Sampling, testing and modeling particle size distribution in urban catch basins

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ABSTRACT

The study analyzed the particle size distribution of particulate matter (PM) retained in two catch basins located, respectively, near a parking lot and a traffic intersection with common high levels of traffic activity. Also, the treatment performance of a filter medium was evaluated by laboratory testing. The experimental treatment results and the field data were then used as inputs to a numerical model which described on a qualitative basis the hydrological response of the two catchments draining into each catch basin, respectively, and the quality of treatment provided by the filter during the measured rainfall. The results show that PM concentrations were on average around 300 mg/L (parking lot site) and 400 mg/L (road site) for the 10 rainfall-runoff events observed. PM with a particle diameter of <45 μm represented 40–50% of the total PM mass. The numerical model showed that a catch basin with a filter unit can remove 30 to 40% of the PM load depending on the storm characteristics.

Key words | catch basins, granulometry, particulate matter, stormwater, urban drainage systems

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INTRODUCTION

Particulate matter (PM) and its components, such as metals, nutrients and organic matter, generated by traffic and construction activities, accumulate on catchment surfaces during dry periods. During rainfall-runoff events, the mixture of hetero-disperse PM and pollutants is washed off urban surfaces. Catch basins are the first entry point where the mixture of PM and runoff is conveyed into a combined sewer system (CSS). The removal of PM in catch basins reduces the likelihood of PM deposition in CSSs, ultimately mitigating the pollutant discharge into receiving water bodies (Han *et al.* 2006; Sulej *et al.* 2012). The hydraulic and PM loadings of these systems are highly variable and their effectiveness depends largely upon catchment characteristics, such as land use, traffic activity, and storm-events (Li *et al.* 2012). According to Butler & Karunaratne's data (1995), in urban areas the average suspended solids concentration in stormwater is approximately 350 mg/L. Kim & Sansalone (2008) showed that on an event basis, fine PM (<75 μm) accounted for 25 to 80% of the total PM mass, and gravel-size PM (>2,000 μm) proportion ranged from 0.5 to 30%. Karlsson & Viklander (2008) showed average hetero-disperse particle size distribution (PSD) ranges from 20 to 1,000 μm, with a d_{50} of 70 μm for 10 urban catch basins.

A conventional catch basin with a sump can remove 30% of the incoming PM (measured as total suspended solids, TSS) and up to 57% of coarse solids (Barrett 2005). Howard *et al.* (2011) showed that, if properly maintained, a standard sump can be used as a pretreatment unit for stormwater. Mineart & Singh (2000) indicated that the total sediment removed by catch basins improved on an annual basis when the maintenance frequency increased from once to twice per year. An understanding of the partitioning and the distribution of PM loading across the PSD within hydrological events is essential for designing *in situ* treatment strategies (Piro *et al.* 2007). In comparison to bulk PM indices, such as TSS or suspended sediment concentration, few authors have focused on PM distribution (Li *et al.* 2005; Ying & Sansalone 2008; Kayhanian *et al.* 2012). Therefore, information about influent PM PSD is useful for defining which treatment (physical or chemical) is the most effective for removing targeted pollutants.

The first objective of this study is to evaluate the PM load associated with six PM size fractions delivered into two catch basins in different locations in a highly urbanized

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watershed for 10 hydrological events. The second objective is to experimentally test the treatment performance of a catch basin filter unit in the laboratory. The final objective is to evaluate the effective efficiency of the system, given by two components: removal efficiency of the filter medium and hydraulic efficiency (i.e. volume actually subjected to treatment). During a real event not the whole volume entering the catch basin goes through the filter medium, but a relevant part of it leaves through the overflow system. This rate varies from event to event and depends essentially on hydrological/hydraulic conditions. Such data could then be used to evaluate the treatment performance of a filter catch basin in field conditions (Rossman 2010).

