Combined sewer overflows in urban areas – interpreting and comparing European CSO monitoring results

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Abstract
Since the initiation of environmental legislation, monitoring campaigns have been done to estimate the characteristic pollutant concentrations of combined sewer overflow water. Such local campaigns are expensive due to the large number of events which should ideally be followed. This study focused on whether available concentration ranges from campaigns published in the literature could be used to estimate the pollution concentration of the overflow water at other CSO locations, and to which extent catchment characteristics explain the observed differences in pollutant concentrations. For this study, a database was composed with measurement data from CSO monitoring campaigns available in the literature. In total, the characteristics of 287 CSO events from 24 catchments at 8 European countries were included. The results showed that the TSS, COD, BOD, TKN, P, Cd, Pb and Zn event mean concentrations were different between the catchments but not NH_4^+. The correlation analysis revealed that the pollutant concentrations couldn't be explained by the catchment size, impermeable area or annual rainfall, but rather by storm event characteristics and number of previous dry weather days. It is suggested that catchments could be possibly characterized in terms of those characteristics. Monitoring campaigns should further include information about variables such as the sewer system.
Keywords combined sewer overflow, correlation, monitoring, pollutants

INTRODUCTION

Since the initiation of environmental legislation in Europe in the 1970's, attention has been paid to the impact of combined sewer overflows (CSO) on the receiving water quality. The adoption of the Urban Waste Water Directive in 1991 (European Commission ,1991) and the Water Framework Directive in 2000 (European Commission, 2000) has further motivated CSO monitoring campaigns in all European countries with the aim to study the pollution discharge to the receiving waters.

The pollution of CSO water can be traced back to three sources: sanitary sewage (i.e. dry weather sewage), runoff and erosion of in-sewer sediments (Gromaire et al., 2001). The composition of sanitary sewage is described in many sources such as Tchobanoglous et al. (2004). Gobel et al. (2007) provided an in-depth analysis of the pollutant concentrations found in runoff water. Chebbo et al. (2001) among others studied the transport processes of in-sewer sediments. The composition of CSO water should then be the weighted average of pollutant concentrations from each source (Gromaire et al., 2001; Gasperi et al., 2010).

In practice, each source is influenced by a number of variables from the catchment, the sewer system, the storm and the overflow event. The measured range of CSO pollutant concentrations can therefore strongly vary between catchments and events (Kafi et al., 2008). This makes defining a characteristic (local) pollutant concentration a serious challenge. Mourad (2005) found that sometimes data from 100 events might be required to define an average pollutant concentration with an uncertainty of about 25%. In the Netherlands where the theoretical overflow frequency is set to 6 per year, this would lead to a monitoring campaign of 16 years! On the other hand, the option to use deterministic models is limited due to the incomplete knowledge about sewer transport processes and the large calibration needs of the models.

This study focused on whether pollutant concentration ranges from CSO campaigns published in the literature are representative for the pollution concentration of the overflow water at other CSO locations or local monitoring campaigns are still needed. It was further studied to which extent catchment characteristics could explain the observed differences in pollutant concentrations. Additionally, the explanation from other characteristics such as the storm event was evaluated. The database which was built in this perspective contained measurement data from CSO campaigns done at 24 European catchments. While such database didn't exist yet, it could further serve to evaluate monitoring campaigns or as a general reference for pollutant concentrations that one may expect in the overflow water.

MATERIAL AND METHODS

Origin of the data

The literature search has been performed based on a number of criteria for literature selection: the monitoring campaign occurred at a European CSO location; the measurements were taken at the CSO device or at the catchment outlet of the sewer during active CSO operation; at least data were available about the catchment location and one pollutant; the data were numerically supplied; the data were presented as Event-Mean-Concentration (EMC) of an individual CSO event or it was possible to calculate EMC from the data provided.

