Mobilized pollution indicators in a combined sewer system during rain events

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Abstract An intense campaign was carried out in a urban combined catchment over a 14 month period to characterize concentrations and loads of a large number of pollutants including suspended and total solids (SS, TS), COD, BOD_5, Total-N and Total-P. The urban catchment is located in Galicia (northwest of Spain), a geographical zone with an average annual rainfall over 1500 mm. The main objective of the study was to gather more in-depth knowledge of pollutant mobilization during rain events in combined sewers and the possible pressures on water receiving bodies due to combined sewer overflows (CSOs). Hydrographs and pollutographs of these substances in dry weather flows (DWF), on weekdays and weekends, and wet weather flows (WWF) during 9 rain events have been characterized. In order to meet pollutants mobilization during rain events from hydrologic-hydraulic parameters, three types of contamination prediction indicators have been developed: first-flush indicator (I_{FF}), event mean concentration indicator (I_{EMC}) and mass mobilization indicator (I_{MOVE}). These indicators can reliably predict, respectively, event maximum concentration (EMAX), event mean concentration (EMC) and event mobilized load (EML) of most important conventional pollutants during each rain event in the studied catchment.
Keywords CSO; EMC; first flush; pollution indicator, urban drainage, urban wastewater

INTRODUCTION

Combined sewer overflows (CSOs) imply a loss of efficiency in the system and a major impact on the aquatic environment owing to the discharge of all types of substances (Butler and Davies, 2011). To become more familiar with the effect of CSO pressures on receiving waters (Adams et al., 1997; Even et al., 2007), in recent decades, wet weather flow pollutant loads have been studied extensively (e.g. Chebbo and Saget, 1995; Gupta and Saul, 1996; Diaz-Fierros et al., 2002; Suarez and Puertas, 2005; Gasperi et al., 2010; Del Rio et al., 2013). Therefore, an accurate knowledge of the generation and mobilization of pollutant loads is necessary to develop management strategies to mitigate CSO impacts on the aquatic media. These strategies allow meeting the European Council Urban Wastewater Treatment Directive (EC, 1991) as well as European Water Directive Framework (EC, 2000) requirements.

A useful tool to predict the mobilized pollution in a rainfall event is the determination of simpler relationships between the hydrologic-hydraulic parameters and pollutant loads and concentrations. Thus, in the literature several works attempt to describe the behaviour of the pollutants in urban combined sewer catchments during wet weather conditions by using this kind of performance indicators (e.g. Charbeneau and Barret, 1998; Dechesne et a., 2004; Brodie, 2007).

Therefore, the main objective of this research is to develop three different pollution indicators from multivariable hydrological-hydraulic parameters: first-flush indicator (I_{FF}), event mean concentration indicator (I_{EMC}) and mass mobilization indicator (I_{MOVE}). These indicators can reliably predict, respectively, event maximum concentration (EMAX), event mean concentration (EMC) and event-mobilized loads per active or impervious area (EML) of most important conventional pollutants during each rain event in the Ensanche urban catchment (Santiago de Compostela). As the developed indicators are normalized they can be tested in other different urban catchments.

MATERIAL AND METHODS

Catchment description

The Ensanche catchment, located in Santiago de Compostela (Northwest Spain), is the major catchment area of the city's urban drainage and sewer system. It is mostly combined sewer system that collects wastewater from a population of 13,000 inhabitants. The urban catchment under study serves mainly residential and commercial areas whose characteristics include high population density and heavy traffic. The catchment area is about 23.8 ha, with an imperviousness of 94%. Furthermore, 68% of the area is built, while the rest is distributed among streets and parking zones. Green zones are practically non-existent, so that the Ensanche catchment can be described as predominantly "urban dense".

One of the main characteristics of this catchment is the steep slope of its streets, with an average of 4.2% and a maximum of 13.3%. This is an important fact to bear in mind in terms of the hydrologic-hydraulic behaviour and pollutant mobilization in rainy weather conditions, with a time of concentration of only 10-15 minutes. The average annual rainfall in the city ranges between 1600-1800 mm (Meteogalicia).

Control section

A control section was installed in the final part of the combined sewer of the Ensanche catchment between June 2008 and August 2009 (14 months). This section contains a submerged Area/Velocity Sigma 950 Open Channel flowmeter, an automatic Sigma 900 portable sampler and a communication GPRS module, which transmits measured data (level and flow) on-line. Samples were taken over six dry weather days, workdays and weekends in the autumn and summer seasons, and during nine rain events over the four seasons of the year. Precipitation data were obtained from a rain gauge installed in the study area with data recorded at 10 minute intervals. The average dry weather flow measured was 22.4 L/s.

