EFFECTS OF FINE SUSPENDED SEDIMENT RELEASES ON BENTHIC COMMUNITIES IN ARTIFICIAL FLUMES

Effets des particules fines en suspension sur les communautés benthiques dans des canaux artificiels

Maria Cristina Bruno[1*], Mauro Carolli[2], Beatrice Palmia[1,3], Guido Zolezzi[2]

[1] Sustainable Agro-ecosystems and Bioresources Department, Fondazione Edmund Mach, IASMA Research and Innovation Centre. Via E. Mach 1, San Michele all'Adige (TN), Italy
cristina.bruno@fmach.it (corresponding author)

[2] Department of Civil, Environmental and Mechanical Engineering, University of Trento. Via Mesiano, 77, Trento, Italy
mauro.carolli@unitn.it, guido.zolezzi@unitn.it

[3] Department of Bioscience, University of Parma. Parco Area delle Scienze, 11/a, Parma, Italy
beatrice.palmia@studenti.unipr.it

Abstract

The Italian Alps feed a large number of reservoirs for hydropower production, which are losing storage capacity due to natural inflow of sediment of different origin (alluvial, glacial). Local government and local environmental agencies authorize periodical sediment flushes with a mandatory release regime when such measure is technically feasible. Management of reservoirs often includes fine sediment pulses, which cause several ecological impacts on downstream water bodies. We conducted a set of simulations in five semi artificial flumes naturally fed by an unimpacted Alpine stream (Trentino region, NE Italy), to: i) identify threshold of concentration of fine suspended sediment (expressed in NTUs) inducing drift in the benthic community and, ii) assess the dynamic and intensity of the drift responses in the dominant taxa. The results can help to identify the least impacting release management practices. Sediment pulses were simulated by adding fine material of known concentration to the upstream end of the flumes. The benthic organism drifting from the whole flume were collected by filtering the whole outflow for consecutive short time intervals. We tested four different concentration, i.e. 10x,100x,250x,500x the base concentration of 4 NTU, and we repeated the simulations in two periods: July, when the community is composed mainly of young larval instars and the sediment wave lasted ten minutes, and October, when later larval stages are dominant and the wave lasted 20 minutes. In July, the maximum concentration induced a significantly higher drift response than the three lower ones. In October, even if the sediment wave was twice as long as July one, drift responses where lower, and only the responses to the highest and lowest concentrations differed significantly. In our simulation, the only possible cause for the observed increase in drift was the sediment in the suspended phase, as the deposition of sediment was negligible, and discharge did not increase, thus allowing to disentangle the effects of increasing suspended sediment from those of increasing discharge. Our results, although restricted to Alpine streams, and with a seasonal bias which needs further investigations, allowed to assess the dynamics of benthic community and taxa, rather than assessing the resulting effects on the benthic community (as it occurs with the studies based on a before-after sampling design). Our results will possibly provide indications towards the future management of sediment release in Trentino.

KEY WORDS

zoobenthos, drift, sediment flush, suspended fine sediment

RESUME

Les Alpes italiennes alimentent un grand nombre de réservoirs hydroélectriques, dont la capacité de stockage diminue dû à l'afflux naturels de sédiments d'origines diverses (alluvial, glaciaire). Lorsque cela est techniquement possible, les autorités locales et les agences environnementales locales autorisent la vidange périodique des sédiments, avec un débit imposé. La gestion des réservoirs implique souvent des courants de particules fines ayant des impacts écologiques sur les milieux aquatiques en aval. Nous avons effectué une série de simulations dans cinq canaux semi-artificiels, alimentés par une rivière Alpine non impactée (région Trentino, N-E Italie), pour : i) identifier la limite de concentration des particules fines en suspension (exprimés en UTN) provoquant une dérive de la communauté benthique et, ii) évaluer la dynamique et l'intensité de la dérive sur les taxa dominantes. Les régimes sédimentaires ont été simulés en additionnant

