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EFFECTS OF COMBINED SEWER OVERFLOWS ON A PERIURBAN STREAM ECOSYSTEM : Methodological approach

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ABSTRACT

Here we develop from a long term field experiment an assessment method of interstitial fauna resilience to combined sewer overflows (CSOs) effect. We address the case of "small water courses" for which the ratio of CSOs to natural flow can be 1 to much more. Biotic material was collected in the benthic and hyporheic layers. Biotic material focussed mainly on oligocheates species whose diversity, species category and abundance are resumed into metrics, called functional traits (FTrs), giving indications on flux dynamics and nutrient bio-assimilation capacity. The biotic resilience is assessed through the analysis of the response time of the biota to CSOs and natural flow characteristics, here called hydrological indices (HIs). In this aim, a series of hydrological indices are defined to reveal varying aspects of the dynamics of CSOs and natural flows. A main result is that CSOs can have both degrading and boosting effects on the biota of a stony stream. Some CSOs characteristics can explain the physical processes supporting these contrasting effects. In particular the geomorphic characteristics of the water course. Management perspectives emerge from the CSOs hydrological indices and resilience of the biota.

Key words: (Peri)urban development, Combined Sewer Overflows (CSOs), aquatic ecosystem, resilience

1. INTRODUCTION

The total length of separated and combined sewer network in France is estimated to 250 000 km (OIE, 2006). From this length, 43% are made of combined systems where domestic and urban runoff waters are mixed together during wet weather periods. Combined systems are equipped with CSOs' devices to avoid overflows on streets or house basement during storm events with intense rainfall. Exceeding waters are often directly released to streams or ponds. Combined system was historically developed in France in large towns when separated was lately mainly used in rural areas. Giving the global trend of the urban development throughout the word, and particularly in periurban areas (UNEP, 2003), we can observe that old combined systems must carry more and more waters coming from surrounding areas. It results in an increase of the CSOs impact on receiving waters. At the same time countries of the European Union are expected to manage their water resources in the aim to reach and maintain a good ecological status (EU, Directive 2000). For highly modified water masses like in urban and periurban areas, the objective of a maximal ecological potential must be defined and reached. Concerning CSOs, it exists a range of ecological situations depending on the quality, quantity and frequency of overflows. The CSOs discharges can reach ten folds the receiving stream discharges, that result in a great ecological impact.

The ecological status in water courses (European Union 2000) is related to the water quality, the geomorphic and hydrological features integrity and the biotic quality. Any ecological impact is assumed to result from an alteration of one or some to all of these components of the aquatic ecosystem. CSOs can affect both the water quality (organic and toxic substances) and the physical

quality by eroding banks and aquatic habitats. In addition, they are also introducing pathogens in the natural biotope. CSOs water quality, quantity and frequency can vary depending on dry periods durations and human activity (holidays, seasons). In the case of streams, the flow variability can be greatly affected by CSOs, particularly when their discharges is greater than that of the stream. To assess their ecological impact it is necessary to develop a method that enables relating biotic data to their habitat flow conditions.

We consider here small watercourses that can be met around large cities which have been built along large rivers, a common case in Europe. The aim of this paper is to identify constraining flow features when addressing the question of CSOs ecological impact and mitigation in stony periurban streams. Such features can be related to the resilience capacity of the receiving system. Biotic, flow and water quality data come from an experimental reach of a seasonally stream (the Chaudanne) located in the periurban area of Lyon (France). We hypothesize that flow variability is considered as the major driving force governing water fluxes and aquatic habitats (cite references!!).