Sampling campaign methodology

For the dry weather methodology 3-L grab samples were taken every 3 hours, with a total of eight for each day sampled, including both workdays and weekends. In rainy weather, the sampler starts through a signal provided by the flowmeter. This signal is activated immediately when the flow rises over the dry weather maximum, calculated using flowmeter data obtained from the control section operation. The sampler was programmed to take eight 3 L samples, according to the following sampling sequence: 0’, 5’, 10’, 15’, 20’, 30’, 40’, 60’. This protocol was selected based on the short time of concentration of the catchment.

In each grab sample (3 L) about 200 pollutants were analyzed including “conventional” parameters (COD, BOD_5, suspended solids,…), metals, priority substances, etc. (see more details in Del Rio, 2011). For each sampled event hydrograhps and pollutograhps were plotted and EMAX, EMC and EML were calculated for each pollutant analyzed. Table 1 shows the main characteristics of the nine rain events sampled.

Table 1. Characteristics of rain events sampled.

RAIN EVENTS	1st	2nd	3th	4th	5h	6th	7th	8th	9th
Date	10/21/08	01/12/09	04/15/09	04/25/09	05/10/09	05/23/09	06/04/09	06/25/09	08/24/09
Number of samples collected	8	8	8	8	8	8	6	6	8
PRECIPITATION DATA									
Preceding dry weather period (PDWP, days)	4.8	9.9	0.8	6.9	0.2	6.3	0.2	14.4	22.9
Rainfall duration (hh:mm)	1:30	3:00	1:20	1:00	1:00	1:30	0:20	0:50	1:30
Total precipitation (mm)	9.7	4.4	2.0	1.8	2.6	4.6	1.4	1.1	4.2
Mean intensity (mm/h)	6.5	1.5	1.5	1.8	2.6	3.1	4.2	1.3	2.8
Minutal ten maximum intensity (mm/h)	12.6	4.2	3.6	2.4	7.2	4.8	4.8	3.0	4.8
RAIN EVENT FLOWS									
Minimum (L/s)	102.1	51.0	28.9	25.2	46.5	75.0	42.6	45.9	36.1
Maximum (L/s)	446.8	133.1	132.6	107.5	91.3	169.5	204.5	106.1	125.0
Average (L/s)	183.8	98.4	58.0	64.0	65.1	135.4	105.3	69.7	81.2
Max./Average dry weather flow	19.9	5.9	5.9	4.8	4.1	7.6	9.1	4.7	5.6
VOLUME									
Total (m3)	784.3	443.8	301.0	273.4	281.8	589.6	235.7	138.7	390.7
Dry weather flow (m3)	111.2	135.4	124.9	103.9	116.8	105.8	63.3	71.6	120.4
Runoff (m3)	673.0	308.4	176.1	169.5	165.0	483.8	172.4	67.0	270.3
Runoff / Total	85.8%	69.5%	58.5%	62.0%	58.5%	82.1%	73.1%	48.3%	69.2%

Definition of indicators

At first, correlation matrices between hydrologic-hydraulic parameters and EMAX, EMC and EML of major pollutants (COD, BOD_5, total-N, total-P, TSS and TS) were developed with the sampling campaign data. These results showed that no hydrological-hydraulic parameters, individually, may be used to predict the pollutant mobilization in the catchment. Then three types of pollutant indicators have been defined from the next hydrologic-hydraulic parameters (Figure 1):

- Preceding dry weather period (PDWP) in days.
- Maximum flow registered in event period (Q_{max}) in liters per second.
- Mean flow registered in event period (Q_m) in liters per second.

• Stormwater volume in cubic meters (V_{event}).
• Time elapsed since the beginning of the event to the moment at which is reached maximum flow in the hydrograph (Δt_ff) in minutes.
• Total sampling event time period (Δt) in hours.
• Catchment concentration time (tc) in hours and the cathment active or impervious area (A_{active}) in ha.

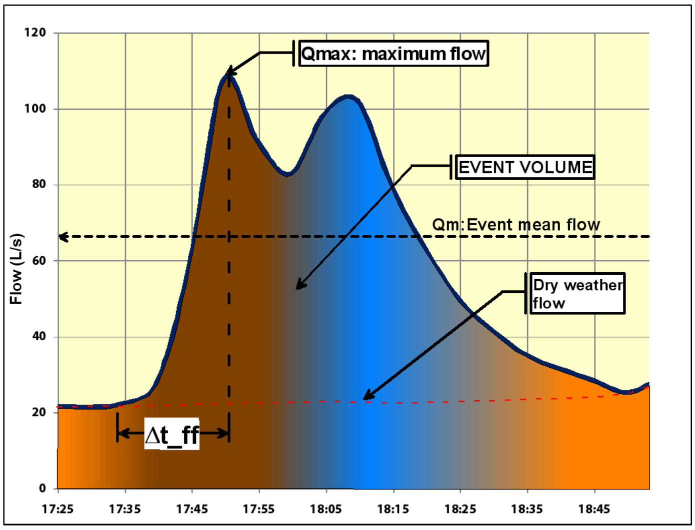

Figure 1. Event hydraulic variables considered in the indicators.

