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Ecological Impact of Hydraulic Dredging from an Alpine Reservoir on the Downstream River

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Abstract: The evacuation of impounded sediments is one of the most critical aspects associated with reservoirs, with possible drawbacks on the water quality, biodiversity, and ecosystem integrity of downstream river reaches. In this study, the impacts of hydraulic dredging at the Ambiesta Reservoir (Eastern Italian Alps) on the physical habitat and the biological communities (i.e., benthic macroinvertebrates and fish) of the downstream river were assessed by comparing the pre-dredging conditions with data collected on three post-dredging occasions. The dredging operation lasted 68 days and removed an overall sediment volume of 30,600 m^3. During this operation, suspended sediment concentration (SSC) was monitored by turbidimeters and, on average, it was considerably lower than the SSC limit of 1.5 g/L, which exceeded approximately 15% of the overall operation time. Additionally, the dredging operation resulted in negligible deposition of fine sediment on/into the riverbed (0.24–0.7 kg/m^2). Results for fish and benthic macroinvertebrate communities indicated weak differences in the density (~20% reduction) and diversity of these organisms between pre- and post-dredging sampling occasions. Moreover, the results on the biomonitoring indices based on macroinvertebrates showed a recovery during the last two sampling occasions. Compliance with the SSC limit and avoidance of high SSC peaks, along with limited fine sediment deposition, allowed to successfully mitigate the ecological impacts of this relatively long operation of sediment removal.

Keywords: reservoir desilting; hydraulic dredging; fine sediment; suspended sediment concentration; physical habitat; macroinvertebrates; fish; biomonitoring; sediment management; eco-sustainability

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1. Introduction

Water storage in reservoirs is one of the primary elements for coping with the increasing demand for regulated water and hydropower. The construction of dams peaked during 1960s and 1970s [1] and, following a period of relative stagnation during the past 20 years, a new increase in hydropower dam construction is expected within the next 10–20 years [2], though contemporary data still indicate relatively low growth rate of the hydropower sector at the global scale [3].

Dams disrupt the longitudinal continuity of the river system, by trapping sediments and releasing hungry water, thus resulting in armoring and incision of downstream riverbed [4]. Sediments accumulating in reservoirs are "resources out of place" because these sediments are needed to maintain the morphology and ecology of downstream river systems, as well to replenish coastal zones [5]. Moreover, sediment accumulation has relevant negative consequences on the same reservoirs (e.g., storage depletion, structure abrasion or blockage) [6].

Reservoirs have traditionally been designed based on the "life of reservoir" concept. Under this paradigm, the designer estimated the rate of sediment inflow and provided storage capacity for 50–100 years of sediment accumulation, thus postponing sedimentation problem and undervaluing downstream impacts. Currently, the worldwide annual loss of reservoir storage through sedimentation is estimated to be around 0.5% (i.e., more than 33,000 Mm^3). Even in the Italian Alps, where rates of soil erosion are generally low (e.g., [7]), the problem is of growing importance due to the advanced age of many reservoirs and the practical impossibility of building new ones. As it has been pointed out since the 1990s [8], the approach of designing and operating reservoirs requires substantial upgrading, accounting for effective ecosystem management of the downstream rivers that includes not only flow regime but also sediment regime [9]. Even if the identification of a suitable sediment management regime is recognized as an important part of designing ecologically sustainable flows below dams and water diversion structures, up to now, the practical implementation of such sediment management regimes is not clearly defined [10]. For instance, Wild et al. pointed out that devising "environmentally friendly" sediment management techniques, so as not to affect the many ecological features the management efforts attempt to preserve, represents the crucial issue of the upcoming advances [11].

Improvement in the management of reservoir sediments is even more important if climate change issues are considered. In fact, according to the scenarios produced by different climate models and the current changes in catchment land use, water resources will become more variable, with more intense floods that may significantly increase sediment yields [12,13].

Different strategies to counteract the effects of siltation and extend the useful life of reservoirs are discussed in the literature [14]. Apart from sediment flushing that has been successfully implemented in many dams globally, another sediment management technique is dredging, which involves excavating material from beneath the water, without interfering with normal impounding operation [5]. Dredging is especially expensive, so it is often used to remove sediment from specific areas near dam intakes [5]. In hydraulic dredging the sediment is mixed with water and transported from the point of extraction to the point of placement as a sediment-water slurry. Dredged material can be discharged into a containment area or the river below the dam. Hydraulic dredging can efficiently handle material, even coarse sand [8]. During hydraulic dredging, when sediment-laden water is discharged into the downstream river, the high sediment concentrations could be detrimental for riverine biocoenosis, as well as during sediment flushing. The most striking consequences of these sediment management techniques may be fish mortality [15] and severe habitat alterations such as pool-filling [16]. These operations can therefore deteriorate the quality of downstream water bodies by increasing the sediment load and fine sediment deposition, contravening national and international standards regarding ecological quality and habitats (e.g., Water Framework Directive 2000/60/EC—WFD [17]—and Habitats Directive 92/43/EEC [18] in the European Union).

Only in recent years, the attention has been directed at developing sediment management strategies with reduced environmental impacts in the downstream river reaches. For instance, controlling suspended sediment concentration (SSC) during operations of sediment evacuation may constitute a measure to minimize the adverse ecological effects mentioned above [19]. Quantitative aspects, such as the magnitude, frequency and duration of sediment releases, and the optimal time of the year for the operations would ideally be specified after having assessed the related environmental impacts (e.g., [16,20]). Sediment perturbations are regularly experienced by river biota during natural floods, to which it is adapted in terms of magnitude and timing; however, sediment management operations may add further and potentially heavier stress to the river environment. A large body of field evidence is needed to cover the knowledge gap on the response of aquatic biota to such a complex perturbation, and to adequately sustain decision making. In particular, at least to our knowledge, downstream effects of hydraulic dredging are poorly documented in the specialized literature concerning sustainable management of reservoir siltation. The primary objective of this work is thus the analysis of a case study of hydraulic dredging at the Ambiesta Reservoir (Eastern Italian Alps), with special focus on the related sediment perturbation (i.e., sediment transport and streambed sedimentation after the monitored event) and subsequent ecological impact, evaluated through the monitoring of benthic macroinvertebrate and fish communities in the downstream river.