---

[*] Corresponding author

une concentration connue de matière à fine granulométrie en amont du canal. Les organismes benthiques dérivant dans le canal ont été collectés par filtration en aval à de courts intervalles de temps. Nous avons testés quatre concentrations différentes : 10x, 100x, 250x, 500x la concentration de base de 4 UTN, et nous avons répétés ces simulations à deux périodes : Juillet, lorsque la communauté benthique est principalement composée de jeune larves et Octobre, lorsque les derniers stades larvaires sont dominants ; en appliquant une durée de flux sédimentaire de 10 et 20 minutes, respectivement. En Juillet, la concentration maximale a entrainé une dérive significativement plus grande que les trois autres concentrations. En Octobre, même si le flux sédimentaire était deux fois plus long que celui de Juillet, la dérive des organismes benthiques était inférieur et seule les concentrations maximale et minimale différaient. Dans nos simulations, le dépôt sédimentaire et le débit sont restés négligeables, l'augmentation de la dérive benthique était due aux matières en suspension. Bien que restreints aux rivières Alpines, nos résultats permettent d'évaluer la dynamique des communautés benthiques et de leur taxa, plutôt qu'une unique évaluation sur les communautés benthiques (comme cela se retrouve sur les études basées sur un échantillonnage avant-après). Nos résultats pourraient donner des indications quant aux futures gestions des vidanges de réservoirs situés dans le Trentino, afin de limiter leur impact écologique.

MOTS-CLEFS

Mots clés: zoobenthos, dérive, canaux artificiels, régime sédimentaire

1. INTRODUCTION

The preservation of reservoir storage threatened by siltation is becoming a relevant issue given the increasing demand for hydropower [Zarfl et al., 2015]. Sediment flushing is the effective technical method to desilt small–medium-size reservoirs [Morris and Fan, 1997], even though the impacts on downstream watercourses are relevant, due to sediment flow and increased water discharge during the flush, and to riverbed alteration as a result of deposition of the flushed material during and after the flushing event [Espa et al. 2014].

In Trentino Alto Adige (NE Italy) hydropower production is a relevant income source, with 33 large dams and reservoirs, which are losing storage capacity due to natural inflow of sediment of different origin (alluvial, glacial). The largest public data available for the region refers to the sediment flush from the Pezzè di Moena dam into the Avisio River (left tributary to the Adige River) to restore the reservoir to its capacity volume of 460000 m^3. Programmed flushing have been conducted from 1982 at 1- or 2-year time intervals and with different sediment management operations. The last sediment flushing was conducted in June 2012, following more restrictive regulations to reduce as much as possible the impact of sediment on the aquatic ecosystem. The next operation was scheduled for June 2015 but, due to the scarcity of rainfall and hence of water storage in the reservoir, it was postponed of one year.

The difficulties to determine whether the declines in benthic fauna abundance and diversity measured during the flushing events can be attributed to the high concentration of suspended solids or to the increase of hydraulic force associated to flushing, or to the interaction of the two [Crosa et al., 2010] can be overcome by using experimental channels where sediment transport can be directly manipulated without altering discharge or other variables. Hence, we conducted a set of simulations in semi artificial flumes to: i) identify threshold of concentration of fine suspended sediment inducing drift in the benthic community and, ii) assess the dynamic and intensity of the drift responses in the dominant taxa. The results can help to identify the least impacting release management practices.

2. MATERIALS AND METHODS

Experiments were conducted in a set of metal flumes situated on the riparian zone of the Fersina Stream (Trentino Province, Northeastern Italy) (for details on the geographical setting and detailed description of the flumes, see Bruno at al., 2013). The experimental setting consists of five 20 m long, 30 cm wide metal flumes (bottom surface area: 6.0 m^2), each flume has an adjustable sluice gate to control discharge and is connected to a loading tank that is directly fed by water diverted from the stream. Benthic invertebrates can freely colonize the flumes by downstream drift and egg deposition. The flumes are filled to the same depth with two layers of cobbles of approximately 10 cm diameter and a deposited fine layer of silt/sand/gravel has naturally collected around the stones. The flumes were run continuously at a baseflow of 5 l s^{-1}, velocity 0.4 m s^{-1} from the beginning of April 2013 for other simulations. During simulations, the upstream entrance to the flumes was netted-off to prevent incoming drift from upstream.

