FIELD INVESTIGATION OF CONTROLLED SEDIMENT FLUSHING AT SERNIO PONDAGE

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Abstract

Sernio barrage (central Italian Alps) dams the Adda river 75 km above its mouth in lake Como. The project diverts water to a run-of-the-river hydropower plant (30 MW installed capacity, 40 m^3/s rated discharge). At maximum headwater, a 0.75 Mm^3 pondage develops up to 1.5 km above the barrage.

Controlled sediment flushing took place in 2009 and in 2010 during maximum seasonal runoff (late spring/early summer) in non-consecutive days to increase the environmental sustainability and to meet the requirements of the other river stakeholders. In 2009, about 100’000 tons of sediment (predominantly smaller than coarse sand) were flushed in 16 days. About 25’000 tons were evacuated in 6 days in 2010. During the flushing works, the typical discharge was between 70 and 100 m^3/s, while minimum flow released below the barrage is of 2 m^3/s.

Two limits for the Suspended Solid Concentration (SSC) were fixed, i.e. 1.5 g/L (average value on the whole working day) and 3 g/L (alert threshold to adjust the ongoing activity). SSC control was successful and constraints were essentially fulfilled.

About 5 km below the barrage field surveys were carried out to quantify the impact on river biota (Adda river below the barrage is characterized by suitable habitats for grayling and marble trout, both catalogued in the EU Habitats Directive and in the IUCN red list of threatened species - least concern category).

The operation seems overall tolerable and the reported values could be useful to plan future sediment management in analogous contexts.

Keywords: *controlled sediment flushing, suspended solid concentration, sustainable sediment management, macroinvertebrates, STAR_ICM index, regulated catchment*

1 INTRODUCTION

In a world context characterized by increasing exploitation of water resources and need of renewable energy [1], sustainable preservation of reservoir storage is going to become crucial. Flushing may represent an effective technical alternative to desilt reservoirs [2], but concerns arise over the ecological consequences on the river receiving the removed sediments: the operations should therefore be managed aiming to reduce the impact on downstream ecosystems.

The biological impact of flushing operations can be essentially related to:

- the direct effects on living organisms of both suspended solids and high flows usually released in the course of the evacuation activities,
- the morphological modification of river habitats following sedimentation of the flushed material [3; 4].

SSC thresholds prescribed by the standard guidelines are well below acceptable values to perform effective sediment flushing [5] and just few works document the environmental effects of these operation. Only increasing our knowledge on this poorly investigated subject, it could be possible to reliably predict the impact of the planned flushing works and adequately sustain decision making.

In the case-study presented in this paper, two SSC thresholds were adopted:

- 1.5 g/L, as average value on the whole working day,
- 3 g/L, as alert threshold to adjust the ongoing activity.

These values were determined in a rather empirical way, on the basis of past evidences concerning the effects on fish caused by flushing operations in the same area [6]. However, these thresholds might be not enough protective of benthic fauna. In fact, according to Pruitt et al. [7], a sediment concentration larger than 258 mg/L results in biological impairment, while a concentration of 58 mg/L or less provides an adequate margin of safety and is protective of aquatic invertebrates.

The main objective of this study is to provide experimental evidence on the biological consequences of an accurately described flushing operation, focusing on fish and invertebrate fauna. Furthermore, the benthic community health was described by different indices in order to assess the most suitable metric for detecting the effects of flushing in the investigated context.

2 MATERIALS AND METHODS

2.1 Flushing operations and SSC monitoring campaign

Sernio barrage (Valtellina, Northern Italy, Figure 1) dams Adda river 75 km above its mouth in lake Como. The project diverts water to the run-of-the-river hydropower plant of Stazzona (30 MW installed capacity, 40 m^3/s rated discharge). At maximum headwater, a 0.75 Mm^3 pondage develops up to 1.5 km above the barrage.