2. METHODOLOGICAL APPROACH

2.1. Biological assessment

The biological assessment is based on oligochaete assemblages collected in porous habitats (coarse surficial sediments and hyporheic system) (Lafont et al. 2006). Four sites located in a small water course were sampled fourth a year during six years. Site 1 was the reference upstream site next to the source. Site 2 was 50 metres upstream a CSO device. Sites 3 and 4 were located 50 and 500 metres downstream the same CSO device. Surficial (or benthic) sampling are referred later as S3 and S4 and Hyporheic as H3 and H4. The examination of oligochaete assemblages enabled us to distinguish between 4 biotic metrics called functional traits (FTrs). The FTr1 "permeability" is obtained by measuring the proportion (%) of oligochaete species which are indicators of active water exchanges between surface and groundwater (AED species, Lafont & Vivier 2006). The FTr2 is defined by the percentage of pollution-intolerant oligochaete species and is associated with good chemical quality of waters (Lafont et al. 2006). The FTr3 is defined by the percentage of water pollution-tolerant species. It is associated with poor chemical quality and particularly with high nitrate and ammonium salt contents. The FTr4 ("sludge effect") is defined by the percentages of species living in fine sediment and sewage bacterial-bed. It indicates the presence of polluted sludge within sediment interstices, with very high ammonium salt contents, low nitrate concentrations and the significant presence of heavy metals (copper, zinc and lead). The gradient of FTrs has been validated through a range of water courses across France (Vivier, 2007). The association FTr1 + FTr2 is recorded at sites with slight or without pollution (high water exchanges and good chemical quality). The association FTr3 + FTr4 is characteristic of ecological alterations, and the FTr4 strongly predominated in the most impaired situations. FTrs can compensate each other revealing the ecological quality moved along a gradient but this is not systematic because FTr1 is mostly a physical indicator, FTr2 a water chemical when FTr3 and FTr4 are pollution and trophic resource indicators.

2.2. Biota response time

Giving the fact that living species can integrate past habitat conditions in their behavior, correlations with instant habitat conditions from the sampling moment are not adapted. This issue was addressed developing a computer routine to calculate a series of antecedent hydrological indices(HIs) into incremented periods backwards from each sampling date. The Preceding Period Duration (PPD) is expressed in day unit. In the aim to scan a range of past aquatic habitat conditions the PPD was incremented with a duration step of 10 days till 120 days before each biotic sampling date. It resulted into 12 PPDs. It allowed us to examine the effect of each hydrological indices from 10 days before to 120 days before the date of biotic sampling. The objective was to identify what hydrological indices in the past were the most able to explain the observed ecological quality. Spearman rank correlation coefficient was calculated for each PPD. Correlations were computed using each functional trait (FTs)

as the dependant and each hydrological indices as the independent variable. It resulted in a table of 12 PPDs by 4 FTrs for each of the 4 sampling location S1, S2 , H1 and H2. Such a table was computed for each of the 13 hydrological indices (HIs).

Results were interpreted as follow : only R correlation value over 0.5 with a significance level of 2% were retained for interpretation. The maximum of correlation (when observed) should belong to a series of continuous values to avoid any fortuitous (isolated) correlation with consecutive PPDs. We retained a minimum of 3 consecutive values as a threshold. According to the mentioned conditions we used R versus PPDs plots to asses the biota response time. It was considered to correspond to the maximum R value(Fig. 1). Also the sign of each significant correlation was interpreted in terms of improvement or degradation effect of HIs on FTrs. In the case of a constant R value over several consecutive PPDs two cases were examined. A near constant R value reveals there are only slight changes in some HIs' values when the PPD increases. It happens mainly for HIs corresponding to an extreme flow characteristics that occurs only once over the PPDs. In that case we consider the shorter PPD to be the response time (Fig. 1). Constant R value was also observed for mean (or cumulative) flow characteristics. It indicates that kind of HIs have an homogeneous distribution along the PPDs. The persistence of the corresponding flow conditions can explain the persistence of the correlation value. The response time was then estimated to be the larger PPD value of the constant R sequence.
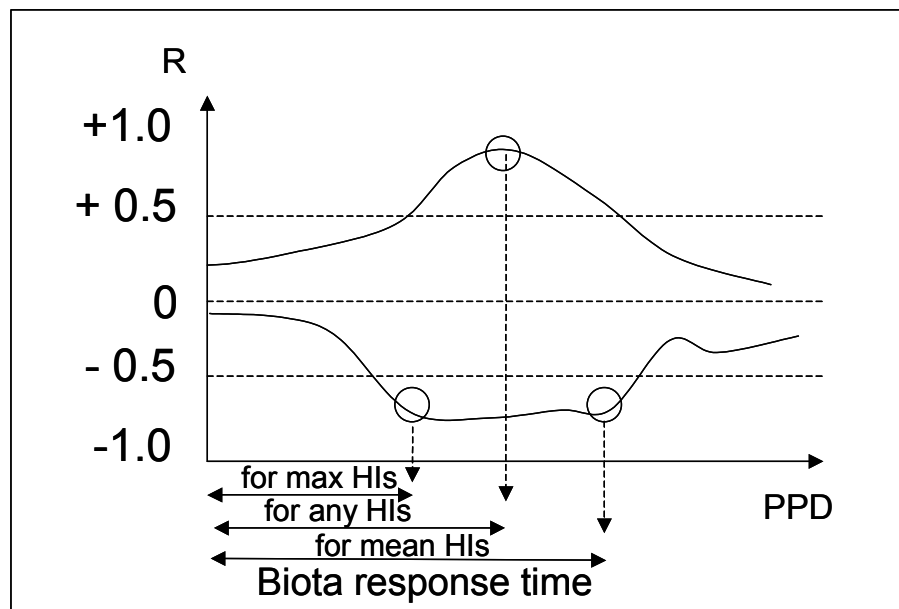