2. Materials and Methods

2.1. Study Area

The Ambiesta Reservoir is located in North-Eastern Italy within the southern edge of the Alps (Figure 1). The Ambiesta Dam was closed in 1959, impounding the Ambiesta River 6 km downstream of its springs and 4.8 km upstream of its inlet into the Tagliamento River, the last morphologically intact river in the Alps [21]. The dam crest is at 486.5 m above mean sea level (AMSL), the power intake is at 444.8 m AMSL. The Ambiesta project comprises a surface spillway at 481 m AMSL (equipped with a 3 m high and 8 m long flap gate) and a 2.5 m diameter bottom outlet at 433.2 m AMSL. Both these structures bypass water from the reservoir into the Ambiesta River by means of few-hundreds-meter long tunnels. A further bottom outlet, a 1.2 m diameter pipe, is located in the body of the dam at 432.8 m AMSL. The original gross and effective storage capacities of the reservoir were 3.9 Mm^3 and 3.1 Mm^3, respectively. A bathymetric survey in 2011 indicated a historical loss of gross storage capacity of 0.54 Mm^3. According to the estimates provided by the company managing the hydropower system in the area, the average annual rate of storage loss is less than 0.2%.

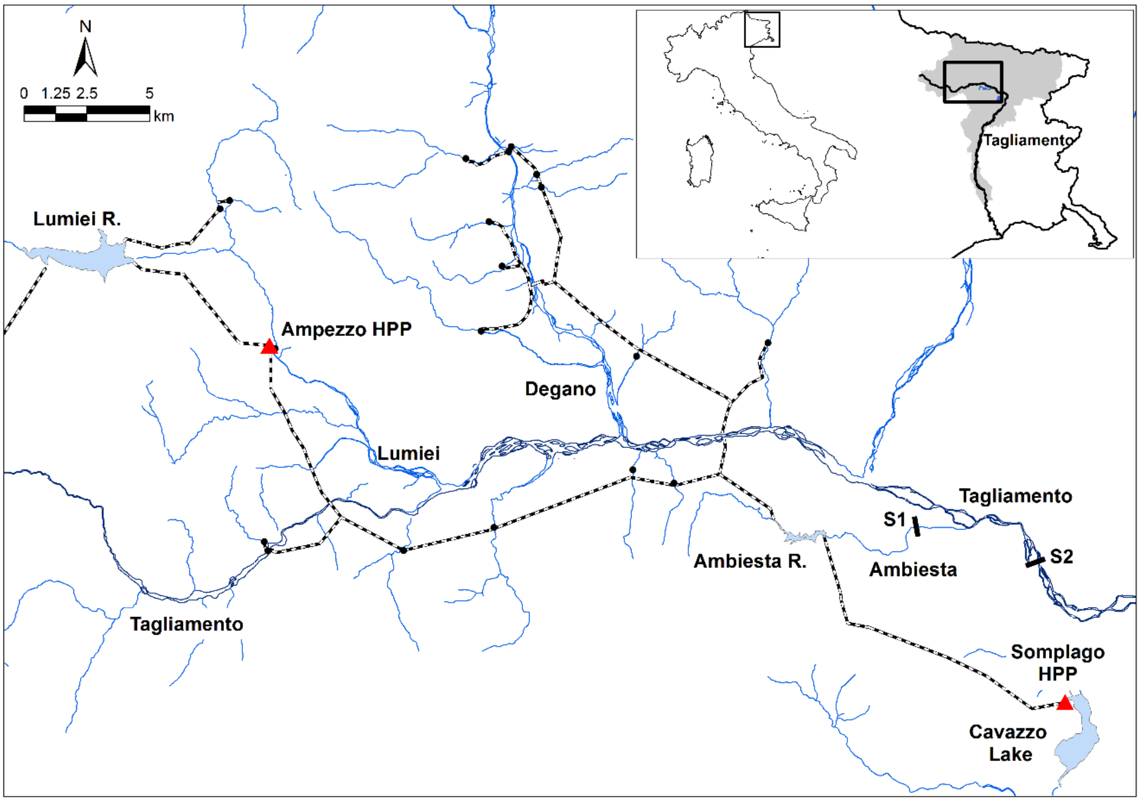

Figure 1. Study area. Location in Italy and in the Tagliamento River basin. Main tributaries, water ducts (dashed lines), hydropower plants (HPPs—red triangles), reservoirs (R.) and monitoring sites (S1 and S2) are indicated in the map.

The natural catchment area at the Ambiesta Dam is 9 km^2. The diversion of water released from the Ampezzo hydropower plant—HPP (55 MW installed capacity, 455 m effective head, Figure 1) and from several other intakes located in the surrounding rivers (i.e., Lumiei, Tagliamento and Degano rivers) increases the catchment area up to 647 km^2. The basin develops in the Alpine and pre-Alpine area, mainly consisting of limestone, calcareous flysch and molasse [21], and overall characterized by minor anthropogenic activities.

The Ambiesta Reservoir performs the regulation of the incoming water volumes, basically on a daily/weekly time scale, and supplies the Somplago HPP (166 MW installed capacity, 280 m effective head) that drains water into Lake Cavazzo (18.75 Mm^3). Also this lake has a small natural catchment (i.e., 9 km^2), that is mainly supplied by the water released by the Somplago HPP. The sediment deposited into the Ambiesta Reservoir is mostly fine-grained (80% silt and 20% clay) according to the peculiarities of the water supply system (water is sand-trapped at intakes or is provided by the upstream Lumiei Reservoir).