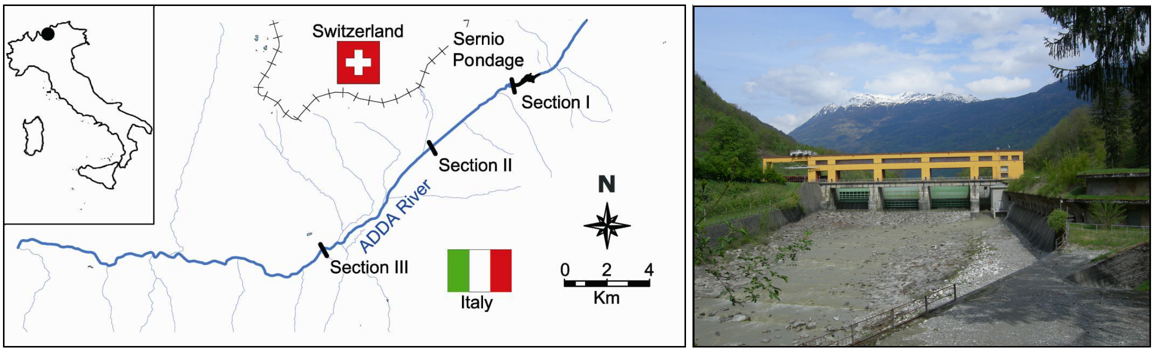

Figure 1. Study area with monitoring sections (left) and Sernio barrage during flushing works (right).

Catchment area at barrage section is 885 km^2 with elevations ranging from 490 to 4,000 meters. This watershed is highly exploited for hydropower, with overall installed capacity of 780 MW. Average discharge at the barrage section is 25 m^3/s, with monthly maximum in June due to snow melting (50 m^3/s). Minimum flow of 2 m^3/s is released below the barrage.

Pondage bed sediments are predominantly smaller than coarse sand (0.50 mm) with significant fraction in the silt/clay range (sediment size below 62 μm).

Sediment flushing took place in 2009 and in 2010 during maximum seasonal runoff. Works were performed on non-consecutive days to increase environmental sustainability and to satisfy requirements of other river stakeholders (irrigation, fishing, recreation).

SSC control was first achieved through gradual gate opening and regulation of pondage inflow. Later, when full gate opening was possible, earth-moving equipment was employed. An optical turbidimeter (mod. Lange SC100) was installed few hundred meters below the barrage (Section I in Figure 1) and real time results were used to manage flushing activities. Turbidimeter records were calibrated a posteriori through lab analyses of one liter samples as discussed in [8].

Analogous sampling was conducted by portable turbidimeter (mod. Partech 740) on selected days and only during daytime at Section III of Figure 1 (Tresenda, 12.5 km downstream of the Sernio barrage). SSC survey was extended up to 40 km below the barrage, but, for the sake of brevity, results concerning the river reach downstream of Section III won't be discussed herein.

The average slope of the river profile is about 0.015 between Sections I and II, and it is less than a half in the downstream investigated river reach (0.006 between Sections II and III).

During the 2010 flushing operations, suspended sediments were sampled at Sections I and III in order to detect particle size distribution.

2.2 Biological sampling and data analysis

The biomonitoring site was located at Section II, about 5 km downstream of the Sernio barrage. According to the fish vocation of Huet [9], Adda river above the barrage has suitable habitat for brown trout *(Salmo trutta trutta*) and bullhead (*Cottus gobio*), while below the barrage for grayling (*Thymallus thymallus*) and marble trout *(Salmo trutta marmoratus*), both catalogued in the EU Habitats Directive (92/43/EEC) and in the IUCN red list of threatened species (least concern category). Fishing activities are performed from March to October in the case of trout and from May to October for grayling. Juveniles of brown trout are introduced every year for re-stocking. Moreover, at this site another species, telestes (*Leuciscus souffia muticellus*), can be found.

Fish populations were quantitatively sampled by electrofishing surveys (removal method with two passes) using a backpack electrofishing device (mod. ELT60-IIGI 1.3 kW DC, 400/600V).