figure 1: Method to asses the biota response time to past water flux characteristics. Plot of R value versus time before date of sampling (PPD).

2.3. Hydrological indices (*HIs)*

Natural flow and CSOs time series were computed individually to generate 13 flow characteristics, each being calculated on a same PPD. They are divided into 3 categories:

- 8 HI*s* give CSOs features like magnitude, amount, number, and duration. In this set 5 HIs are dedicated to the greater (in magnitude) observed CSO peak in the PPD. They are Qmax (magnitude), Vmax (the volume of the event), Dmax (the duration), D_qmax (duration between Qmax and date of sampling) and Rmax (log ratio of Qmax to the natural mean flow). This last indicates the diluting capacity of the water course. The maximum CSO event can have both a chemical and a mechanical effect on the biota. It can also be followed by a natural flood in the water course which tends to reinforce its effect. The other 3 HIs of this category tend to resume all CSOs information. They are Vtdo (total CSOs volume), Ttdo (total duration of CSOs) and Ndo (number of CSOs).

-     4 HIs relate to periods without CSOs. They intend to express the "dry weather" effect on the ecological status evolution in the water course because CSOs result from rainfall events. Such dry periods allow the accumulation of pollutants on impervious areas and the development of biofilms in the sewer pipes. It can then can contribute to the ecological impact of CSOs that follow it. It can also support the natural improvement of the ecological status of the water course during the dry period. HIs are Ntsec (number of dry weather periods), Tsec (total dry weather duration), Tsecx (maximum duration of a continuous dry period), Tsecxx (dry weather duration just previous to Qmax),

-     1 HI corresponds to the mean natural flow of the water course. It relates also to the diluting and cleaning capacity of the water course.

Ndo and Ntsec like Ttdo and Ttsec are complementary numbers or durations for a given PPD. It means they should have same R correlation values but with converse signs.

3 RESULTS

3.1. Biotic metrics

As expected, the oligochaete assemblages exhibited an increasing alteration of the FTr associations from the upstream site 1 top site 4. FTrs moved from FTr1 + FTr2 to progressively FTr3 + FTr4 and last by the large predominance of the sole FTr4 at site 4 (Lafont et al. 2006; Vivier, 2006). But the ecological effects were surprisingly the most acute at the last site far downstream the CSO and more pronounced in the hyporheic system than in the benthic sediments. Also surprising was the biological quality of the site 3 located 50 m below the CSOs which was not significantly different from that at site 2 (50 m above the CSOs).

For example, the evolution of the FTr4, which is characteristic of heavy ecological alteration in sediments, showed that it was generally more marked in the surface coarse sediments at site 4 only when CSOs occurred during low stream discharge periods (end of June 2000, August and October 2000). But the FTr4 was constantly occurring in the hyporheic system at this site, and not at the site 3 (50 m below the CSOs). In addition, at the site 3, the FTr4 was always low in the hyporheic system and less marked during low stream discharges in surficial sediments than at site 4. As an attempt to give an explanation to those conflicting results, we considered the statistical relations between the various selected hydrological indices and the functional traits at sites 3 and 4.