The flow regime is influenced by both spring snowmelt and autumn precipitation, thus showing a bimodal flow pattern with peaks in May and October. The mean annual inflow of the Ambiesta Reservoir is ca. 15 m^3/s, 20% of which consists of water discharged by the mentioned Ampezzo HPP. No flow is released below the dam; the mean annual flow of the Ambiesta River at the Tagliamento inlet is 0.4 m^3/s, i.e., the contribution of the residual basin (4.7 km^2).

The Ambiesta River downstream of the Ambiesta Reservoir flows for approximately 3.3 km, mainly through a deeply incised canyon characterized by step-pool morphology and average slope of 0.039. Access is rather difficult, except for the final 1.7 km where the profile is smoother and the average slope decreases to 0.004. This section has a pool-riffle morphology.

2.2. Dredging Operation

The 2014 hydraulic dredging of the Ambiesta Reservoir was planned to remove 25,000–35,000 m^3 of sediments burying the bottom outlets. The dredging area was defined as 5000–6000 m^2. This operation was carried out without interfering with the normal reservoir operation. Hydraulic dredging was carried out by a barge installing a standard cutter suction system. The slurry was then conveyed towards the surface spillway by a polyethylene pipe provided with floats. The sediment together with the dilution water were then discharged to the Ambiesta River through the mentioned bypass tunnel. The system was designed for pumping 0.04–0.08 m^3/s with maximum sediment concentration of 200–300 g/L. The clean water flow adopted for dilution purpose and for increasing the downstream transport capacity was fixed to at least 1.6 m^3/s. The corresponding maximum SSC was therefore in the range 5–15 g/L.

The months of October and November were selected considering water availability and environmental requirements. In particular, the trout (i.e., the dominant and most valuable fish species in the study area) spawning period (December–February) and spring (i.e., when trout are in their early life-stage) were avoided. Furthermore, the high flow period expected in April–May was also excluded to avoid reducing water availability for the following irrigation period. A limit on SSC was set applying the Newcombe & Jensen dose/response model [22]. A severity of ill effect (SEV) of 11 was accepted, corresponding to fish mortality in the range 20–40%. Considering 60 days duration, the resulting SSC threshold was 1.5 g/L at S2, a Tagliamento River reach located 2.7 km downstream of the Ambiesta junction (Figure 1).

2.3. Sediment Monitoring

Optical turbidimeters were installed to continuously record SSC at S1 (3.7 km downstream of the dam) and S2 (Figure 1). The turbidimeter was factory-calibrated with a suspension of Fuller's earth and provided an SSC output (a mean value per 15 min, with 3 Hz sampling frequency). The probe was mounted on a steel frame installed on the stream bank. Turbid water samples were collected during the first two days of operation to perform a posteriori calibration of the turbidimeters. These samples were randomly taken during daytime as close as possible to the probes using 1-L handheld buckets (N = 13 at S1 and N = 11 at S2). The SSC of these samples was measured in the lab using the Standard Method 2540 D-F [23]. The raw SSC data were correlated to the corresponding lab data and linear functions, one per station, were obtained through standard least-squares fitting. The agreement between the two measures was predominantly good and determination coefficient R^2 typically exceeded 0.96. The coefficients of the linear functions were then used to modify the factory calibration curve of the turbidimeters. The total volume of removed sediment was assessed by bathymetric surveys in the reservoir carried out before and after the dredging operation.

2.4. Riverbed Sampling

The accessible section of the Ambiesta River was surveyed by visual inspection one month before and after the dredging operation. Quantitative riverbed sampling was performed at three transects, approximately 20 m equally spaced: S1A, S1B and S1C (from upstream to downstream). The most downstream transect S1C is located ca. 100 m upstream of S1. Each transect was sampled in three points, two about one meter from the river edge and one in its center. The silt/clay content in the uppermost layer of the riverbed was detected through resuspension technique using a McNeil corer [24]. A McNeil corer with a 135 mm internal diameter tube was used to collect one-liter samples of turbid water. All samples were dry-sieved, analyzed for the content in silt/clay and then extrapolated to the riverbed after measuring the water depth, and therefore the water volume, in the corer tube. In the post-dredging survey, care was taken to sample the riverbed in the same points as in the pre-dredging survey. Furthermore, volumetric riverbed sampling was performed at each transect close to the central point already collected. Sampling was carried out using a 0.6 m high cylinder with a 0.5 m diameter. Water depth at the sampling points ranged from 0.1 to 0.25 m. Particles larger than 31.5 mm were measured and weighted in the field. All three axes were measured, and the corresponding sieve diameter was estimated from the particle intermediate and shortest axis dimensions [25]. The remaining subsamples of 4.5–7 kg were dried and sieved in laboratory. Overall, the analyzed samples weighed 10–25 kg. As indicated by Rex and Carmichael, one liter of turbid water was also collected after the removal of core samples to take the finer materials into account [24]. Additionally, a pebble count (as per Wolman, [26]) was performed between S1A and S1C to determine the bed surface grain distribution.