We conducted two set of experiments, on July 22nd 2016, and October 10th 2016. Simulations pumping water at a known concentration of dissolved fines from two tanks into one treatment flume at the time; discharge was contemporarily reduced to compensate for the slight discharge increase. The base turbidity was measured at least twice per day in the 5 days prior to each simulation. We simulated fine sediment waves increasing the turbidity of 10x (40 NTU), 100x (400 NTU), 250x (1000 NTU), and 500x (2000 NTU) the base turbidity of 4 NTU and contemporarily adjusting the inflow through the sluice gates so to keep the discharge constant. Sediment concentrations were chosen based on published data on the Pezzè di Moena dam 1998 and 2012 flushes [APPA, 1998; 2013] when NTUs measured downstream the release point peaked at 43 and 33 times the base turbidity but reached 490 times (data available only for 2012) the turbidity recorded upstream the dam. Turbidity was measured with a Multiparametric Probe IDROMAR ver.1.49 (IL036A) at 1 second time interval. In October, we assessed the deposition of the sediment by deploying two Whitlock-Vibert type sediment traps in each flume by burying them in the flume bed flush with the sediment level, and recovering them at the end of samples 12, drying the sediment in open air, and weighting it with a precision scale. Drift samples were collected by filtering the whole volume of water leaving the flumes with 350 μm mesh drift nets. Immediately after starting the sediment wave, we started a continuous drift collection by filetring the drift for 5 consecutive 2-minutes (samples 1-5), followed by 2 consecutive 5-minute drift samples (6-7), 4 10-minute drift samples (8-11), and one 60-minute final drift sample (12), accounting for the entire drift collected for 120 minutes of the experiment. The sediment wave lasted 10 minutes in July simulation (samples 1-5), and 20 minutes in October (samples 1-7). Biological samples were filtered in the field with a 350 μm sieve and fixed in 75% ethanol. Samples were sorted in the laboratory and organisms identified to the lowest possible taxonomic level. We retained for the analysis all insect larvae and pupae, they belonged to the orders Coleoptera, Diptera, Ephemeroptera, Trichoptera, Plecoptera.

Drift rate (number of animals drifting min^{-1} m^{-2}) represents the number of benthic invertebrates from a defined benthic surface area drifting each minute. Differences in drift rate were analyzed according to General Linear Models (factorial ANOVA), significant differences between pairs of levels within each significant factor were assessed with post-hoc Tukey tests. Differences in drift composition were (log+1) transformed and analysed with PERMANOVA based on a Bray-Curtis similarity matrix for the same factors and interactions, and with pairwise comparisons within significant factors. We analyzed the single and interactive effects of the following factors: i) MONTH (to assess seasonal effects in drift), ii) TURBIDITY INCREASE (10x, 100x, 250x, 500x tha base turbidity value, to assess if drift responses differed with different increases); iii) SEDIMENT WAVE PHASE (during the wave, and after the wave, to detect the eventual presence of long-lasting effects of the sediment wave); iv) Interactions: TURBIDITY INCREASE x WAVE PHASE, MONTH X WAVE PHASE, TURBIDITY INCREASE x MONTH, TURBIDITY INCREASE x MONTH X WAVE PHASE. The level of similarity among samples was visualized by running a nMDS analysis.

3. RESULTS

The sediment retained in the traps (= depositing on the bottom of the flume) did not correlate with the maximum turbidity recorded in each flume ($R^2 = 0.1558$), and was negligible, ranging from 0.01 to 0.19 g cm^{-2}. Significant differences in mean drift rate were present for different urbidity increase, overall and between months, and during and after the simulations (Table 1). Drift differed as well for different turbidity increases for the two months, and for the two wave phases (Table 1, Figure 1). Significant pairwise comparisons for interactions are shown with an asterisks in Figure 1 (500 x between months, 500x and 250 x before and during simulations). Drift composition differed for the same factors and interactions as for the mean drift rate (Table 1).

	GLM (Factorial ANOVA)					PERMANOVA				
	SS	df	MS	F	p	SS	MS	df	Pseudo-F	P perm
Intercept	358.3	1	358.3	124.2	0.000			1		
Turbidity increase	160.3	3	53.4	18.5	0.000	37502	12501	3	11.9	0.001
Month	12.6	1	12.6	4.3	0.040	10994	10994	1	10.5	0.001
Wave phase	103.3	1	103.3	35.8	0.000	27322	27322	1	26.1	0.001
Turbidity increase x month	42.1	3	14.0	4.9	0.004	10992	3664	3	3.5	0.001
Turbidity increase x wave phase	58.1	3	19.4	6.7	0.000	12094	4031	3	3.8	0.001
Month x wave phase	2.8	1	2.8	1.0	0.330	1503	1503	1	1.4	0.200
Turbidity increase x month x wave phase	11.7	3	3.9	1.3	0.266	3082	1027	3	1.0	0.481
Error (GLM) or residuals (PERMANOVA)	231.2	80	2.9			82829	1049	79		

Table 1: Results of statistical GLM and PERMANOVA analyses for single factors and interactions. Significant p values in bold.