The pre-flushing survey of the 2009 event was carried out 2 km upstream of Section II, in the centre of the Tirano village, where fishing activities are forbidden. Unfortunately, this site proved unsuitable for fish monitoring purposes because the large discharge during the sediment flushing determined the drift of the fish fauna downstream. The next samplings were performed at Section II few days (July 2009) and five months (December 2009) after the first flushing event and before (May 2010) and after (October 2010) the second flushing event. Further observations (April and August 2011) were carried out also in 2011.

Fish were identified to species level, counted, and their total lengths measured. Population densities (individuals/hectare) were calculated taking into account the sampled areas. Sampled areas were different in the various sampling campaigns: a 2,400 m^2 area was sampled in July 2009, 5,000 m^2 in December 2009 and 3,400 m^2 in all the other occasions. The age structure of the fish populations was depicted. In the case of brown trout the specimens were also weighted to calculate Fulton's body condition factor K. ANOVA with Scheffè test was performed to compare K mean value of different samples using length as covariate.

The surveys of the benthic invertebrates were carried out six times during 2009 (February, April, May, August, September and December), five times during 2010 (February, May, July, September and December) and two times in 2011 (February and April). Macroinvertebrate samples were collected according to the AQEM strategy [10], a quantitative multi-habitat approach developed in accomplishment of the WFD (Water Framework Directive, 2000/60/EC), in a riffle stretch with a Surber sampler. Collected macroinvertebrates were preserved in formalin (4%), identified to family level and counted. Quality classes (five in all, from high to bad status) were determined using the STAR_ICM index, the new official Italian method for classification based on macroinvertebrate communities, developed for WFD inter-calibration purposes [11]. The STAR_ICMi is based on six different metrics (ASPT index, Log_{10}(sel_EPTD+1), 1-GOLD, number of families of EPT, total number of families and Shannon-Wiener diversity index). The structure and function of the benthic community were also evaluated using mean density (individuals/m^2), Margalef's richness, Simpson's dominance and Evenness indices and the ratio between EPT and Chironomidae.

3 RESULTS AND DISCUSSION

3.1 Flushing operations and SSC monitoring campaign

The overall evacuated sediment during the 16 working days of the 2009 flushing amounted to 100,000 tons, with daily rates ranging from 400 to 13,000 tons (Table 1). The 2010 flushing was smaller (25,000 tons of sediment removed in 6 days) and more regular (evacuated mass per day between 1,200 and 6,000 tons - Table 1).

Even if the threshold of 3 g/L was occasionally exceeded during 2009 works, with maximum values up to 6.2 g/L, daily average SSC was successfully kept below the fixed limit (1.5 g/L) with the exception of only one day. During the 2010 flushing, both average and peak SSCs were lower than those recorded in 2009. This reduction is basically related to the better control of the system during 2010 work thanks to the works performed one year before. It might suggest that similar operations would be performed yearly to increase control and sustainability.

Transported sediment sampled at Section I were predominantly smaller than very coarse sand (1 mm) with daily variable percentage of silt/clay content (between 30 and 65%). Analogous measurements carried out at Section III showed sediment size smaller than medium sand (0.25 mm) and silt/clay fraction of about 70%.

SSC measurements at Section III were not as detailed as for Section I; however, they allowed for a rough estimate of sediment deposition between the two sections of about 40% of the mass flowed through Section I [8]. A larger amount of sediment would be probably settled below Section II, taking into account the slope reduction recalled at point 2.1.

Table 1. Hours of evacuation works per day (Δt_W), daily averaged flow rate and SSC (Q_{AVE} and SSC_{AVE}), daily maximum SSC (SSC_{MAX}), and daily evacuated mass (M_{TOT}). Up: 2009 flushing. Down: 2010 flushing.