2.5. Biomonitoring

The ecological impact of dredging from the Ambiesta Reservoir on the downstream aquatic ecosystem was evaluated through a pre-post monitoring of benthic macroinvertebrate and fish communities at S1. Benthic macroinvertebrates were collected one time before the dredging operation (in September 2014, i.e., pre-dredging sample) and three times after the desilting works (in January, April, and October 2015, i.e., post-dredging samples). Samples were collected with a Surber sampler of 0.1 m^2 area and 500 μm mesh following the quantitative multi-habitat protocol developed for the computation of the standardization of river classifications_intercalibration multimetric index (STAR_ICMi), the current Italian normative index developed for WFD inter-calibration purposes. It is ranked into five quality classes (bad, poor, moderate, good, and high), set at 0.24, 0.48, 0.71, and 0.95, respectively [27]. The quality class assigned to a river reach depends on the annual mean of the STAR_ICMi seasonal values. Additional metrics were also considered, including total taxon richness, total density (individuals/m^2), EPT (Ephemeroptera, Plecoptera and Trichoptera) richness, Shannon–Wiener index, and density of macroinvertebrates belonging to ecological group A. The ecological group A is a group of rheophilous macroinvertebrates that prefer the typical alpine habitats, characterized by coarse substrates and fast-flowing water [28]. Moreover, two stressor-specific indices, the siltation index for lotic ecosystems (SILTES) and the deposited fine sediment index (DFSI), were calculated. The SILTES is obtained using total taxon richness, EPT richness and ecological group A density. This index is calculated by averaging the values of the three metrics scaled accounting for the whole dataset. Thus, the SILTES varies between 0, which represents the worst condition, and 1, which represents the best condition [29]. The DFSI was developed using indicator taxa identified through the application of the threshold indicator taxa analysis (TITAN). The sum of each individual taxon's median multiplied by the corresponding z-score and the abundance class, is divided by the sum of z-score multiplied by the abundance class. A higher fine sediment impact is indicated by a higher index value [30]. To have greater discriminatory power in the assessment, benthic macroinvertebrates were divided into functional feeding groups (FFGs) [31] to get the community-weighted means (CWM) of trait categories, which is represented by the percentage abundance of each individual functional category in the whole community.

Fish were sampled in September 2014 in a reach of approximately 1700 m^2 to assess the community before the operation, and then were removed to avoid a relevant fish mortality. However, to depict the recolonization of the monitored stream reach, fish sampling was also carried out after the works (i.e., in April and October 2014). Fish sampling was performed using a backpack electrofishing device (ELT60-IIGI 1.3 kW DC, 400/600 V, removal method with two passes). Fish were identified to species level, counted and then released. Population densities were calculated considering the sampled area.

3. Results

3.1. Dredging Operation and Sediment Monitoring

The dredging operation was carried out between the 2 October and 12 December 2014, for a total of 68 consecutive days, without relevant interference with the hydropower generation at the Somplago HPP. The sediment removal was interrupted for two days (5 and 6 November) due to heavy rainfall. During this event, a daily maximum precipitation of 285 mm was measured at the Ambiesta Dam (Figure 2). The operation allowed to remove an overall sediment volume of 30,600 m^3, estimated through bathymetric survey.

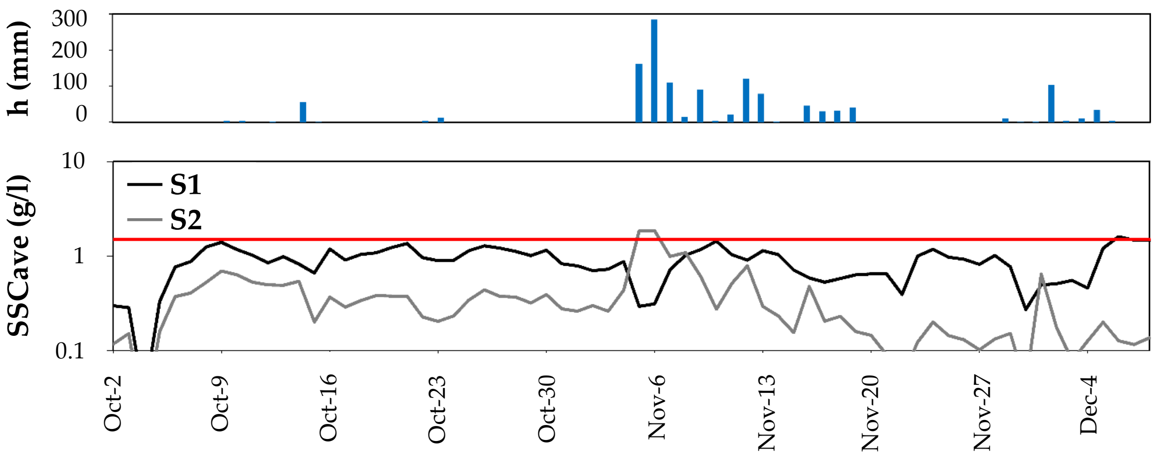

Figure 2. Time series of daily average SSC at S1 and S2, SSC threshold at S2 (red line) and daily precipitation height (h) measured at the Ambiesta Dam during the dredging operation.

The dilution flow released from the surface spillway of the dam did not change significantly neither during the day nor during the dredging operation, generally ranging between 1.7 and 1.8 m^3/s; higher values were recorded only during the two days following the above-mentioned precipitation event, with mean and maximum daily value of 2.6 m^3/s and 4 m^3/s, respectively.

The SSC pattern detected downstream of the dam showed regular daily pulses in response to the dredging activities: at S1, SSC peaked 2–8 g/L during daytime, dropping to less than 0.1 g/L during night-time (Figure 3). The daily averaged SSC at S1 was lower than 1.6 g/L; the maximum hourly SSC was generally 2–6 times higher than the daily average

SSC (Figures 2 and 3). The SSC averaged over the whole operation was 0.9 g/L at S1. At S2, SSC was usually approximately 2/3 lower than at S1 with peaks less than 1–2 g/L during the days without precipitation. On the other hand, rainfall clearly influenced the SSC at S2 (Figure 2). In particular, the daily average SSC at S2 during the rainy days was about two times larger than during the other days. This relevant SSC increase was not recorded at S1 due to the small catchment area. Comparing the SSC threshold of 1.5 g/L with the daily average SSC at S2, the limit was exceeded only during the two days of heavy rainfall, when the dredging operation was interrupted (Figure 2). The SSC averaged during the dredging days was 0.3 g/L at S2, that is significantly lower than the mentioned threshold. SSC above 1.5 g/L was measured ca. 15% and 1.5% of the operation time, at S1 and S2, respectively.