METHODS

In situ monitoring of two catch basins

The area studied is located in the municipality of Cosenza, Italy. The urban watershed drains an area of 414 ha. Further studies of this urban watershed are reported in Piro *et al.* (2010, 2011, 2012) and Piro & Carbone (2014). In this study, two sampling sites are selected according to the following characteristics: (1) sufficient vehicular traffic to allow a build-up of pollutant loads; (2) safety of study personnel and road-users during sampling procedures; (3) the nature of the adjacent areas (storm drains sited downstream of the point source of solids). Catch basin A is located in a parking area characterized by low traffic activity. The contributing catchment area is 430 m^2. The nature of the traffic in the surrounding area is mainly residential, with approximately 500 vehicles/day (low traffic activity). Catch basin B is located near a heavily used road intersection, close to the downtown. The contributing catchment area is 480 m^2. The nature of the traffic in the surrounding area is mainly residential with approximately 5,500 vehicles/day (high traffic activity). The traffic intensity was determined by counting the number of vehicles every day during the period of sampling (February 2010). The number of vehicles per day was averaged over the entire month. There were no construction activities in the vicinity of either site. Samples were collected manually in 1 L bottles at the inlet of two storm drains during 10 rainfall-runoff events in February 2010 at 2 min intervals throughout the duration of the storm. The sampling began when runoff started to enter the catch basin. The samples were taken simultaneously at the two sites. Sampled events are reported in Table 1S in the Supplemental Material (available online at http://www.iwaponline.com/wst/070/409.pdf) together with the storm main characteristics, such as the total rainfall volume, duration and antecedent dry weather period (ADWP). Samples were collected every 2 minutes until the end of the rainfall-runoff event. Since the main aim of this study was to characterize PM PSD, manual sampling was used in this study to capture the entire range of particle sizes, without missing the coarser PM fraction, as may occur with the automatic sampling. The manual sampling is limited to collecting discrete samples, representative of instantaneous concentrations throughout the entire stormwater event, and hence it may neglect pollutant peaks. To reduce the effects of this limitation, in this study the sampling time interval was set rather short (2 minutes) (Harmel *et al.* 2003). In Figure 1S in the Supplemental Material (available online at http://www.iwaponline.com/wst/070/409.pdf), a schematic of the sampling procedure is reported. At the end of the storm the discrete duplicate samples were brought to the laboratory. One set of samples was used for the water quality characterization by the laboratory analyses described in the following paragraph. The other set was utilized as an input for the experimental testing on a filter unit to evaluate its treatment performance. The samples were analyzed in the laboratory for PM size fractions and the concentration of solids, expressed as TSS. A total of six particle size ranges were analyzed. First, a wet sequential sieving using three metal sieves ($d = 106$, 75 and 45 μm) was used to determine the PM size fractions for particle sizes ranging from 45 to 106 μm. A filtration procedure was used to determine the PM fraction associated with particle sizes ranging from 0.45 to 3 μm using three glass fiber filters ($d = 3$, 1.2 and 0.45 μm). The TSS was analyzed for each sample according to the 2540D protocol (APHA 2005). PM concentration was calculated for each event and an average was then computed across the 10 rainfall-runoff events.

Laboratory testing for evaluating the treatment performance of a filter media

For the laboratory testing a batch system was constructed from a 33 cm by 33 cm box, with a filter medium of 15 cm thickness supported by a geotextile layer, a polyurethane sponge with thickness of 4 cm with the scope of uniformly distributing the flow over the filtration system and absorbing oil and grease. The filter medium was made of a mixture formed by 70% of silica sand and 30% of zelbrite. The PSD of the filter material is reported in Figure 2S (Supplemental Material, available online at http://www.iwaponline.com/wst/070/409.pdf). The d_{50} of the medium is equal to about 1.5 μm. Each run was conducted by loading the unit with discrete samples taken from the field study during each event. Therefore, a total number of 20 runs was performed. Samples were collected at the outlet of the filter unit and analyzed in the laboratory for determining TSS concentration and PSD of PM by using a diffraction laser. The performance of the filter was evaluated by comparing the inlet and outlet TSS concentrations for each run.

