsen for Q50 and Q81, as the effects of morphological features tend to diminish, and depths over riffles, pools, and bars become overall too high.

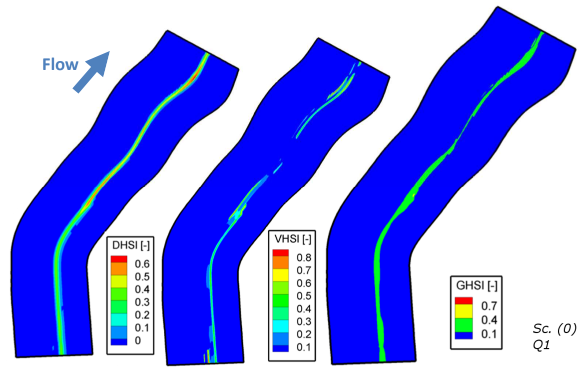

Figure 5. Construction of the global habitat suitability index for the reference scenario at Q1.

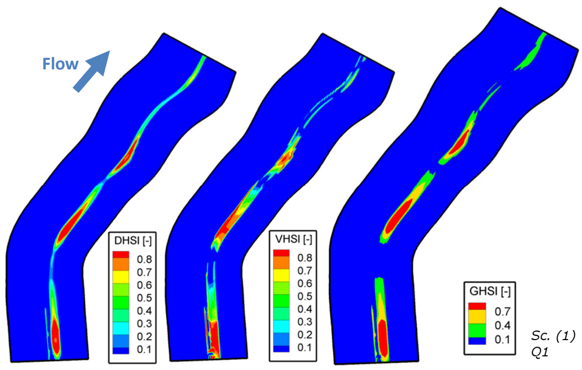

Figure 6. Construction of the global habitat suitability index for the riffle-pool scenario at Q1.

4.2. Spawning Habitat Suitability

Juvenile habitat analysis previously showed that the ideal living conditions occurred at low flow, and that these were systematically improved by SR induced morphology. Spawning habitat on the other hand benefits from an increase in discharge, and optimal conditions were yielded at Q20. Therefore, an adapted dam outlet management, established according to these facts, could simply increase the fish living conditions throughout the year. In winter, spring and summer, maintaining the natural Q1 flow would be suitable for juvenile and maturing fish. Then, during the Ayu's spawning season in autumn, a slight increase in the outflow would increase velocities and allow optimal spawning conditions.

Another interesting result which appeared by comparing the spawning and non-spawning habitat preferences in scenario 1 was the delimitation of the high quality zones. Indeed, it was shown that mature fish had their high quality habitats coinciding with pools along the reach (Fig. 6). By analyzing more accurately this result with the delimitation of the high quality spawning areas, it appears that the latter systematically stretch a bit further towards emerging riffles. This was previously observed by many researchers (Hunter, 1991; Brown, 2008; Wheaton, 2004), which pointed out that salmonids preferably spawn in gravel beds located at riffle heads or at pool downstream edges. On Fig. 7, it is noticeable that spawning preferences begin inside the pools, and end near riffle heads, which corroborates both the consistency of the numerical model, and the suitability indexes.

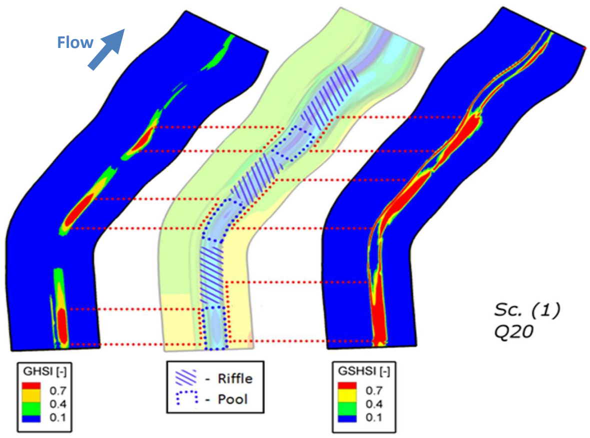

Figure 7. Streamwise delimitations of habitat (left, GHSI) and spawning (right, GSHSI) habitat preferences. Maturing fish find comfort in pools, whereas spawning is best if located at pool ends and riffle heads.

4.3. Sediment Mobility

In order to assess the relevance of the designed morphologies, and also to evaluate bed stability, which is partly required for optimal spawning conditions, dimensionless shear stresses were calculated at Q1 and Q81 for two different grain sizes (Fig. 8).

Predicted results were fairly consistent with those from HEC-RAS. During low flow, an alternating pattern of high and low shear stresses appears. Interestingly, it matches the riffle-pool structure adopted in scenario 1. This result illustrates how riffle-pool structures may arise from erosion and deposition fluctuations such as these computed by Morpho2D. This pattern is not visible anymore for Q81, however the stress distribution in the bend similarly illustrates how the monitored sand bar, represented in scenario 2, could arise.

Because Shields stress values were systematically larger than the critical entrainment value for the replenished grain size (τ^*_{cr} = 0.0369 [-]), a second substrate was tested, with larger characteristic diameters. A net decrease in τ^* values was thereby obtained. At Q1, transport is only partial in most of the reach, and complete stability occurs in the central part of the reach. For Q81, despite a decrease in overall shear stress, full mobility is still achieved, allowing transport of such material during high floods. This result may be of interest to future SR operations, as selecting slightly coarser sediments may increase stability during low flows, which may be beneficial for salmonid spawning, without preventing normal transport process of the replenished volumes.