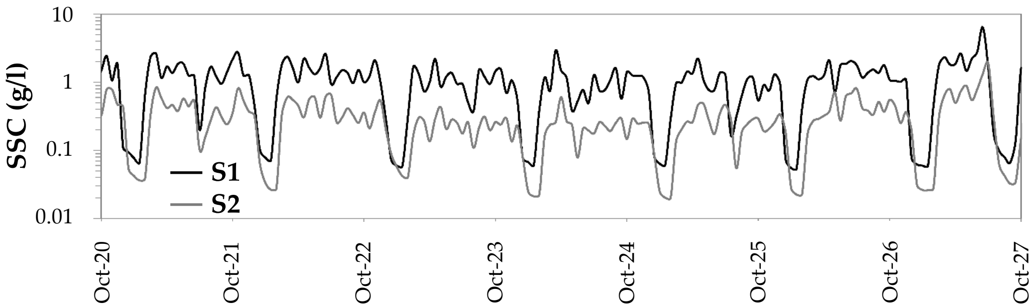

Figure 3. Example of time series of hourly average SSC at S1 and S2.

3.2. Riverbed Sampling

Grain-size distribution of the volumetric samples of deposited sediment is provided in Figure 4, and the photographs of the three monitored transects (i.e., S1A, S1B and S1C) in Figure 5.

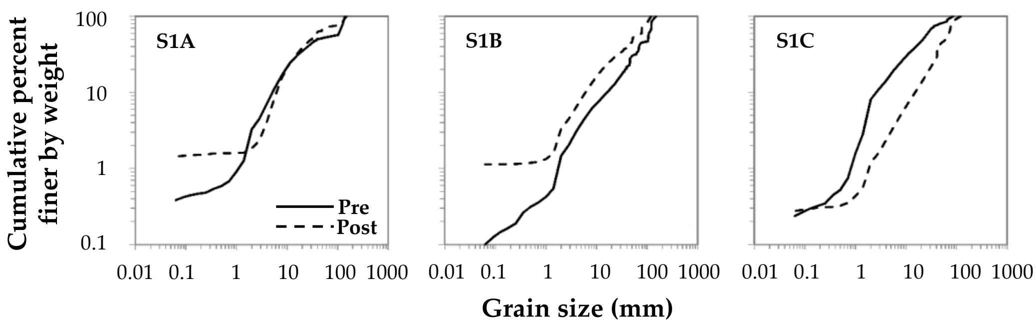

Figure 4. Grain-size distribution of the McNeil samples at S1A, S1B and S1C.

The representative percentiles D_{16}, D_{50} and D_{84} detected through the pebble count performed between S1A and S1C were 8 mm, 17 mm, and 51 mm, respectively, i.e., in the gravel range. Silt/clay deposits were not observed at the three monitored sections. On the other hand, occasional silt/clay deposits were found in further zones of the surveyed reach, presumably in areas wetted during increased flow and characterized by locally low velocity during the dredging operation.

The percentage of silt/clay in the pre-dredging samples ranged between 0.1% and 0.4%. This percentage increased to approximately 1% in two (i.e., S1A and S1B) of the three sampled transects; in the last one (i.e., S1C) it remained constant. The silt/clay content (mass per unit area) ranged from 0.11 to 0.35 kg/m^2 and from 0.27 to 1.06 kg/m^2, respectively in the pre- and post-dredging samples collected with the resuspension technique (Table 1). The increase per unit area varied between 0.24 and 0.7 kg/m^2 as transect average (Table 1).