Hydrological and water quality treatment modeling under *in situ* conditions

To predict the hydrological behaviour of the two catchments draining to catch basins A and B in the city of Cosenza, a hydrological–hydraulic model, distributed by the US Environmental Protection Agency, called Storm Water Management Model (SWMM), was used. The SWMM model is a distributed model in which a study area can be composed of a number of subcatchments to capture the effect of spatial variability in topography, drainage pathways, land cover, and soil characteristics on runoff generation (Rossman 2010). For each watershed, the parameters required for the SWMM model simulation of drainage flow hydrographs included physiographic characteristics of the catchment, physical characteristics of the sewer pipes and the hydrological/hydraulic parameters (Piro & Carbone 2014). The pollutant transport, including the phenomena of build-up and wash-off, was not modeled in SWMM. The two catch basins in SWMM were directly loaded with the influent PM concentration values, measured during the water quality monitoring campaign. However, the importance of building a SWMM model is to simulate the hydrographs entering the catch basins, using the parameters obtained in Piro & Carbone (2014) (Table 1S). Therefore, in this study the SWMM model is used on a qualitative basis, and not as a calibrated model of the actual watershed. The model also can predict the water treatment in a unit located in the urban drainage system by routing the user-defined water quality constituents through the drainage system and the attenuation of constituent concentrations through treatment in storage units (Rossman 2010).

In this study the treatment unit was represented by a catch basin equipped with the filter medium unit tested in the laboratory, and it was modeled in the SWMM as a series of hydraulic elements as shown in Figure 3S (available online at http://www.iwaponline.com/wst/070/409.pdf). In the catchment, a node was used as a divider bypassing the flows exceeding the maximum treatment unit capacity without receiving any treatment. The node divider was linked with the node draining into the catch basin, where the actual treatment occurred. The node is a hydraulic object in the SWMM, characterized by the maximum depth, specific geometry and the ponded area. The node does not have only a hydraulic function, but also a treatment functionality and therefore a user-defined function was linked to this object. The user-defined function was implemented in the SWMM to describe the treatment performance of the filter unit. The user-defined function was obtained from the laboratory data measured during the experimental testing, as described earlier.

The two treatment functions obtained for catch basin A and catch basin B were used in conjunction with SWMM modeling to analyze and compare two different scenarios: with and without treatment units. The model was then loaded with the 10 rainfall-runoff events characterized in the field study and reported in Table 1S. The field data, including PM concentrations and PSDs, and hyetographs were used as inputs to the SWMM model. The outputs of the numerical model are the runoff hydrographs entering the catch basin, the different fractions of TSS eluted from the system and the removal efficiency of the system.

RESULTS AND DISCUSSION

Characterization of PM entering the experimental catch basins

The PM fractions (measured as TSS) associated with six particle size ranges were measured for each event, and an average was computed over the 10 rainfall-runoff events observed (Table 2S, available online at http://www.iwaponline.com/wst/070/409.pdf). The PM concentrations were on average 293 mg/L and 403.5 mg/L, respectively, for catch basins A and B, and indicated to some extent the relative wear of the pavement at the two sites.

The pavement of the parking area where the catch basin is located is significantly worn, and therefore, may represent a relevant source of sediment and debris. The difference in terms of total PM load between the two catch basins may also be due to traffic conditions and structure location. While catch basin A is situated in a parking lot, the inlet of the catch basin B is placed on the sidewalk edge of a road with high traffic intensity. According to Sartor *et al.* (1974), 70% of the total PM load on street surfaces accumulates in the band within 15 cm from the curb. This supports the findings obtained in the present study that catch basin B, located at the edge of a sidewalk is loaded with higher PM mass than catch basin A, located in a parking area. Previous literature studies have shown that pollutant mass load, which builds up over impervious surfaces during dry weather conditions, is directly proportional to the area of the contributing catchment (Sartor *et al.* 1974). The observed data in this study indicate that the pollutant mass load to the catch basin increases with the contributing area. In addition, studies have demonstrated that the pollutant level in road runoff also depends strongly on the traffic density (Hvitved-Jacobsen *et al.* 2011). Therefore the higher concentration of PM in catch basin B may be due to the proportionally high traffic load. Despite the differences in PM concentrations between the two basins, their average PM concentrations are nevertheless slightly higher than the values reported in literature. In addition, the contributing area to each catch basin may have also a relevant impact on the results in terms of PM concentration. Indeed, the higher concentration of PM in catch basin B may be due to the greater area drained, equal to about 480 m^2. The contributions of impervious catchment surfaces to the catch basins are also related to the mass build-up during dry weather conditions and the mobilization of PM during rainfall-runoff events. Figures 1(a) and 1(b) show the trend of PM distribution across the six particle size ranges. PM mass was obtained by the product of the average TSS concentration and the runoff volume, which was obtained from the hydrological–hydraulic model (SWMM). For both catch basins the highest value of PM fraction (approximately around 0.5) is exhibited for the range of particles with a diameter between 3 and 45 μm. The PM mass fraction associated with a particle size greater than 106 μm and within the range of 75–106 μm, and 45–75 μm, varies from 0.1 to 0.2 for catch basin A.