3.2. Hydrological indices (HIs)

Only results for HIs selected under the conditions given in §2.2 are presented. Whether maximum correlation value are not exceeding 0.89, one can argue that trends in correlations are confirmed by (i) the continuity of R values over 0.5 and (ii) that no change along PPDs in the sign of the R correlation coefficient has been observed. This later observation confirms the non ambiguous effect of a given HI on the improvement or degradation of the ecological status. The table 1 gives a synthesis of the R values. Dark and grey cells respectively indicate a positive (+) and a negative (-) correlation sign. The ecological quality improves from FTr4 to FTr1. Hence a positive correlation with FTr1 and FTr2 indicates the corresponding HIs are factors of ecological improvement (and reverse). On the contrary, a positive correlation with FTr3 and FTr4 indicates the corresponding HI is a factor of ecological degradation. FTr2 and FTr3 correspond to a gradient of water quality. They must be interpreted respectively with FTr1 and FTr4. In accordance to remarks from §2.2, the biota response time to flow conditions has been estimated. It is indicated by a cross into cells of table 1.

PPD	HI	TRF1				HI	TRF2				HI	TRF3				HI	TRF4			
	D_qmax	S3	H3	S4	H4	D_qmax	S3	H3	S4	H4	D_qmax	S3	H3	S4	H4	D_qmax	S3	H3	S4	H4
100																				
110			X					X						X						X
120																				
	Qmax	S3	H3	S4	H4	Ndo	S3	H3	S4	H4	Qbmo	S3	H3	S4	H4	Qbmo	S3	H3	S4	H4
10																				
20		X																		
30			X																	
40								X												
50																				
60														X						
70				X															X	
80																				
90																				
100					X															
110																				
120																				
	Rmax	S3	H3	S4	H4	Qmax	S3	H3	S4	H4	Tsecx	S3	H3	S4	H4	Ndo	S3	H3	S4	H4
20				X																
30		X																		
40					X			X												
50														X						
60																				
70																				
80																				
90																				
100										X										
110																			X	
120																				
	Vmax	S3	H3	S4	H4	Rmax	S3	H3	S4	H4	Ttdo	S3	H3	S4	H4	Qmax	S3	H3	S4	H4
30																	X			
40										X										
50																				
60			X																	
70				X																
80					X															
90																				
100																				
110																				
120													X							
						Vmax	S3	H3	S4	H4	Ttsec	S3	H3	S4	H4	Vmax	S3	H3	S4	H4
40																				
50								X	X											
60										X									X	
70																				
80																				
90																				
100																				
110																				
120													X							

Table 1. Spearman coefficient sign (dark = positive; grey = negative) for the rank correlation of functional traits (FTrs) versus hydrological indices (His). Biota response time estimation (cells with a cross).

In the benthic layer S3 only the FTr1 correlates positively with Rmax and Qmax which are indicators of a maximum CSO event. The ecological quality is improving 20 to 30 days after the event. The associated process can be the renewal, mixing and aeration of the surface sandy substrate during the event.

In the benthic layer S4 the good ecological quality improvement (with FTr1) is again explained by Qmax, Rmax and Vmax. The response time is short only for Rmax (20 days) when it rates 70 days for Qmax and Vmax. FTr2 correlates also positively after 50 days, then before FTr1, with Vmax. Referring to §2.1, this indicates the ecological quality is improving with time. We can argue for the same physical cleaning process than for FTr1 at S3. The poor water chemical quality indicator FTr3 increases with Qbmo, the mean natural flow, since 60 days before the sampling date. At the same time the "polluted sludge" indicator FTr4 regresses also with Qbmo since 70 days before the sampling date. This temporal gradient of ecological and water quality improvement (from FTr4 to FTr3) probably results from the good quality water renewal in S4 during persistent natural flow conditions. Such conditions are related to important rainfalls that can generate great CSOs as the correlation with Qmax, Rmax and Vmax tends to confirm. FTr3 can also regress with Tsecx, the maximum dry sequence observed 50 days before. It globally means that ecological quality at S4 can improve in the absence of CSOs and the persistence of a natural flow.