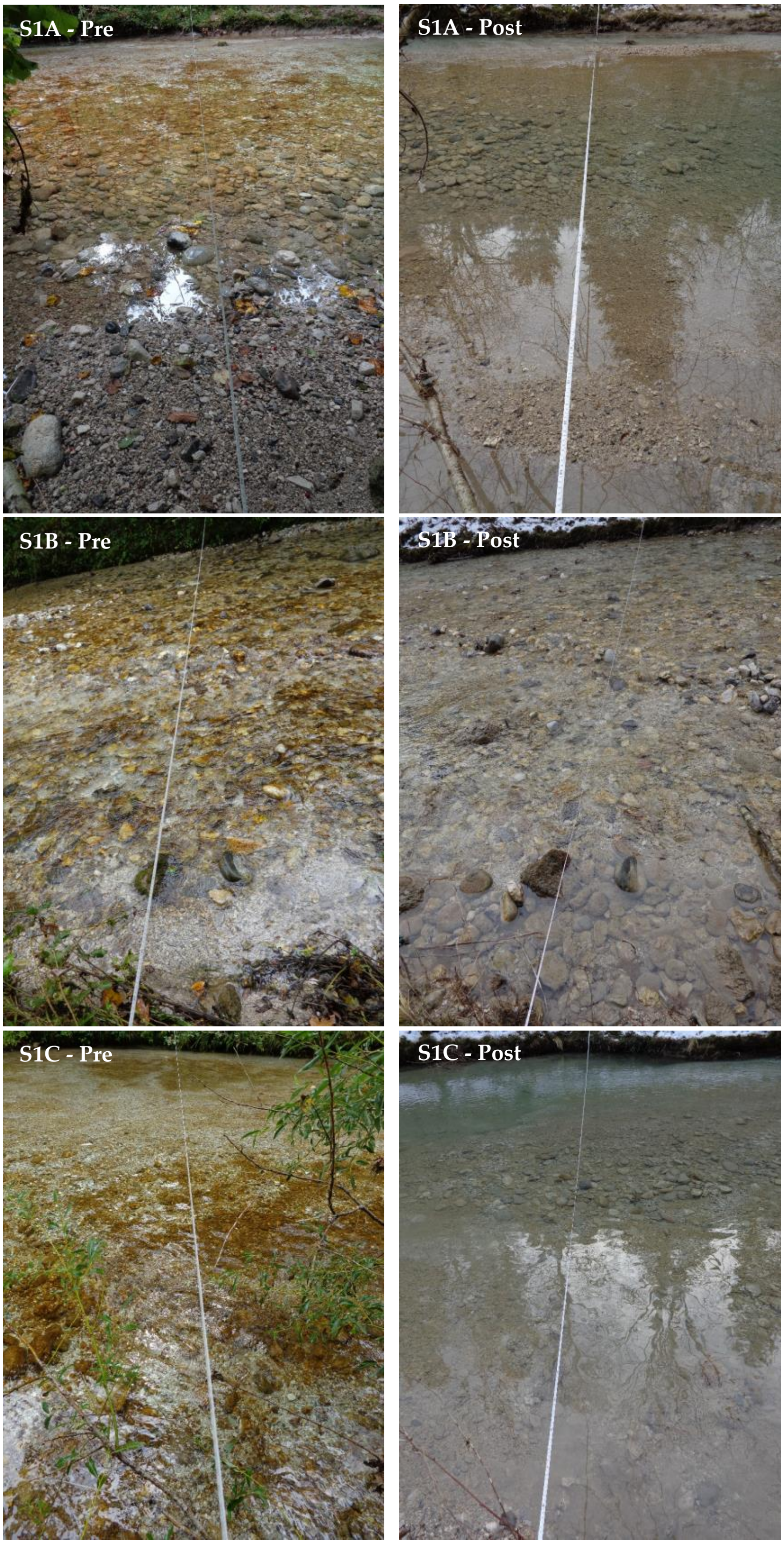

Figure 5. Streambed of the Ambiesta river one month before and after the dredging operation at S1A, S1B, and S1C (S1 geographic coordinates: 46°22′56.00″ N, 13°00′53.95″ E).

Table 1. Silt/clay content (kg/m^2) in the uppermost layer of the riverbed of the three monitored transects. Pre and Post indicate the sampling, respectively carried out one month before and one month after the 2014 dredging operation.

Section	Sample Position	Silt/Clay Content		Difference	Average Difference
		Pre	Post	Post-Pre	Post-Pre
S1A	Right	0.14	0.66	0.52	0.27
	Centre	0.29	0.32	0.03	
	Left	0.20	0.46	0.26	
S1B	Right	0.28	0.50	0.22	0.24
	Centre	0.35	0.27	−0.08	
	Left	0.13	0.73	0.60	
S1C	Right	0.13	0.84	0.71	0.70
	Centre	0.11	1.06	0.95	
	Left	0.27	0.73	0.46	

3.3. Biomonitoring

The pre-dredging community of benthic macroinvertebrates collected at S1 was composed mainly of Coleoptera Elmidae, Plecoptera Leuctridae, Ephemeroptera Baetidae and Diptera Athericidae, Limoniidae and Chironomidae (Table 2). In the sample collected short time after dredging, no relevant density reduction occurred, while a non-negligible decrease in family richness (i.e., N families) and diversity (i.e., Shannon–Wiener) was detected (Table 3). Indeed, the first post-dredging sample was composed of 15 families with the dominance of only two taxa, Elmidae and Trichoptera Hydropsychidae (Table 2). However, an almost complete recovery of the benthic community occurred in spring, when some taxa (i.e., Ephemeroptera Ephemerellidae and Baetidae) showed a noticeable increase, probably due to their life cycles (Table 2). Leuctridae and Athericidae are the only taxa that did not recover their pre-dredging densities after one year from the monitored event (Table 2).

Table 2. Composition of the benthic macroinvertebrate community collected at S1 before and after dredging. Density (individuals/m^2) is reported for each family sampled.

Taxon	Family	2014 (Pre)	2015 (Post)		
		September	January	April	October
Plecoptera	Leuctridae	90	7	3	27
	Nemouridae	14	1	8	1
Ephemeroptera	Baetidae	87	0	749	194
	Ephemerellidae	2	0	432	1
Trichoptera	Hydropsychidae	34	157	46	46
	Rhyacophilidae	2	0	14	3
Coleoptera	Elmidae	154	268	186	195
Diptera	Chironomidae	70	10	131	52
	Athericidae	90	15	40	31
	Simuliidae	13	0	130	22
	Limoniidae	10	15	33	17
Oligochaeta	Lumbriculidae	11	13	10	6
Other taxa	-	39	10	117	21

Table 3. Metrics related to the structure of the benthic macroinvertebrate community collected at S1 before and after dredging. Moreover, the STAR_ICMi (G = good quality class), SILTES (fam = computed using families as taxonomic resolution) and DFSI (14 out of 45 taxa were not considered due to lack of information) indices are reported.

	2014 (Pre)	2015 (Post)		
Metric	**September**	**January**	**April**	**October**
Density (ind/m^2)	616	496	1899	616
N families	28	15	25	24
N EPT	13	10	10	11
Shannon-Wiener	2.26	1.27	1.89	1.92
STAR_ICMi	0.89 (G)	0.76 (G)	0.80 (G)	0.79 (G)
ECOgA (ind/m^2)	15	4	25	2
SILTES$_{fam}$	0.86	0.03	0.59	0.34
DFSI	1368	1395	1431	1379

Although these changes in the benthic community, the ecological quality, defined through the STAR_ICMi, remained good for all the study period (Table 3).

Macroinvertebrates belonging to the ecological group A showed a marked reduction on the first post-dredging sampling, but, even in this case, it was possible to notice a complete recovery in the spring sample. The values of SILTES were consistent with the evidence of the ecological group A; pre-dredging sampling showed the highest value of the index (0.86), while the lowest value (0.03) was observed on the first post-dredging sampling. Then, the SILTES increased again on the next two sampling dates (Table 3). However, the DFSI did not allow to highlight a relevant effect of increased fine sediment deposition on the first post-dredging sampling; the highest value was found on the second post-dredging sampling (1431), although the difference is minimal, as it corresponded to less than 5% of the control (Table 3). Among the FFGs, the percentage abundance of shredders increased on the first post-dredging sampling, while the relative abundance of deposit-feeders and scrapers showed a reduction. The functional composition of the macroinvertebrate community on the second and the third post-dredging sampling was similar, but differed from the previous dates as the relative abundance of shredders decreased, while the opposite trend was detected for scrapers (Figure 6).