PM from catch basin B is slightly coarser than that from catch basin A. The PM mass portion with a particle size greater than 106 μm and between 75–106 μm, and 45–75 μm varies from 0.18 to 0.3 for catch basin B. The PM mass fraction associated with particle sizes smaller than

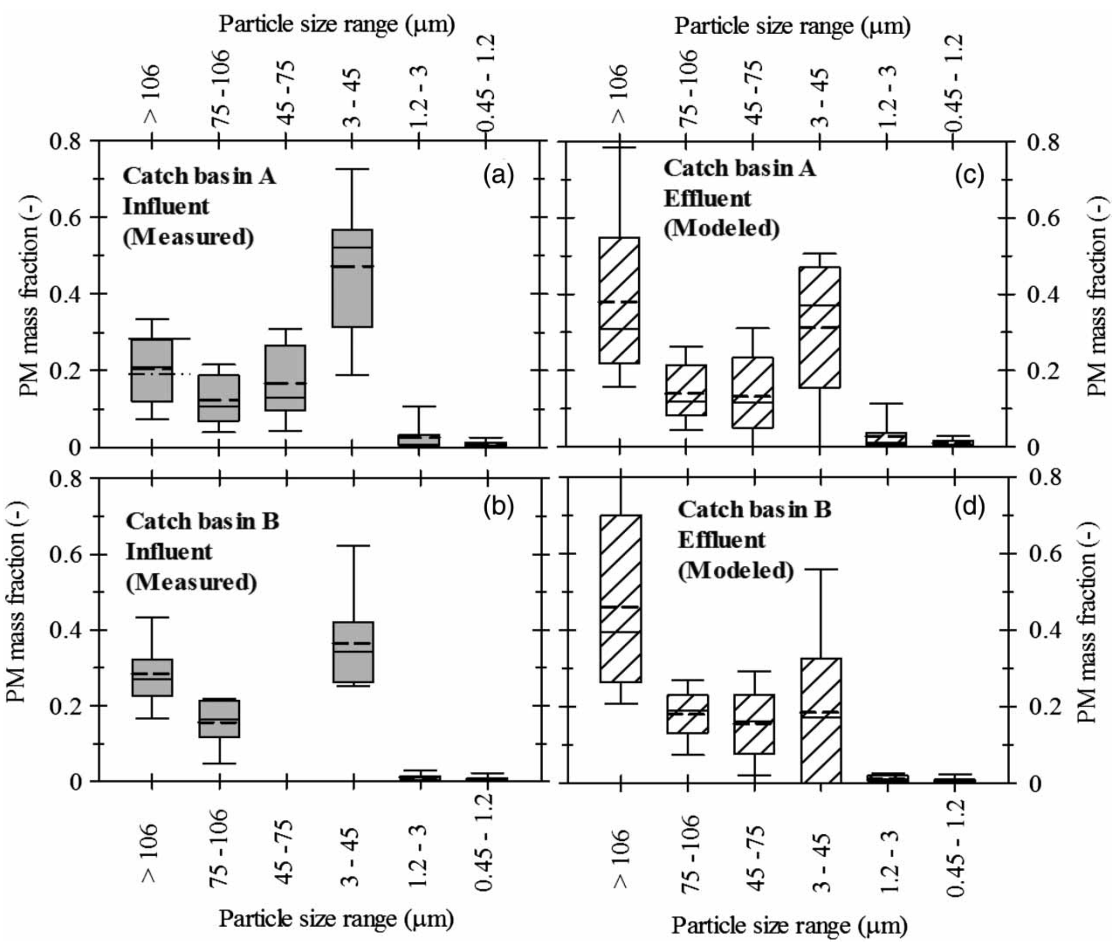

Figure 1 | Measured influent ((a), (b)) and modeled effluent ((c), (d)) PM mass fraction for six particle size ranges for catch basin A and catch basin B. For each particle size range the median value (continuous black line) and the mean value (dashed line) are reported. In addition to the median and mean values, the box plots indicate the percentiles of 5, 25, 75, 95. The statistics are based on a sample size of 10 hydrological events.

3 μm tends to approach zero for both catch basins A and B. The *p*-values reported in Table 3S (available online at http://www.iwaponline.com/wst/070/409.pdf) show that the difference in PM for all particle sizes is not statistically significant, except for the particle size >106 μm. These results demonstrate that the PM PSD is coarser for catch basin B than for catch basin A and that most of the PM is associated with particles with a diameter greater than 3 μm. The results show that 40–50% of the PM is associated with PM consisting of particle sizes ranging from 3 to 45 μm, regardless of the catch basin location. These findings indicate that most of the PM consists of suspended particles, which can be easily transported by runoff. Coarser particles are instead less likely to be mobilized by rainfall-runoff washoff and will deposit on the surfaces, even during heavy rainfall events, whereas particles with a PM of <3 μm are far more likely to be transported by runoff (Kim & Sansalone 2008). However, the fine PM percentage by mass is almost negligible with respect to total PM (Kayhanian *et al.* 2012). The *p*-values reported in Table 3S show that the difference in PM for all particle sizes is not statistically significant, except for particle size >106 μm.