Day	Duration of the works Δt_W [h]	Daily averaged flow-rate Q_{AVE} [m^3/s]	Daily averaged SSC SSC_{AVE} [g/l]	Maximum SSC SSC_{MAX} [g/l]	Daily evacuated mass M_{TOT} [10^3 kg]
23/05/09	3	70	0.4	3.6	1’800
24/05/09	3	75	0.1	1.4	400
25/05/09	17	90	1.2	3.7	9’600
26/05/09	13	80	1.0	2.4	7’600
27/05/09	17	80	0.4	1.5	2’800
29/05/09	2	70	0.5	3.0	3’600
04/06/09	8	60	0.4	1.8	2’800
05/06/09	8	55	0.6	2.8	4’600
18/06/09	9	80	1.0	5.5	8’600
19/06/09	9	80	1.3	6.2	12’000
02/07/09	8	70	1.9	3.8	13’000
03/07/09	8	50	1.4	4.0	6’900
07/07/09	8	80	1.4	4.4	11’500
08/07/09	8	70	1.5	2.9	9’700
09/07/09	8	60	1	2.7	6’500
10/07/09	3	40	0.6	3.1	3’300

Day	Duration of the works Δt_W [h]	Daily averaged flow-rate Q_{AVE} [m^3/s]	Daily averaged SSC SSC_{AVE} [g/l]	Maximum SSC SSC_{MAX} [g/l]	Daily evacuated mass M_{TOT} [10^3 kg]
08/07/10	12	63	0.7	2.5	4’300
09/07/10	12	53	0.8	2.2	3’400
15/07/10	12	67	0.9	3.6	5’800
16/07/10	12	57	0.9	2.2	4’400
19/07/10	9	59	0.9	3.0	6’000
20/07/10	10	44	0.3	0.9	1’200

3.2 Biological effects on fish

As suggested by Lloyd [12], it could be assumed that high levels of SSC might be lethal to sensitive fish species, whilst prolonged levels of lower values of SSC and turbidity could cause chronic sub-lethal effects, such as reduced weight, since individuals are not able to feed efficiently [13]. Both of these biological effects are expected to modify fish population dynamics by threatening recruitment.

Data on fish collected at Section II from July 2009 to August 2011 are shown in Figure 2. In May and October 2010 and April 2011, because of the larger seasonal discharge, only a qualitative approach was possible: the number of sampled individuals should therefore be regarded as an estimate.

During the study period, the bullhead population was the most abundant with a tendency to increase in the last sampling campaigns, from October 2010, suggesting the natural reproductive success. The lack of individuals less than 70 mm in length (juveniles) is due to the difficulty of their capture (Figure 3). However, from October 2010 there was also an enrichment in the population composition with the presence of individuals shorter than 100 mm (Figure 3).

The brown trout was the second fish species in abundance, although hampered by an altered age structure because of the fishing and re-stocking activities.

In the case of bullhead and brown trout the lower values of density were registered in December 2009 (Figure 2): the winter period is generally difficult to face for the low temperatures and the scarcity of food. Moreover, trout sampled in this period had significantly low K values (ANOVA; $p<0.05$). The other species sampled were grayling, rainbow (*Oncorhynchus mykiss*) and hybrid (brown x marble) trout and telestes. They were represented by few specimens in all samples (Figure 2).

The results of the fish monitoring activities show no apparent adverse effect of the sediment flushing on the fish community. Although some samplings were not quantitative, the bullhead population seems even to increase after the second flushing.

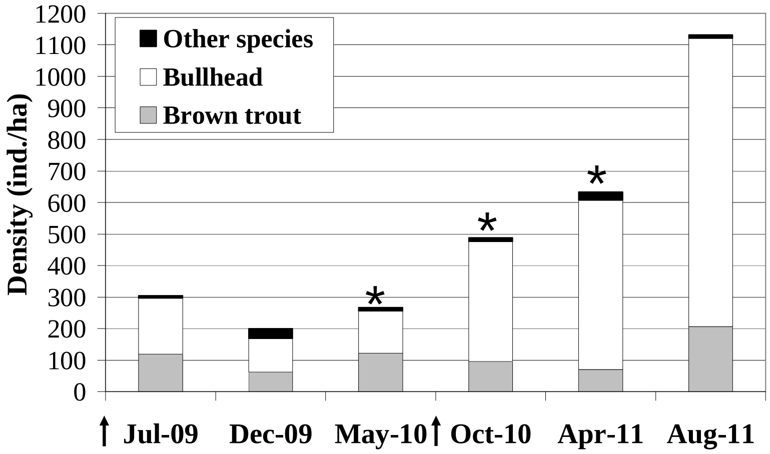

Figure 2. Trend of fish density (individuals per hectare) from July 2009 to August 2011 at Section II. The arrows show the periods of the two flushing events, while the asterisks the sampling campaigns of qualitative character.