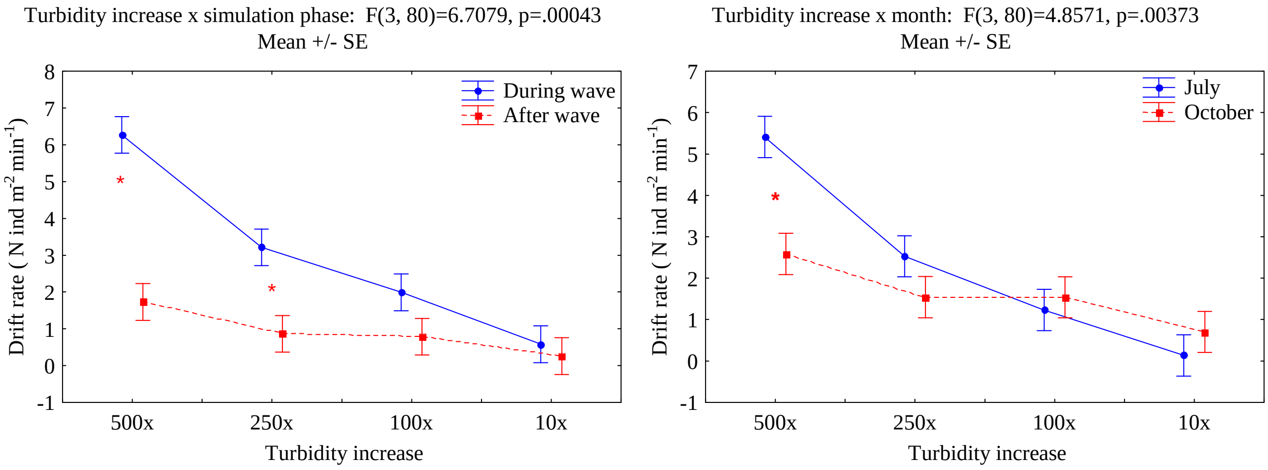

Figure 1: Mean drift rate for each turbidity increase and wave phases (left) and month (right). Significant pairwise differences between paired samples marked with asterisk.

The results of pairwise comparisons of drift rate and composition between pair of turbidity increase levels are listed in Table 2. Particulalry relevant is the comparison during the two phases of the simulation: during the wave, mean rate differed between all pairs of concentrations; after the wave drift rate was more similar and only the drift rate of the lower concentration differed from all higher ones. Species composition differed as well during the wave except in two cases (100x with 250X and 100X with 10x), and was similar after the wave. The nMDS plot (Figure 2) shows a change in composition with increasing turbidity, with the 10x drift generally more diversified than the other groups of drift.

Based on the benthic densities and the drift rate, an hypothetical total depletion time (i.e., the total time required to remove all the benthos for a given sediment concentration wave) can be estimated (Table 3), ranging from 92 to 3 hours in July for increasing sediment concentration, and 38 to 8 in October.

	GLM (pots hoc Tukey test)					PERMANOVA Pairwise				
	Overall	July	October	During wave	After wave	Overall	July	October	During wave	After wave
500x, 250X	0.001	**0.007**	0.716	0.003	0.873	0.007	0.037	0.053	0.015	0.127
500x, 100x	0.000	0.000	0.684	0.000	0.784	0.003	0.002	0.463	0.003	0.136
500x, 10x	0.000	0.000	0.065	0.000	0.295	0.001	0.001	0.001	0.001	0.001
250X, 100x	0.631	0.724	1.000	0.799	1.000	0.176	0.067	0.308	0.026	0.502
250X, 10x	0.012	0.050	0.873	0.016	0.978	0.001	0.001	0.002	0.001	0.001
100x, 10x	0.210	0.820	0.893	0.489	0.994	0.001	0.001	0.001	0.001	0.001

Table 2: GLM and PERMANOVA analyses: p-values for pairwise comparison of significant factors (see Table 1).