The hyporheic layers H3 and H4 are all correlated with D_qmax. Correlation signs are negative for FTr1 and FTr2 at H3. It means that longer is the time of the dry sequence before a major CSO, larger is the degradation of the ecological quality. It can be explained by the fact that pollution accumulates on urban surfaces and develops in sewer pipes during dry sequences. Then the amount of pollution a CSO can deliver can be great. Surprisingly, the ecological quality seems to be improved at H4 because larger is the dry sequence smaller is FTr4 and larger is FTr3. In fact, site 4 is a natural deposit site and a long dry sequence seems to improve the ecological quality of this site. Thus H3 seems to be more sensitive to large pollution loads linked to large CSOs and H4 seems to be more sensitive to frequent CSOs with medium pollution load.

In the hyporheic layer H3 improvement of ecological quality is again linked to Qmax, Rmax and Vmax for FTr1 and Vmax, and Ndo for FTr2. The physical effect of maximum CSO has already been discussed. The biota response time for Ftr1 and Tr2 with Vmax again illustrates the gradient of improvement which starts at 50 days for Ftr2 and at 60 days for FTr1. The improving effect of the number of CSOs (Ndo) on H3 can be explained by the associated flow variability. This variability induces variable water head gradients in banks and substrates of the water course not far from the CSO device like for site 3. It would emphasize the exchange of water between the surface and hyporheic layers (Breil *et al.* 2007). Then the just downstream CSO receiving waters would benefit from frequent inputs of nutriments but also from an activation of the biotic metabolism in the water course substrates. For TRF3, Ttdo and Ttsec are both correlated for the same PPDs but with opposite signs. This is because these HIs are strictly complementary to the total duration of each PPD. It means the ecological quality is improved as the total duration of CSOs increases. This is in accordance with the effect of Ndo on FTr2 as exposed before. The biota response time is however longer (110 days) than for FTr2 (40 days) which can illustrate the kinetic of cleaning processes in the FTrs. FTr4 is always negatively correlated to Ndo, Qmax and Vmax for this layer. Again the ecological quality is improved when CSOs number increases and large CSOs occur. This is in conformity with other correlated FTrs in this layer.

In the hyporheic layer H4 the ecological quality is again improved by Qmax, Rmax and Vmax both for TFr1 and TFr2. It confirms site 4 requires great CSOs event to be cleaned. Also biota response time is larger than for site 3. A great CSO event is normally followed by a natural flood in the water course. The S4 layer is then cleaned or removed which can reconnect surface and hyporheic waters. This process can explain a longer time of response and improvement of the biota.

4. DISCUSSION

Mean response time of FTr1, FTr2, FTr3 and FTr4 are respectively of 57, 65, 92 and 81 days. It indicates the most reactive FTrs are FTr1 followed by FTr2 which depend mainly on flow transfer capacity (see §2.1.). Then come FTr4 and FTr3 which take on average 30 days more to be reflected by the biota. An explanation would be that biotic metabolism are slower to reduce pollution than only physical based processes that are inherent to FTr1 and FTr2. The mean response time values of S3, H3, S4 and H4 layers are respectively of 25, 73, 56 and 88 days. It indicates the effect of HIs requires longer time to be reflected by the biota living in the deeper porous media (H3, H4). Several explanations arise : it can result from the lower flow velocity in the deeper layers or from the lower kinetics of the biotic metabolism in these layers or either from the predominance of physical mechanisms, like scouring, in the surficial layers. Also the time of response increases going downstream from site 3 to site 4 when comparing the same layers. This is quite understandable as the pollution can accumulate and be removed from place to place through time. We must also consider the bottom gradient is lower at site 4 than at site 3, which facilitates deposits of pollutants from the water column an transported substrates. As all the TFrs were present in each layer excepted for S3 our result can be interpreted as follow : the resilience capacity of the studied aquatic ecosystem is governed both by physical and biological factors. Two months on average are necessary to get an improvement of the ecological quality when there is only a slight to moderated pollution level. The management of flow dynamics (and water quality) would be sufficient to recover a good ecological quality Three months are required for more impacted situations. In that case, natural metabolism should be give more time to

bio-assimilate the pollution load. It would be implemented using a storm water detention tank with adequate management rules.