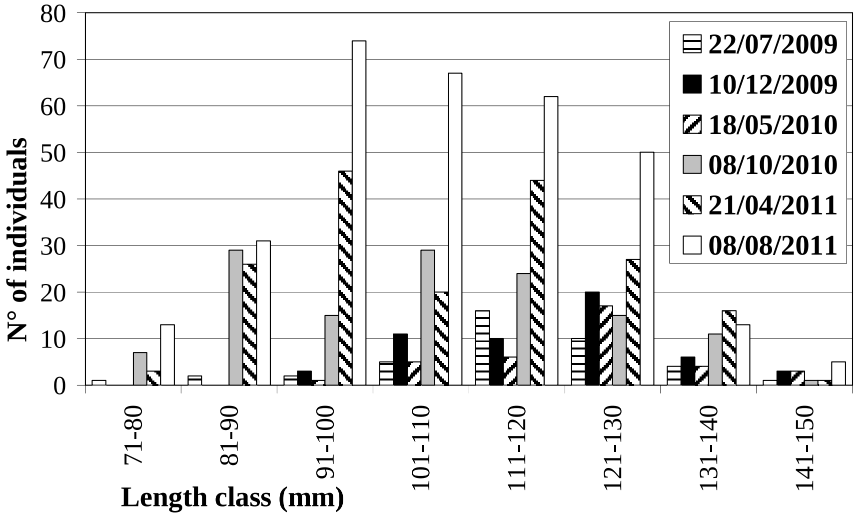

Figure 3. Number of individuals per length class (mm) of bullhead sampled from July 2009 to August 2011 at Section II.

In the case of brown trout, the interpretation of the available data is not straightforward because of the bias of human activities as sport fishing and restocking that alter the natural population structure. In a previous study [5] in the same area, when larger SSCs were recorded, a significant drop of brown trout density and biomass was measured, with the heavier effects on juveniles.

As the flushing operations were carried out in non-consecutive days, it was preferred not to apply specific models for the prediction of the direct effects of suspended sediment on fish population, as the Newcombe and Jensen [14] concentration/duration response model.

3.3 Biological effects on benthos

Baetidae, Limnephilidae, Chironomidae and Simulidae were the more abundant taxa (typically with percentage larger than 30%) of the benthic community composition at sampling area of Section II. The other representative taxa were Leuctridae, Rhyacophilidae, Limonidae and Naididae, that were detected in more than one sample with a percentage in some cases above 5%.

As in a previous study in the same area [5], after a non negligible reduction in abundance following the first flushing operation (from 1,700 to 900 ind./m^2), the zoobenthic assemblages showed substantial recovery within few months, depending on the taxa (Figure 4).

Ephemeroptera Baetidae (*Baetis*) and Trichoptera Limnephilidae were the most sensitive taxa to flushing events. In fact, before the first flushing they were the most abundant taxa (their sum was more than 50%), while after the works they dropped to 7 % and 0 % respectively.

Our results show that both taxa have a great resilience and recovery capacity, especially Baetidae. This family, in fact, having a fast life cycle and good colonizing ability, rapidly re-established, confirming previous works on the subject [15; 16]. Considering the trend of density, Limnephilidae appears the most suitable taxa to indicate the occurrence of this kind of perturbation. This taxa disappeared after the first flushing and reappeared five months later (in December 2009 sampling). An analogous capacity of recovery was also noticed after the consistent drop occurred in July and September 2010. The Diptera Limoniidae and the Trichoptera Rhyacophilidae decreased in abundance after the first flushing and the pre-flushing level was regained only in April 2011 and December 2010 respectively.