The literature search resulted in a selection of 15 papers. The publications together described 287 overflow events in 24 catchments divided over 8 countries: Austria (1), Denmark (6), France (3), Italy (2), the Netherlands (3), Spain (7), Belgium (1) and the UK (1). The publications included were written by de Boer (1978), de Zwart (1989), Saul and Thornton (1989), Chebbo (1992), Miljostyrelsen (1997), Rioned/Stowa/WrW (1999), Vaes et al. (2000), Ciaponi et al. (2002), Diaz-Fierros et al. (2002), Calomino et al. (2005), Dorfer (2005), Suarez and Puertas (2005), Miljstyrelsen (2006), Temprano et al. (2006), Becouze-Lareure (2010) and Gasperi et al. (2010).

Data analysis

Analysis of Variance (ANOVA) was used to compare the (average) pollutant concentration between the catchments. Only pollutants which were measured in at least 3 catchments were analysed.

The influence of the catchment, rain and overflow characteristics on the (average) pollution concentration was studied by Spearman rank correlation analysis. To maximize the number of data included in the analysis, a paired (one to one) analysis was done. This explains the different number of events and catchments of each correlation coefficient. Due to the limited number of catchments, the relationship with the catchment characteristics was only studied for pollutants measured in more than 2 catchments. Sewer system characteristics were not included in the correlation analysis due to a lack of data. The analyses were performed with Matlab (MathWorks, 2013) and SPSS (IBM Corp, 2013).

RESULTS AND DISCUSSION

The database

Table 1 presents the database with the external variables and pollutants which were monitored in at least one of the reviewed campaigns. The range and the median value as well as the number of events and catchments where the pollutant was monitored is included in the table. Calculated over all events, a wide range of pollutant concentrations could be observed. The distribution mainly corresponded to right-tailed distribution functions.

A comparison with the concentration range of wet-weather flows measured in 8 French catchments (Kafi et al., 2008) revealed that the concentrations of the 90% percentile were higher in this study while the median values could be similar, higher or lower depending on the pollutant. Comparing to the worldwide and Central-European CSO concentrations given in the database from Brombach and Fuchs (2002), the 90% percentile was higher in this study and (much) higher median concentrations were found for TSS, COD, BOD, total-P, NH_4^+ and the heavy metals Hg and Pb.

The catchment characteristics were given by the catchment size, the size of the impermeable area and the annual rainfall. A strong correlation (r = 0.95) was observed between the area and the impermeable area of the catchment. Some correlation was also seen between the catchment area and the annual rainfall (r = 0.56). It is assumed that other characteristics such as terrain roughness, land use, soil type, climatological region and the sewer system characteristics also influence the pollutant concentration. Though, the reviewed papers didn't provide complete information on those characteristics.

Comparing pollutant concentrations between the catchments

The question whether local data collection is needed to estimate the local average pollutant concentration at a CSO location depends first of all on the significance of the differences of the pollutant concentrations between the catchments. The results of the ANOVA showed that the TSS, COD, BOD, TKN, tot-P, Cd, Pb and Zn concentration was significantly different for at least one of the catchments (Table 2).

The NH_4^+ concentration did not differ between the 8 catchments where this pollutant was measured. A possible explanation could be that NH_4^+ is a dissolved component while the other pollutants are more related to solids. Moreover, NH_4^+ mainly originates from the sanitary sewage. This leaded to the hypothesis that the average contribution of sanitary