		500x	250x	100x	10x
Drift rate	July	59	27	14	2
	October	34	20	20	9
Number of drifting taxa	July	18	17	14	10
	October	22	20	16	17
Hours to deplete flume	July	3	7	9	92
	October	8	11	18	38

Table 3: Total drift rate and number of drifting taxa and calculated time required to remove all the benthos by drift (hours), calculated for each turbidity increase and month.

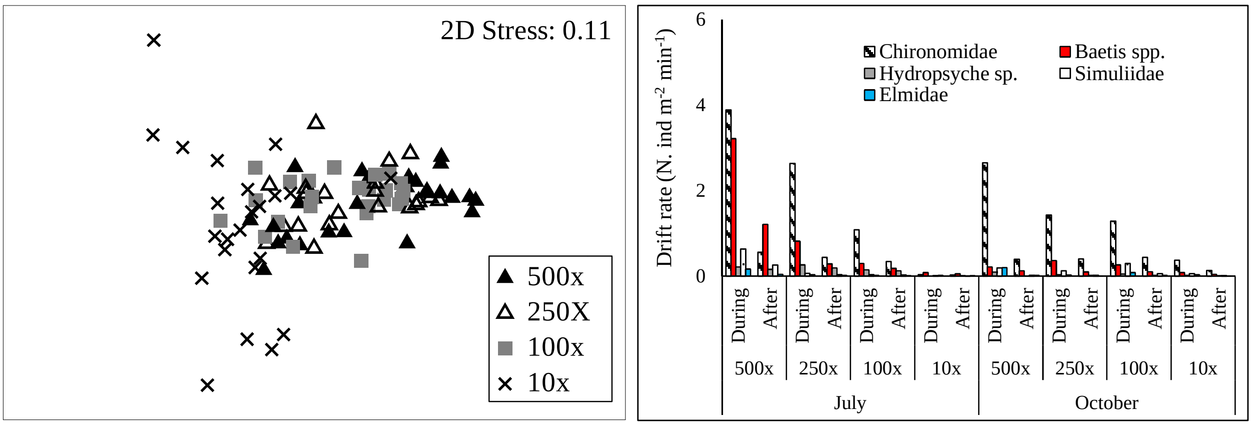

Figure 2: Left: NMDS of drift density for each sample. Data Log (x+1) transformed, Bray-Curtis Similarity matrix. Right: total drift rate for the dominant taxa, calculated for each turbidity increase and month.

The total mean drift rate always decreased immediately following the end of the sediment wave for all taxa; drift during and after the wave proportionally decreased in intensity with decreasing turbidity and was generally higher in July for all taxa except Elmidae which, overall, drifted slightly more in October (Figure 2). The responses of each taxon to the sediment waves can be measured comparing the drift rate during and after the wave (Figure 2) . Chironomidae responded to 500, 250 and 100x increases in turbidity by drifting more during the sediment wave, especially in July. *Baetis* spp. drifted much more in July, and had low resposes to the turbidity wave and to the different turbidities, except in October for 250x. *Hydropsyche* sp. had much higher drift and very low or zero responses in July, in October had a very high response only with the 500x. Simuliidae as well showed a seasonality, with slightly higer drift in July but responding more in October with intensities decreasing with decreasing concentration, whereas in July the strongest responses were with 10x.