Diptera families (Figure 4), overall Chironomidae, were the most tolerant taxa to flushing. After the first event it represented the 79% of the sample. After the second flushing, this family was not subjected to an increase of density of the same extent, probably for the high flows recorded in the months immediately before and after the operations that impaired the whole benthic community. In fact, in July 2010 (before the flushing event) the density of macroinvertebrates decreased by 90% respect to the previous sample (from 900 to 90 ind./m^2 - Figure 4), probably as a consequence of high flows due to snowmelt. It may suggest that the abundant discharges during the flushing operations (between 70 and 100 m^3/s) were the main cause of the macroinvertebrates drop (accustomed to very low flow condition).

In February 2011 the highest density (4,800 ind./m^2) was recorded, more than two times larger than the mean value recorded before the first flushing event (2,000 ind./m^2 - Figure 4), thus indicating the complete recovery of the benthic community.

The trend of STAR_ICMi scores during 2009 and 2010 show the short-term impact of flushing (and, as mentioned, of other hydrological events) on benthos, with a decrease from good to poor-moderate biological quality class (Figure 4). This largely depended on the significant reduction in taxonomic richness. The density and the number of families (with individuals ≥ 10) dropped in August 2009, then recovered in May 2010, dropped in July and September 2010 and then recovered in December 2010. The STAR_ICM index showed the same trend (Table 3). The lowest value was reached in September 2009 due to the Log(sel_EPTD+1) index (equal to 0 - Table 3). This metric is based on the presence in the sample of specific families of the orders of Ephemeroptera, Plecoptera or Trichoptera and, in the sampling area, it was strictly dependent on the presence of Limnephilidae, not yet recovered after the first flushing event.

In general, all the metrics dropped after the first flushing (Table 3), showing a worsening of all the structural and functional characteristics of the benthic community, but later on their trends were not correlated to this perturbation. Although Jones et al. [4] reported that EPT taxa seem to be negatively impacted by increased loads of fine sediment, whereas certain Diptera and Oligochaeta are positively impacted, the ratio between EPT and Chironomidae does not appear useful to detect the effects of flushing. It was below 1 after the first flushing (August 2009), in February and July 2010 and about 1 in December 2009, September 2010 and February 2011.

As for previous fish data, some contradictions emerge, showing that the dynamics of macroinvertebrate assemblages are not only driven by the sediment flushing but also by other elements (seasonality, increase of discharge in late spring, …), particularly in a so heavily regulated water system.

It is also difficult to determine whether the declines in benthic fauna abundance and diversity measured after the flushing events can be attributed to the hydrodynamic action [17] or to the high SSCs, since these factors may interact [18]. The findings of controlled experiments on this subject [19] are limited to maximum SSCs generally lower than those measured in this study (i.e. 600 mg/L) and suggest that flow increase alone can disturb benthic fauna. Robinson et al. [20] showed that a peak flow of 43 m^3/s and a discharge of 25 m^3/s for about 7 h with a baseline flow of about 2 m^3/s significantly reduced macroinvertebrate densities and changed the taxonomic structure of the community. In our investigation, considering the baseline flow at Section II of the order of few cubic meters per second, the magnitude and the duration of flow during sediment flushing (>70 m^3/s) and the negative effects on benthos of the high flow recorded before July 2010 (30 m^3/s), it seems reasonable to deduce that the physical disturbances of the flowing waters mainly contributed to alter benthic invertebrate communities.

In genera, the adverse ecological consequences of flushing releases can also be related to the modification of river habitats following sedimentation of the flushed material. In fact, the loss and degradation of habitats arising from fine deposition might cause negative effects on macroinvertebrates [4]. However, the deposition in the bio-monitoring site can be considered negligible as pointed out in 3.1.

Table 2. Values of different metrics used to characterized benthic community and of STAR_ICMi quality class from February 2009 to April 2011 at Section II.