In stony streams, it is now well-recognized that the dynamics of hydrologic exchanges between surface water and groundwater greatly stimulate the nutrient cycling (Jones and Mulholland, 2000; Boulton and Hancock, 2006). When the stream-bed is impervious (artificial concrete bed), the transport of pollutants prevails, but pollutants may be stored in downstream areas. In particular, pollution discharges excessive to the size of the receiving aquatic habitat induce downwellings of surface polluted water and storage of pollutants in the hyporheic layer of gravel streams (Ruysschaert and Breil, 2004; Lafont *et al.* 2006; Breil and Lafont, 2007; Breil *et al., in press*). Management practices have to account for this pollutant storage, which is a time-bomb triggered off by the occurrence of environmental conditions favourable for pollutant release (e.g., upwellings of polluted hyporheic waters up to the surficial sediments). In addition, the geomorphic context is strongly related to the dynamics of hydrologic exchanges between surface and groundwater, and geomorphic typologies become now essential tools that are integrated in management schemes (Schmitt et al. 2006, Schmitt et al. in press). The already-mentioned conflicting results between sites 3 and 4 of the Chaudanne stream cannot be explained if we do not refer to the hydrological and geomorphic contexts.

The derived management perspectives for stony periurban streams must take into account all those results. All our results tended to demonstrate that it is a simplistic view to consider that the alteration of oligochaete assemblages was only related to the presence of a polluted inflow and that the detrimental effects must be more acute nearby the pollution source. In addition, if one considers the surface sediments only, that is generally the case in current biomonitoring studies, the storage of pollution in the hyporheic layer is not overseen. The monitoring of both surface and hyporheic layers might be an indispensable first step to understand the functioning of streams (Boulton, 2000; Boulton et al. 2003), in particular to assess the pollution storage in the hyporheic layer (Lafont & Vivier, 2006; Lafont et al. 2006). This pollution storage is a deleterious "time bomb" for biodiversity, particularly because it is underestimated or even ignored (Lafont et al., in press). An example of those recommendations is given here under :

i)   preserve or rehabilitate the geomorphic type of each site, the hydrologic connectivity and the dynamics of hydrologic exchanges between surface water and groundwater,
ii) prevent pollutant storage in the hyporheic layer: no inflows in areas were downwellings of surface water predominate, either for natural (geomorphic type) or artificial causes (imperviousness of surrounding landscapes, water streaming, alteration of the hydrologic regime…);
iii) avoid excessive pollution discharges with respect to the size of the receiving aquatic habitat, a minimum stream discharge must be preserved; which depends on the local hydrologic pattern;
iv) where preserved areas exist provide hydrological connections between those areas,
v)   permit pollution inputs only if the resilience domain is preserved
vi) check every year the efficiency of remediation measures and sustainability of the resilience domain by biomonitoring tools that integrate the effects of both physical and chemical alterations, like FTrs.

5. CONCLUSION

However, the results gained from the study of the Chaudanne stream cannot be strictly extrapolated to other streams because the hydrologic and geomorphic patterns are changing from a stream to another one. On the other hand, general but operational recommendations for management schemes can be derived from the study of the Chaudanne stream (Vivier, 2006).

The dorsal bone of the management schemes is to promote that hydrologic and geomorphic backgrounds bear the same importance as chemical inflows, but that the eradication or severe limitation of polluted inflows is the first step that must be performed. After sources of pollution has been eradicated or limited, it becomes necessary to preserve the resilience of the system. A realistic

objective might be to define the "resilience domain" (Lafont et al., in press), in which assimilation processes (= nutrient cycling) are most efficient. Within this domain, the system quickly rehabilitates when the pollution load has been severely reduced. The term "quickly" implies that rehabilitation might be achieved over a reasonable time, such as one year after significant pollution reduction (Vivier, 2006).

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