4. DISCUSSION

In our simulation, the only possible cause for the observed increase in drift was the sediment in the suspended phase, as the deposition of sediment was negligible and discharge did not increase. The results can help disentangling the effects of increasing suspended sediment from those of increasing discharge. As reported in literature [see Jones et al., 2011, and references therein], the most immediate response to an increase in the concentration of suspended fine sediment is an increase in the number of animals entering the drift due to some accidental dislodging by moving particles, but mainly by a behavioral, active drift to avoid the negative impact of increased concentrations of suspended sediment (i.e., the transport of fine particles can disrupt the normal functioning of gills and filter-feeding apparatus, making respiration and feeding difficult). In fact, the most abundant drifting taxa are either ubiquitous, opportunistic and with high tendency to drift and high mobility (Chironomidae, Baetidae, Elmidae) or are filter feeders (Simuliidae, Hydropsychidae) and their guts fill with inert particles (Simuliidae), or their nets become clogged with fine sediments (Hydropsychidae) [Jones et al., 2011]. Drift responses were very fast; benthic losses to drift in the first 10-20 minutes of sediment flow were relevant for the higher sediment concentration, where a sustained wave of 3 (July) or 8 (October) hours would have depleted the benthic community (supposing no recolonization via incoming drift). Such relatively short-time effects (much less than one day) have been undetected in other field studies, where benthic samples were collected before, during and after the flush, but usually on larger time intervals. Therefore, our results, although restricted to Alpine streams, and with a seasonal bias which needs further investigations, can help assessing the dynamics of benthic community and taxa, rather than the resulting effects on the benthic community (as it occurs with the studies based on a BACI sampling design).

5. CONCLUSIONS

Although the exposure time in our simulation might be too short to elicit the full potential responses of the benthic invertebrates, it was indeed sufficient to stimulate drift responses in the dominant benthic taxa. The results of our simulations allowed us to identify threshold of concentration of fine suspended sediment inducing drift in the benthic community and to disentangle the effects of increasing suspended sediment from those of increasing discharge. The short-time intervals sampling showed than 10 minutes of high fine suspended sediment can cause considerable drift in the dominant benthic taxa, with the potential to cause a considerable depletion of the benthic community if extended for several hours. As in Alpine reservoirs periodic flushing of reservoirs is usually needed to control loss of effective volume and the duration of the flushing operation must be economically sustainable, it is very important to optimize sediment flushes which would guarantee ecological sustainability downstream of the dam.

ACKNOWLEDGEMENTS

The authors wish to thank the Servizio Bacini Montani, Autonomous Province of Trento, for building and maintaining the flumes; Lorenzo Forti and Martino Salvaro (Department of Environmental, Civil and Mechanical Engineering of the University of Trento) for their help in setting up and conducting the simulations, Bruno Maiolini and Sonia Endrizzi for helping in the field and in macroinvertebrate sorting and identification.

REFERENCES

APPA (Agenzia Provinciale per la Protezione dell'Ambiente della Provincia Autonoma di Trento); (1998). Monitoraggio per il controllo degli effetti sul sistema idrico delle operazioni di dissabbiamento del bacino di Pezzè Maggio 1998.

APPA (Agenzia Provinciale per la Protezione dell'Ambiente della Provincia Autonoma di Trento); (2013). Analisi dell'impatto dello svaso del bacino di Pezzé 2012

Bruno M.C., Siviglia A., Carolli M., Maiolini B.; (2013). – Multiple drift responses of benthic invertebrates to interacting hydropeaking and thermopeaking waves. Ecohydrol., 6(4): 511–522. doi:10.1002/eco.1275

Crosa G., Castelli E., Gentili G., Espa P.; (2010). – Effects of suspended sediments from reservoir flushing on fish and macroinvertebrates in an alpine stream. Aquat. Sci. 72: 85-95. DOI: 10.1007/s00027-009-0117-z

Espa P., Castelli E., Crosa G., Gentili G.; (2013). – Environmental effects of storage preservation practices: controlled flushing of fine sediment from a small hydropower reservoir. Environ. Manage. 52(1): 261-276. DOI: 10.1007/s00267-013-0090-0

Espa P., Crosa G., Gentili G., Quadroni S., and Petts G.; (2015). – Downstream Ecological Impacts of Controlled Sediment Flushing in an Alpine Valley River: A Case Study. River Res. Applic., 31(8): 931-942. doi: 10.1002/rra.2788.

Jones J.I., Murphy J.F., Collins A.L., Sear D.A., Naden P.S., Armitage P.D.; (2012). – The impact of fine sediment on macro-invertebrates. River Res. Applic., 28(8): 1055-1071. DOI: 10.1002/rra.1516

Morris G.L., Fan J.; (1997). – Reservoir Sedimentation Handbook. McGraw- Hill: New York.

Zarfl C., Lumsdon A. E., Tockner K.; (2015). – A global boom in hydropower dam construction. Aquat. Sci., 77(1): 161-170.