First flush Indicator (I_{FF})

This indicator is used to predict the maximum concentration of suspended solids EMAX which can be achieved during a rain event. This indicator has units of time (days) and is described as:

$$I_{FF} = PWDP \cdot \frac{(Q_{max}/Q_{mDW})}{(\Delta t_{ff}/t_c)} \qquad (days)$$

I_{FF} represents the maximum instantaneous surface and sewer wash capacity and expresses the "first flush" event potential ability. Variables are, on the one hand, the degree of pollutant accumulation in the catchment represented by the PWDP and, on the other hand, hydrologic-hydraulic variables indicative of the maximum wash energy during one event: the ratio maximum flow rate versus the average dry weather flow (Q_{mDW}) and ratio between the time to achieve the maximum flow since the start of the wet weather hydrograph and the time of concentration (t_c) of the basin. Q_{mDW} and t_c parameters were introduced into the equation with the aim to normalize the indicator, in order to be used in different catchments in future studies. The I_{FF} has units of time (days) which represents a potential "accumulation".

Event mean concentration Indicator (I_{EMC})

This indicator is used later to estimate suspended solids EMC. The equation is as follows:

$$I_{EMC} = PDWP \cdot \frac{(Q_{max}/Q_{mDW})}{\left(\frac{\Delta t_{ff}}{t_c} \cdot \frac{V_{event}}{A_{active}}\right)} \qquad (days/mm)$$

I_{EMC} arises from considering that once it has reached maximum surface and network washing capacity in the basin, it starts a decrease in the contribution of pollution source proportional to the runoff volume in the event whose final result can be correlated with the EMC of the suspended solids. This indicator has units of time per precipitation (days / mm). It has been normalized with the introduction into the equation of time of concentration (t_c) and the active surface (A_{active}) of the basin.

Mass mobilization Indicator (I_{MOVE})

This indicator allows to predict the specific mass mobilization of suspended solids during each rain event in the studied basin. The equation describing I_{MOVE} consists of two terms, one representing the potential for pollution accumulation in the basin and the other, the wash potential for such accumulated contamination throughout the rainfall event.

$$I_{MOVE} = PDWP + \left(\frac{Q_{max}}{Q_{mDW}}\right)^{\left(\Delta t - \frac{Q_{mDW}}{Qm}\right)}$$

I_{MOVE}, like the previous indicators, is normalized due to the introduction of the dry weather average daily flow (Q_{mDW}), so it can be applied to other basins and comparing the values obtained.

RESULTS

In this section we present the obtained relationship between the suspended solid concentrations and load and the developed sewer performance indicators. First of all, Figure 2 shows the relationship between the maximum SS concentrations and the First Flush Indicator I_{FF}. The linear regression fit is very good (R^2 = 0.988) if the EMAX of suspended solids obtained in the first event sampled is excluded due to limitations in the sampling procedure. In this event, the intense rainfall at the beginning caused a sharp hydrograph, with the first sample located on its rising part. During the intake period of this sample (six minutes) the flow rate increased from 75 L/s (at the sampling start of first bottle) to 400 L/s (at the end of third bottle sampling). The third bottle had, visually, lower suspended solids concentration than the first two bottles due to the sediment washing depletion. Therefore, in this event, the grouping procedure used in consecutive triplets of 1L bottles is not valid for determining the maximum concentration of SS because the obtained maximum concentrations are reduced. Probably, the SS concentration in the first two bottles was more similar to the expected values according to the I_{FF} relationship.

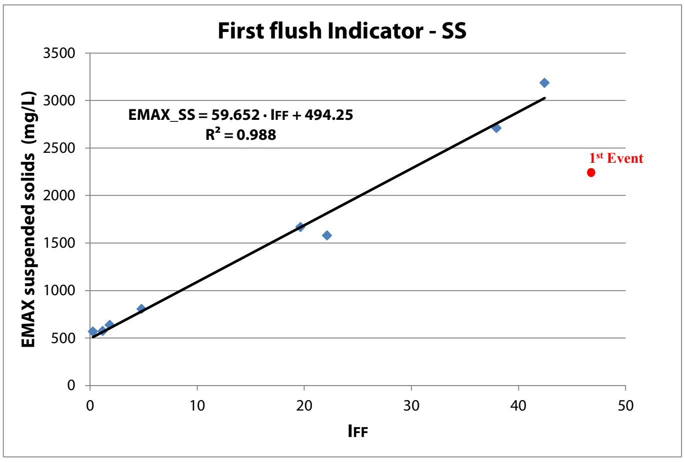

Figure 2. I_{FF} indicator versus EMAX of suspended solids.