	2009						**2010**					**2011**	
Index	**Feb**	**Apr**	**May**	**Aug**	**Sep**	**Dec**	**Feb**	**May**	**Jul**	**Sep**	**Dec**	**Feb**	**Apr**
Margalef	1.57	1.43	1.35	0.88	0.94	1.42	0.91	1.32	1.80	1.16	1.35	1.65	1.65
Simpson	0.26	0.22	0.27	0.64	0.42	0.31	0.42	0.39	0.47	0.29	0.20	0.25	0.39
Evenness	0.61	0.70	0.68	0.40	0.54	0.61	0.56	0.53	0.56	0.73	0.74	0.60	0.49
ASPT	5.27	5.64	5.30	5.00	4.83	5.75	5.83	4.78	5.71	6.43	5.22	5.27	4.40
Log(sel_EPTD+1)	2.78	2.78	2.79	1.43	0.00	2.20	2.40	2.54	0.48	0.60	2.44	3.04	2.65
1-GOLD	0.63	0.60	0.77	0.10	0.34	0.48	0.39	0.89	0.28	0.45	0.35	0.43	0.90
N° family	13	12	11	7	7	10	7	10	9	7	11	15	13
N° EPT	5	5	5	3	3	5	4	4	4	5	5	5	5
Shannon-Wiener	1.57	1.75	1.62	0.78	1.06	1.40	1.09	1.22	1.23	1.43	1.78	1.64	1.26
STAR_ICMi	0.85	0.88	0.86	0.53	0.38	0.78	0.76	0.77	0.53	0.62	0.78	0.88	0.78
STAR_ICMi class	high	high	high	good	moderate	high	high	high	good	good	high	high	high

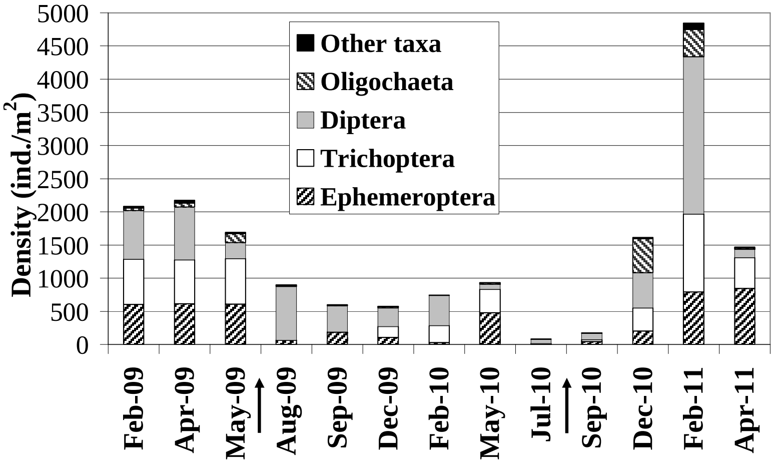

Figure 4. Trend of macroinvertebrate density (individuals per m^2) from February 2009 to April 2011 at Section II. The arrows show when the two flushing events took place.

4 CONCLUSIONS

Sediment flushing works at Sernio hydropower pondage were executed controlling the SSC of the discharged water. About 100’000 m^3 of sediment were evacuated, with daily averaged SSC of about 1 g/L and daily peaks of about 3 g/L (with few exceptions of 5-6 g/L). The operations took place during maximum seasonal runoff (late spring/early summer) with typical discharge between 70 and 100 m^3/s, while minimum flow released below the barrage is of 2 m^3/s.

About 5 km below the barrage field surveys were carried out to quantify the impact on river biota: fish community was sampled by electrofishing and macroinvertebrate sampling was performed through a quantitative multi-habitat approach. The ecological quality of the river was then assessed through the STAR_ICM index, the current official Italian method developed for WFD inter-calibration purposes.

Although a short term impact on macroinvertebrates was noticed, particularly after the 2009 event, the communities appeared to recover to near pre-release conditions after few months and a good/high STAR_ICMi river quality was generally detected. Collected fish data lead to exclude significant impacts.

The operation seems overall tolerable and the reported values could be useful to plan future sediment management in analogous contexts.

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