Table 1. Summary of the database

	Abbreviation	Units	10%	median	90%	Catchm.	Ev.
Catchment characteristics							
population density	D	p/ha	26,04	103,31	253,79	20	
catchment size	A	ha	10,66	121,00	1221,6	24	
impermeable area	A_i	ha	3,54	22,22	95,65	16	
annual rainfall	AR	mm	470	673	1320	11	
Sewer characteristics							
sewer length (collectors)	SwL	km	2,66	9157,00	9157,00	5	
sewer slope	SwS	%	0,03	2,00	6,60	4	
overflow frequency	CSO_f	/year	7	9	9	4	
Event characteristics							
rain depth	RS	mm	1,52	10,50	28,32	16	211
rain intensity	I_m	mm/h	0,60	1,63	8,64	10	167
	I_x	mm/h	1,40	4,65	24,00	6	106
rain duration	RD	min	74,00	402,00	1406,80	9	149
overflow volume	OV	m^3	57,89	1112,00	18297,20	20	274
overflow duration	OD	min	57,50	161,50	917,80	16	208
flow	Q_m	l/s	8,01	229,44	3417,80	16	136
	Q_x	l/s	193,78	877,00	4693,40	11	107
previous dry weather days	PDWD	day	3,00	11,00	20,00	24	287
Overflow water characteristics							
acidity	pH	/	6,24	7,04	7,34	2	6
dissolved oxygen	DO	mgO_2/l	3,44	4,56	6,20	1	5
electrical conductivity	EC		171,37	265,40	389,10	2	19
total suspended solids	TSS	mg/l	61,20	250,70	870,20	22	249
settleable solids	StS	mg/l	1,00	8,00	26,01	2	29
total dissolved solids	TDS	mg/l		169,00		1	1
chemical oxygen demand	COD	mgO_2/l	81,10	311,30	905,99	23	266
soluble chemical oxygen demand	sCOD	mgO_2/l	39,64	84,28	149,50	1	9
biochemical oxygen demand	BOD	mgO_2/l	17,00	79,77	408,60	16	166
total kjedahl nitrogen	TKN	mg/l	3,92	10,35	28,18	13	160
anorganic nitrogen	AN	mg/l	2,83	6,10	14,46	1	8
ammonium	NH4	mg/l	0,90	4,41	15,45	8	39
total phosphate	Pt	mg/l	1,02	2,30	6,90	11	157
ortho-phosphate	PO4	mg/l	0,50	0,95	1,40	1	4
chloride	Cl	mg/l	11,97	22,45	39,73	2	54
cupper	Cu	µg/l	25,40	75,00	161,00	1	29
cadmium	Cd	µg/l	0,20	1,30	80,98	3	27
lead	Pb	µg/l	3,83	91,00	361,90	6	61
zinc	Zn	µg/l	61,40	320,00	698,83	5	69
iron	Fe	µg/l	1380,00	4100,00	12892,00	1	19
chromium	Cr	µg/l	5,00	7,60	54,10	1	24
nickel	Ni	µg/l	4,10	5,00	49,00	2	26
mercury	Hg	µg/l	0,08	6,30	125,00	2	23
arsenicum	As	µg/l	3,20	6,00	16,20	1	27
calcium	Ca	mg/l	15,72	17,74	25,03	1	5
natrium	Na	mg/l	30,55	32,17	40,50	1	5
hydrocarbons	HC	mg/l	0,93	2,82	11,44	1	12
anionic detergents	AnD	mg/l	72,00	226,00	608,60	1	14*

sewage to overflow water is similar over all catchments and so would be the NH_4^+ concentration of the sanitary sewage. This hypothesis couldn't be further tested while insufficient data were available on other dissolved compounds. The result further suggested that concentration ranges from the literature would be sufficient in case of NH_4^+.

Table 2. Significance of pollutant concentration differences between catchments

	TSS	COD	BOD	TKN	NH_4^+	tot-P	Cd	Pb	Zn
p*	<0.05	<0.05	<0.05	<0.05	0.64	<0.05	<0.05	<0.05	<0.05
df*	21	22	15	12	7	10	2	5	4

*p: chance that the hypothesis `at least one of the catchments has a different pollutant concentration range' has to be rejected (α=0.05); df: degrees of freedom which is the number of catchments minus 1

Explanation of pollutant concentration ranges from catchment and other characteristics

The first three columns of Table 3 showed the rank correlation coefficients between the pollutant concentrations and the catchment characteristics size, size of the impermeable area and annual rainfall. None of the coefficients exceeded 0.50 which means that no (monotone) trend could be found between the mentioned catchment characteristics and the average pollutant concentration. Plots of the pollutant concentration in relation to the catchment characteristics confirmed the lack of trend (not shown in this paper).