The resulting values of the I_{EMC} versus EMC of suspended solids are plotted in Figure 3. In this indicator case, one event (second event) does not fit well to linear regression (R^2 = 0.967). This is because the sampling of this event began with delay, the initial rainfall intensity was low and hence the flow data of the initial part of the hydrograph was under the flowmeter signal to start the automatic sampler. This made impossible to characterize the initial part of this event.

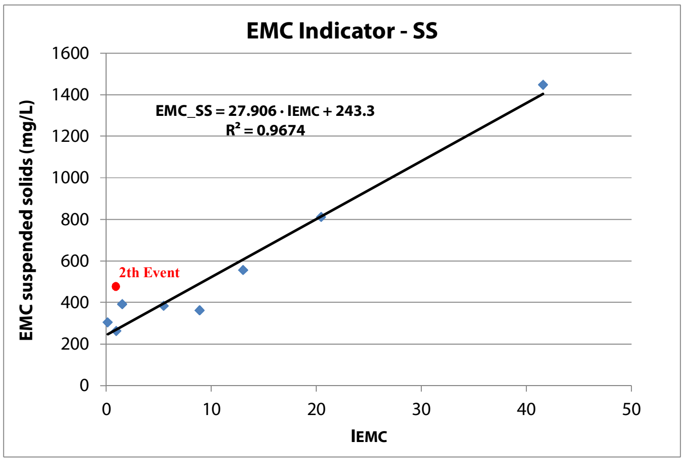

Figure 3. I_{EMC} indicator versus EMC of suspended solids.

I_{MOVE} parameter fits moderately well to a linear regression (R^2 = 0.823) with constant term equal to zero. This has real sense because without rain, wet weather mobilized loads are zero. However, there are pollutant concentrations that do exist in dry weather flows.

In spite of it is essential to emphasize that the adjustment to a logarithmic regression (R^2 = 0.944) is better than the linear (Figure 4, left). It is noteworthy that, in this type of regression, the independent term is not zero, it is negative. This indicates that there is a mass mobilization threshold value (2.6 approximately), below this value does not generate pollution mobilization in this catchment. This term is homologous to the initial depth depression storage in the hydraulic calculation of runoff volume.

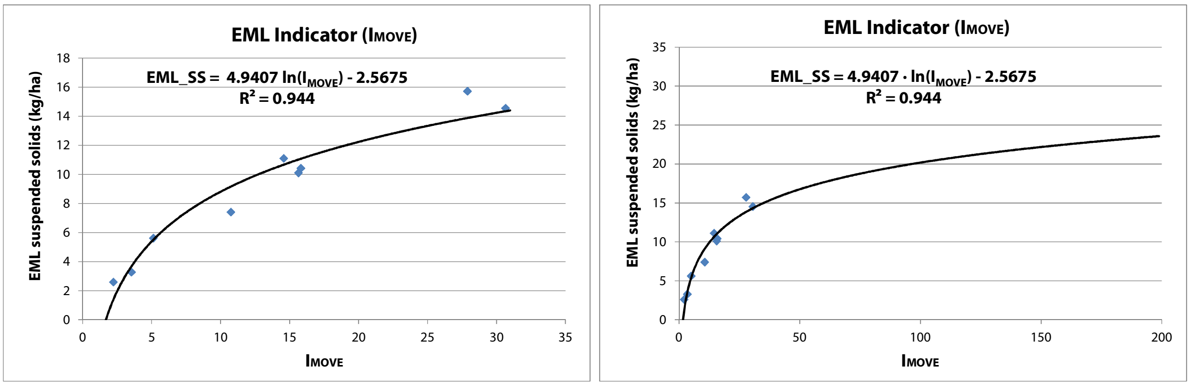

Figure 4. I_{MOVE} indicator versus EML of suspended solids.

The good result for logarithmic regresion is very significant because it seems logical that the pollution mobilization in the catchment has an asymptotic trend towards a maximum value of accumulated pollution, both on the surface and in the sewer system. This is demostrated by extrapolating the logarithmic trendline forward, i.e. increasing the preceding dry weather period and/or hydraulic parameters of the event. From the figure above (Figure 4, right), it appears that the asymptotic value for mass mobilization of suspended solids is 25 kg per active area in the studied catchment.

CONCLUSIONS

In this study three new pollutant indicators have been built from the data collected in 9 rain events in the Ensanche urban catchment. These indicators can reliably predict, respectively, event maximum concentration (EMAX), event mean concentration (EMC) and event-mobilized load (EML) of most suspended solids during wet weather flows. The results of the pollution indicators are well suited to the data collected in field campaigns and can be used to predict pollutant mass mobilization in more economical way than measuring pollutant concentrations and mobilized loads. It is very important to note that these parameters are normalized and, therefore, can be used in other urban watersheds and compare the data.

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