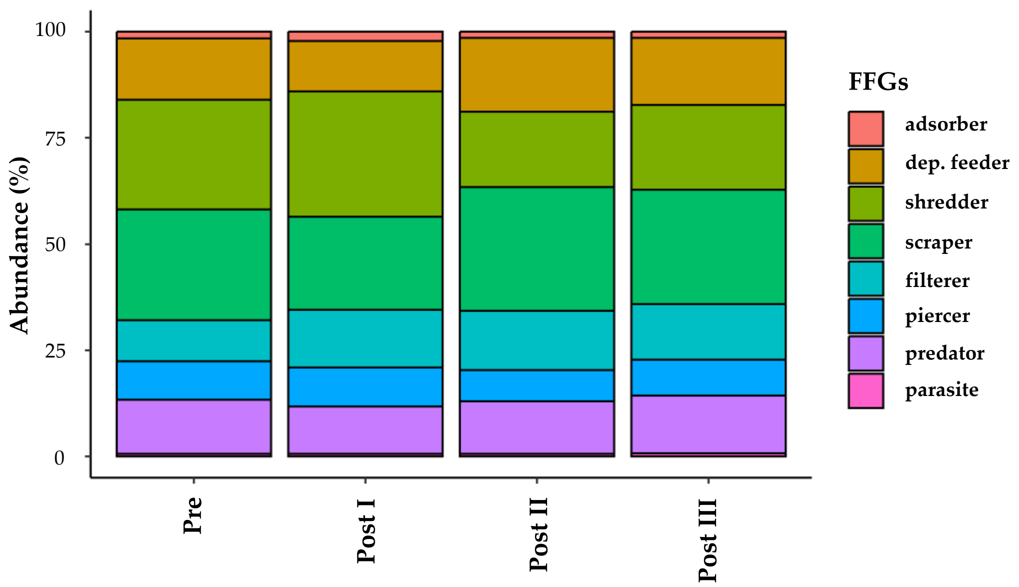

Figure 6. Stacked bars illustrating the percentage abundance of each individual feeding functional categories (i.e., community weighted means of trait value) in the whole benthic macroinvertebrate community on each monitoring date.

When considering the fish monitoring, before the dredging event the community was mainly composed of brown trout (*Salmo trutta* L.) and bullhead (*Cottus gobio* L.), with density of 140 and 170 individuals/ha, respectively. However, in the first post-dredging sample a community comparable to the pre-flushing one was detected (146 and 105 individuals/ha of brown trout and bullhead, respectively), suggesting that the fish habitat conditions were not significantly affected (i.e., that negligible substrate alteration due to sediment deposition occurred). This result was confirmed by the last sampling carried out in October 2015 (82 and 170 individuals/ha of brown trout and bullhead, respectively).

4. Discussion

Dredging in lakes and reservoirs is mostly performed to construct and maintain commercial navigation. Alternatively, dredging in reservoirs rarely involves more than 1 Mm^3 of sediment removal per site, being focused on desilting specific areas of strategic importance, such as hydropower intakes and bottom outlets, due to its high costs [8]. These costs frequently prompt consideration of other, cheaper sediment management strategies. For example, Ji et al. studied the possibility of replacing dredging at the Nakdon River Estuary Barrage (South Corea) with sediment flushing [32]. On the other hand, an interesting application of reservoir dredging is the creation of a bottom channel to facilitate sediment evacuation by turbidity currents during floods [33].

The hydraulic dredging at the Ambiesta Reservoir was mainly carried out for restoring the safety operations of the bottom outlets. The operation was therefore oriented to the removal of a specific volume (i.e., ca. 30,000 m^3 of sediment) within a defined area. The Ambiesta Reservoir is an off-channel reservoir [5] and is generally supplied by diverted water with low sediment concentration of very fine sediment (i.e., silt/clay). Even if dredging is expensive compared to sediment flushing, it was selected because it allows to maintain the ordinary operation of the Somplago HPP, that has been the most important source of water for Lake Cavazzo since the dam construction. Furthermore, it was not possible to perform a sediment flushing operation during the high flow season due to the low capacity of the bottom outlets buried by sediments. The cost of the dredging operation may be estimated in ca. 55 EUR/m^3 (ca. 59 \$/m^3) including the dredging works and the loss of hydropower. In particular, the cost of the dredging works accounted for ca. 70% of the sediment removal cost. Morris reported dredging costs of 5–15 \$/m^3 [20]. This relevant difference is likely due to the small amount of sediment removed and the need to release water for dilution purpose (i.e., a total of 9.9 Mm^3) for a long period (i.e., 68 days). The ratio between the volume of removed sediment and the volume of water used was 0.003. This value is in the range found for the controlled sediment flushing operations performed in the Lake Como catchment in the last decade [19], comparably characterized by efforts to mitigate the downstream environmental impact.

SSC in the downstream river could be completely controlled during a standard hydraulic dredging operation, regulating the amount of pumped sediment-laden water and clear water used for dilution, thus avoiding the acute impacts of hyper-concentrated flow [34]. In contrast, SSC control during controlled sediment flushing operations can be especially difficult in some phases [19]. In this case-study, the SSC limit of 1.5 g/L, fixed at S2 along the Tagliamento River, was largely respected. The SSC peaks were mostly related to an intense rainfall event, rather than to the desilting operation. The SSC averaged on the whole period was 0.3 g/L at S2. Using this value, the SEV value computed by the Newcombe & Jensen model was 10, reducing the predicted fish mortality to 0–20% [22]. Computed SEV at S1 was ca. 10.6, corresponding to a predicted fish mortality between 0 and 20% and 20 to 40%.

The turbidimeters were calibrated by field measurement to improve the reliability of the SSC records used for managing the dredging operation. Specifically, the samples collected had mostly SSCs lower than 1.5 g/L and 0.5 g/L at S1 and S2, respectively. SSCs higher than these values were recorded for the 15–20% of the overall operation time. These SSC data were corrected extrapolating the calibration curve. Therefore, even if the calibration of the probe can be useful for the real-time management of the operation, further sampling is needed during all the dredging period, thus supporting a more robust calibration of the probe avoiding extrapolations.