The storm event characteristics and the number of PDWD showed a slightly stronger correlation with the pollutant concentrations. Correlation coefficients lower than -0.50 were observed with the rain sum and the rain duration. Positive correlations higher than 0.50 were observed with the mean and max precipitation intensity. The pollutant concentrations showed few correlation with the overflow volume and duration. Over all pollutants, the number of PDWD showed the strongest correlation with the concentrations.

Comparing the average storm event characteristics and the number of PDWD between the catchments revealed that at least one of the catchments had different climate related characteristics. This could (partly) explain the difference of pollutant concentrations between the catchments (Table 2). Other variables such as sewer system characteristics are assumed to additionally explain the pollutant concentrations. However, due to the lack of data, this couldn't be further investigated.

CONCLUSION

With the developed database and the presented analyses, an attempt has been done to gather the available measurement data and knowledge on CSO pollutant concentrations in Europe.

It was found that the average pollutant concentration of the overflow water was significantly different in at least one of the 24 catchments. However, this difference couldn't be explained by the catchment characteristics size of the (impermeable) area or annual rainfall. On the other hand, the storm event characteristics rain duration, mean and maximal precipitation intensity and the number of PDWD were found to have an influence on the pollutant concentration.

Table 3. Rank correlation between pollutants and influencing variables ((a) EV* > 200; (b) 100 < EV < 200; (c) 30 < EV < 100; (d) EV < 30); (i) CTM > 10; (j) 1 < CTM < 10; (k) = 1 CTM; fat values are significantly different from zero at α= 0,05)**