Treatment performance of a filter unit in a catch basin

The influent and effluent TSS concentration results from the testing are reported in Figure 2 for each catch basin, separately. The results are fitted with linear regressions with R^2 values of 0.96 and 0.94, respectively. The regression equation represents the overall treatment performance of the filtration system for a given influent PM PSD. For the PM from catch basin A the equation is $TSS_{out} = 0.67\ TSS_{in}$; for the PM from catch basin B the equation is $TSS_{out} = 0.65\ TSS_{in}$. Those relationships indicate that the filter medium is able to remove 33% of TSS concentration when loaded with the PSD delivered to catch basin A and 35% with the PSD delivered to catch basin B. The high removal efficiency of PM is due to the porous structure of zelbrite, which is able to trap small particles by means of its large surface area (20 to 30 m^2/g).

The relationships obtained by applying a linear regression to the experimental test data from the laboratory were implemented in the SWMM model to obtain the PM mass reduction for the 10 hydrological events recorded in the field. From the tests, the removal efficiency of PM fractions by the filter unit was also assessed and implemented in the model. The results of the SWMM simulations reported in Figure 4S in the Supplemental Material (available online at http://www.iwaponline.com/wst/070/409.pdf) show that for each hydrological event recorded in the field the PM removal efficiency of the system unit was between 30 and 40%. This means that the performance of the system is dependent upon the storm characteristics. The highest PM removal efficiency was obtained for the event of 16–17 February, characterized by a small rainfall volume and a high influent TSS concentration in both catch basins. Finally the effluent PM PSD results are also reported in Figures 1(c) and 1(d). For catch basins A and B the results show that the filter unit is able to mainly trap the particles with sizes ranging