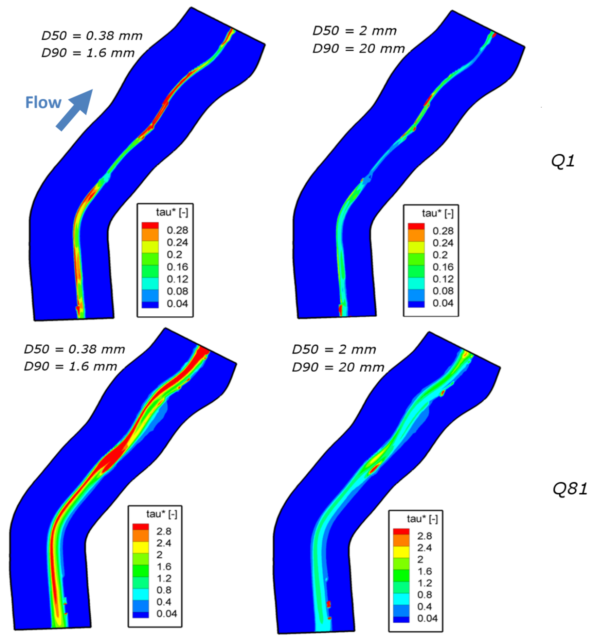

Figure 8. Shields stress is represented for two discharges, Q1 (top row) and Q81 (bottom row), and for two substrate dimensions, fine (left column) and coarse (right column).

5. CONCLUSION

In the opening of this paper, the need to evaluate the effects of sediment replenishment (SR) on the environment was emphasized, and reinforced by the current energy crisis. Indeed, dams may become essential actors in tomorrow's energy policies and all efforts must thus be focused on reducing their ecological side effects. In this context, the present study contributed in increasing knowledge of this underrated reservoir sediment management method.

Put into a sustainable development context, SR faces the necessity of identifying predominant issues and site-specific goals of a reservoir before considering any remedy. Indeed, sediment reservoir management raises conflicting social, economical and environmental interests, which need to be balanced in order to apply SR with optimal efficiency. To help balance objectively the interests of reservoir sedimentation and downstream health, there is a need for effective ecological evaluation tools. Two habitat suitability indexes were proposed, and applied to a test reach in the Nunome River. These allowed evaluating the positive impact of river geomorphology on ecological health. The indexes quantified fish habitat and spawning quality, as well as sediment mobility. The latter could be employed to evaluate habitat quality, but also to predict SR-induced morphologies.

The results established with the numerical model were satisfying on two different levels. First, they showed that Morpho2D was able to reproduce successfully the change in flow patterns expected by the modified bed morphologies. Indeed, the way riffles and pools modify water depths and velocities is well documented, and the model calculated these modifications efficiently. Furthermore, the suitability indexes were able to highlight accurately specific fish habitat preferences. These positive observations appreciate favorably Morpho2D, which to this day remained fairly unpopular outside of Japan.
Second, results almost systematically validated the SR-induced morphologies. At low flow, it was shown how the riffle-pool morphology offered high quality habitats, whereas the reference scenario, lacking such channel diversity, presented only medium to low habitat. At higher flows, despite a generalized loss of habitat quality, the sand bars and riffle-pool structures tended to enhance higher quality areas. Regarding the spawning habitat assessment, results pointed out optimal flows, which could be managed at the dam's outlet during the reproduction season.

The sediment mobility analysis was able to validate the riffle-pool and sand bar developments. Furthermore, the consistency observed between 2-D and 1-D shear stress predictions tends to acknowledge Morpho2D 's reliability.

The assessment method applied in this report is however neither exhaustive, nor flawless. It could be improved for example with a higher computation capacity, allowing finer mesh accuracy. Additionally, the model could include aspects which were disregarded in this study, e.g. water temperature and quality. The indexes applied should be improved with additional local fish monitoring, rather than extrapolating from geographically and physiologically distant measurements. Moreover, in order to discover optimal morphologies, it would be interesting to test habitat quality for different riffle-pool configurations, or sand bar locations and elevations.

Nevertheless, in the light of the methodology applied in this thesis, the next step may now be approached with confidence. That is, trying to answer the following practical questions. How should sediments be replenished? Where should they be deposited in the channel? What volume is necessary to produce proper bed morphologies? Which grain-size is most suited for fish, invertebrates and other organisms? The interaction of replenished material with flow should also be studied. How far will sediments be transported during floods, and where will they settle? How long does it take to recover from the bed degradation? When will significant riffles and pools appear, and how persistent are they? Which brings up the question: what is the required frequency of SR operations to conserve suitable habitats?

As this point, much work is still required to improve SR techniques, however all of the above questions may only be answered by considering the effects on the downstream ecosystems, and being able to quantify them. This thesis therefore strived to develop, discuss and apply the tools able to assess environmental quality, which can now be used to evaluate future SR outcomes in Nunome, and in other dams worldwide.

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