Riverbed sampling, though performed only in a few transects, indicated a marginal sediment deposition, thus excluding the negative effects of severe streambed clogging [35]. This result can be compared with those found for the 2011 Cancano and the 2008 Valgrosina controlled sediment flushing operations [19]. In fact, during these operations, silt/clay sediment was released, and analogous field surveys were conducted in the downstream rivers. The range of fine sediment increase found in the Ambiesta case study is relatively smaller (i.e., 0.24–0.7 kg/m^2) than those found in these study cases. In fact, a range of 0.5–1 kg/m^2 and 1–2.5 kg/m^2 as transect average was reported downstream from the Cancano and Valgrosina reservoirs, respectively. This difference may be related to the lower SSC detected at the Ambiesta monitoring site (i.e., 0.9 g/L as average) compared with 3.1–7.9 g/L and 3.5 g/L recorded after sediment flushing at Cancano and Valgrosina reservoirs. However, in all study cases the estimated deposition represented a very low fraction of the evacuated sediment. Although more sophisticated methods are available to quantify fine sediment deposition and related riverbed alteration, including high resolution topography [36] and sample collection by freeze coring or infiltration bags [37,38], the resuspension technique [24] adopted in this study, along with pebble count [26] and visual estimation [39] represent widely used and more rapid assessment techniques.

The low impact of the dredging operation on benthic macroinvertebrates and the fast recovery of both benthic and fish communities observed after the works agree with the relatively low SSCs recorded during the operation and the small fine sediment deposition. Specifically, no relevant reduction of the total density of benthic macroinvertebrates was observed in the first post-dredging sample as instead it occurred after the controlled sediment flushing operations reported by Espa et al. [19], indicating a less severe effect due to the study event, characterized by comparatively longer duration but significantly lower SSCs and absence of sharp SSC peaks. In general, large sediment releases determine drastic reductions of macroinvertebrate taxa more sensitive to physical stress, such as the insects belonging to the orders of Ephemeroptera, Plecoptera and Trichoptera [19], while favoring more generalist taxa such as Chironomidae or Simuliidae (order Diptera) [40]. In this case study, it is important to emphasize that the slight decrease of macroinvertebrates, observed during the first post-dredging sample, affected not only the most sensitive taxa; consequently, there was no evidence of a community homogenization, which has been detected in other studies of sediment disturbance [41]. Moreover, the density of Hydropsychidae showed a considerable increase during the first post-dredging sample; this finding excludes the possibility that the extent of the perturbation was a limiting factor for these filter-feeding organisms, which prefer substrates with empty interstices for the creation of shelters [42]. The pattern of the Chironomidae density is also consistent with a low impact of the hydraulic dredging over the Ambiesta benthic macroinvertebrate community. In fact, several studies have demonstrated that Chironomidae abundance tends to increase in conditions of physical disturbance or more generally in substrates with high percentage of fine sediments [43], but in this case study the opposite evidence was found when comparing the density between the pre-dredging sampling with the first post one. The STAR_ICMi did not allow to identify any variation in the ecological quality in the different phases monitored, scoring in all cases good quality, and thus complying with the WFD environmental target. However, the results obtained through the application of the SILTES showed a drop in the first post-dredging sample, thus proving evidence of an improved discriminating power of this index concerning the physical stress from sediment [29,44]. The SILTES values associated with the second and the third post-dredging sample (April and October 2015) showed a considerable increase. The SILTES index performance as well as the total density of macroinvertebrates suggest a complete recovery of the community. Correspondingly, the DFSI did not allow to identify any significant variation between the different monitoring phases, according to the slight deposition of fine sediment previously discussed. The absence of changes found through the application of the DFSI confirms the reduced impact of the dredging on the benthic community of the Ambiesta River. In fact, it has been shown in previous studies that it is unlikely to detect significant variations in the DFSI values when fine sediment deposition is not particularly severe [44]. Considering the results of FFGs, negligible functional differences were found as well. Large sediment deposition could cover the leaf debris, making the trophic resource (coarse particulate organic matter, CPOM) inaccessible to shredders, which causes a drastic reduction in their abundance [45]. Another negative ecological impact of fine sediment is the abrasion of periphyton [46], which could damage scrapers particularly, because macroinvertebrates belonging to this FFG prefer the periphyton as a trophic source [31]. In contrast, in this case study, the proportions of the two mentioned groups did not show any reductions, excluding negative effects of the fine sediment deposition. Finally, fish removal from S1 probably allowed to avoid fish mortality, estimated to above 20% (i.e., SEV = 10.6) according to the Newcombe & Jensen model. Despite its simplicity, this model is still widely applied to estimate the short-term effects of increased fine sediment loading over fish assemblages [47,48].

5. Conclusions

The results of this study indicate that if fine sediment removal operations are performed controlling the SSC in the outflowing water and avoiding SSC peaks, the downstream environmental impacts can be effectively limited. The key management factors that allowed to minimize the ecological impact of the dredging operation can be summarized as follows: a relatively low SSC limit over a relatively long operation, the allocation of large clear water volumes for diluting the sediment load and reducing fine sediment deposition, and precautional fish removal from the area closest to the reservoir before dredging.

In this perspective, hydraulic dredging can be considered an effective alternative to counteract reservoir siltation, even though it is characterized by generally high costs. Special care should be exercised when extending the finding of this study to different contexts; for instance, the limited sediment deposition observed after the dredging can be also related to the small grain-size of the evacuated sediment, and increased deposition coupled with higher downstream impact could have been expected in case of coarser evacuated sediment [19,49]. Therefore, in our opinion, the thorough investigation of further case studies is required to gather the necessary field evidence supporting a more eco-sustainable management of reservoir siltation [50]. Finally, although long-term impacts could be reasonably excluded for the Ambiesta case-study, future research would also explore the long-term effects of downstream sediment evacuations, accounting for variations in ecosystem responses under different environmental conditions.

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