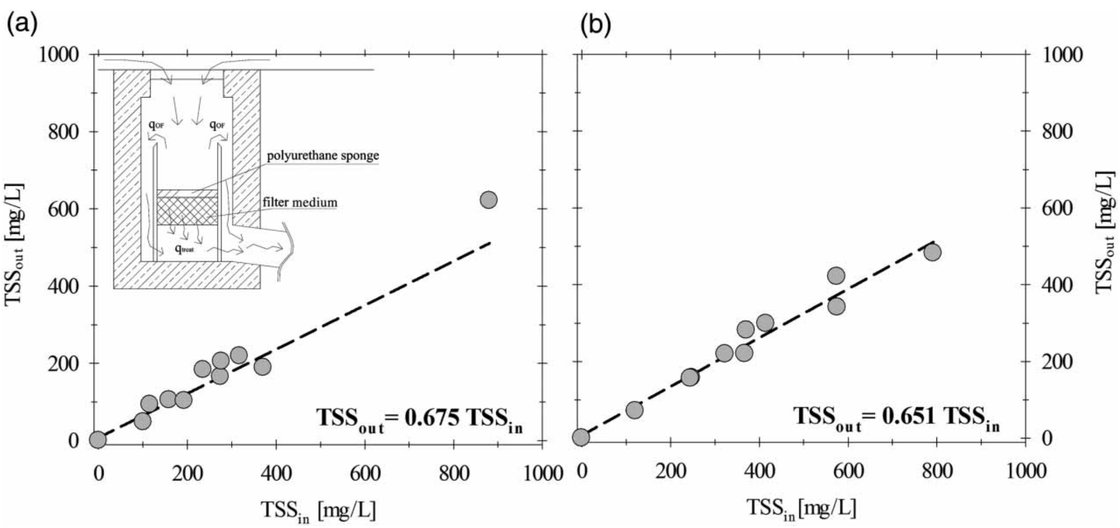

Figure 2 | Influent and effluent PM concentrations (expressed as TSS) for catch basin (a) and catch basin (b). In the inset, q_{OF} and q_{treat} represent the overflow flow rate and the treated flow rate, respectively.

from 3 to 75 μm. This may be due to the large specific surface area of zelbrite.

CONCLUSIONS

This study analyzed the PSD of PM entering two conventional catch basins in different urban traffic conditions. Results indicated that the PM mass (expressed as TSS) was around 300 mg/L for the catch basin in the parking lot and 400 mg/L for the catch basin accepting runoff from the high traffic road. Regardless of the location of the catch basin, 40–50% of PM consisted of particle sizes <45 μm. A statistically significant difference between the two sites with respect to PM load was only observed for particle sizes greater than 106 μm. The PM concentration delivered to the catch basin during rainy events is influenced by many factors, such as traffic activities, impervious surface areas and antecedent dry weather periods. This study shows that the PM concentration delivered to a catch basin increases as a function of the impervious contributing area and traffic activities. However, the results in terms of PSD showed that there is not a statistically significant difference between the two catch basins, probably due to the fact that the main sources of PM are the same throughout the entire urbanized watershed in the City of Cosenza.

Catch basins appear to separate coarse PM from stormwater with the effect of protecting the sewer systems from debris and gross solid material. This study showed that the influent PM into catch basins in a highly urbanized watershed is distributed across the six PM fractions studied. A conceptual schematic of a catch basin was incorporated into the SWMM model, used in this study on a qualitative basis and not as a calibrated model of the actual watershed, which was then run for the 10 observed events. The results showed the potential of a catch basin, equipped with filters, to capture the suspended part of PM. The removal efficiency of the TSS was ranging from 33 to 35% when the system was loaded with two different PSDs, respectively. Catch basins in urban drainage systems capture coarse PM washed off urban surfaces during rainfall-runoff events. The evaluation of influent quality of catch basins, reported in this study, strongly supports the design process and provides essential inputs for the modeling of those components. The stormwater PM results from the monitoring and modeling activities, presented in this study, should contribute to enhancing management strategies. Indeed, the evaluation of particulate-bound fractions provides relevant implications for control-strategy selection to the extent that the particulate phases may be removed through physical mechanisms such as sedimentation and filtration. Implementation of filtration not only increases removal of TSS in catch basins, it also would increase the frequency of their maintenance.

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