	A	A_i	AR	RS	RD	I_m	I_x	OV	OD	Q_m	Q_x	PDWD
pH								-0,14[d,j]	-0,70[d,k]	0,03[d,j]	-0,03[d,j]	
DO								-0,90[d,k]	-0,60[d,k]	-0,78[d,k]	-0,10[d,k]	
EC				-0,30[d,k]	-0,13[d,k]	-0,05[d,k]		0,35[d,j]	**0,90**[d,k]	0,45[d,k]	0,29[d,j]	-0,05[d,k]
TSS	**0,18**[a,i]	0,13[b,i]	-0,08[a,i]	**-0,35**[a,i]	**-0,54**[b,j]	**0,32**[b,j]	**0,24**[c,j]	**0,17**[a,i]	**-0,33**[b,i]	**0,23**[b,i]	**0,22**[b,i]	**0,50**[b,i]
StS				**-0,69**[d,j]	**-0,69**[d,j]	**0,55**[d,j]		**0,56**[d,j]	**-0,60**[d,k]		-0,27[d,k]	**0,60**[d,j]
COD	**0,32**[a,i]	0,08[b,i]	**0,15**[a,i]	**-0,44**[a,i]	**-0,46**[b,j]	**0,16**[b,i]	**0,39**[c,j]	**0,19**[a,i]	**-0,36**[b,i]	**0,21**[b,i]	0,06[b,i]	**0,35**[b,i]
sCOD				-0,45[d,k]				-0,38[d,k]	-0,53[d,k]	-0,17[d,k]	-0,25[d,k]	0,60[d,k]
BOD	**0,37**[b,i]	0,12[b,i]	-0,16[b,i]	**-0,43**[b,i]	**-0,60**[c,j]	**0,60**[c,j]	**0,47**[c,j]	**0,30**[b,i]	**-0,41**[b,i]	**0,33**[c,i]	-0,03[c,j]	**0,59**[c,j]
TKN	**-0,16**[b,i]	**-0,17**[b,i]	**0,34**[b,i]	-0,10[b,i]	**-0,35**[c,j]	0,17[b,j]	**0,51**[c,j]	**-0,18**[b,i]	-0,13[b,i]	-0,01[c,j]	0,05[c,j]	**0,27**[c,j]
AN				0,02[d,k]	0,55[d,k]	-0,64[d,k]		0,17[d,k]			-0,62[d,k]	-0,31[d,k]
NH_4	**0,36**[c,j]	**0,33**[c,j]	0,26[c,j]	-0,09[c,j]	**-0,58**[d,j]	-0,01[d,j]		0,27[c,j]	0,06[c,j]	**0,37**[c,j]	0,05[d,j]	0,27[d,j]
tot-P	0,05[b,i]	0,02[b,i]	0,11[b,i]	**-0,26**[b,j]	**-0,27**[c,j]	0,13[b,j]	**0,61**[c,k]	-0,14[b,i]	**-0,27**[b,j]	-0,14[c,j]	-0,12[c,j]	**0,48**[c,j]
PO_4												0,95[d,k]
Cl				**-0,38**[c,k]	-0,17[c,k]	0,09[c,k]	-0,07[c,k]	**-0,42**[c,j]	**-0,32**[c,j]	-0,57[d,k]		
Cu				0,27[c,k]	-0,27[c,k]	**0,64**[c,k]	**0,44**[c,k]	0,26[c,k]	0,00[c,k]	0,20[d,k]	0,70[d,k]	
Cd	-0,15[c,j]			-0,11[c,j]	-0,37[c,j]	**0,46**[c,j]	**0,43**[c,j]	0,13[c,j]	-0,16[c,k]			0,50[d,j]
Pb	-0,20[c,j]	**-0,26**[c,j]	-0,24[c,j]	-0,08[c,j]	-0,13[c,j]	0,04[c,j]	0,36[d,j]	0,05[c,j]	**-0,32**[c,j]	-0,21[d,j]	-0,14[d,j]	0,18[d,j]
Zn	-0,01[c,j]	-0,05[c,j]	-0,18[c,j]	-0,16[c,j]	**-0,33**[c,j]	**0,35**[c,j]	**0,57**[d,j]	0,06[c,j]	**-0,44**[c,j]	-0,13[d,j]	0,07[d,j]	**0,53**[d,j]
Fe				0,43[d,k]	0,34[d,k]	0,12[d,k]	**0,50**[d,k]	0,13[d,k]	0,03[d,k]			
Cr				-0,02[d]	-0,27[d]	**0,47**[d]	**0,48**[d]	-0,13[d]	-0,17[d]			
Ni				0,02[d,j]	-0,33[d,j]	**0,57**[d,j]	0,35[d,j]	0,03[d,k]	-0,15[d,k]			
Hg				-0,16[d,j]	**-0,47**[d,j]	0,41[d,j]	-0,07[d,j]	-0,23[d,k]	-0,41[d,k]			
As				0,10[d,k]	0,02[d,k]	-0,06[d,k]	0,37[d,k]	0,13[d,k]	0,03[d,k]			
Ca								0,50[d,k]	0,50[d,k]	0,11[d,k]	-0,05[d,k]	
Na								0,70[d,k]	0,30[d,k]	0,89[d,k]	0,82[d,k]	
PAH				-0,41[d,k]	-0,43[d,k]	0,31[d,k]		-0,36[d,k]			0,08[d,k]	0,12[d,k]
AnD				0,12[d,k]		0,09[d,k]		0,05[d,k]	0,29[d,k]	-0,43[d,k]	0,01[d,k]	-0,08[d,k]

*EV = Events; **CTM = Catchments

The significant difference of pollutant concentrations between the catchments could partly be explained by the fact that in this study the storm event characteristics and PDWD were also different between the catchments. This could be due to the small number of events which were monitored at some catchments. It is however suggested that characteristic storm event types and number of PDWD could be found for catchments in different climate regions of Europe, and so catchments could be further characterised according to such variables.

Additional explanation might come from catchment characteristics which were not included in the current database such as the characteristics of the sewer system, land use of terrain roughness. It is suggested to add information about such variables in reports on CSO monitoring campaigns in order to further study those relationships.

This study showed the importance of combining data sources from different CSO locations in order to do correlation analysis with catchment and other characteristics. The research question whether one should monitor at new CSO locations remains however difficult to answer. Including more CSO events in the database, and studying the difference in storm event and overflow types at CSO locations is recommended as future steps in this context.

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