An investigation of wash-off controlling parameters at two urban sites in the town of Genova

Analyses des paramètres de contrôle du processus d'entraînement des particules solides en réseaux d'assainissement sur deux sites urbains dans la ville de Gênes

Berretta Christian, Gnecco Ilaria, Lanza Luca G, La Barbera Paolo
Department of Environmental Engineering - University of Genova
Via Montallegro 1, 16145 Genova, Italy
berretta@diam.unige.it

RESUME
La relation entre les paramètres de la fonction d'entraînement des particules solides et les variables hydrologiques de contrôle sont étudiées dans ce papier en présupposant que le processus de génération de polluants ne dépend que des caractéristiques de la réponse hydrologique du bassin. Les données de deux campagnes de mesure pour caractériser la charge polluante résultante d'une zone résidentielle et d'une installation de recyclage automobile sont utilisées dans cette optique. Il est proposé un critère pour classifier les événements pluvieux comme le type de processus de transport du matériel solide basé sur un facteur de contrôle constitué du maximum flux hydraulique moyen calculé dans un intervalle de temps pair au temps de concentration du bassin.

ABSTRACT
The relationship between the parameters of the wash-off function and the controlling hydrologic variables are investigated in this paper assuming that the pollutant generation process basically depends on the watershed rainfall-runoff response characteristics. Data collected during two monitoring campaigns carried out by the Department of Environmental Engineering of Genova (Italy) within a residential area and an auto dismantler site are used to this aim. The observed runoff events are classified into different mass delivery processes and the occurrence of the first flush phenomenon is also investigated. The maximum flow discharge over the time of concentration of the drainage network is proposed as the controlling factor for the total mass of pollutant that is made available for wash-off during each runoff event.

KEYWORDS
First flush, pollution, storm water, urban hydrology.
1 INTRODUCTION

The production of pollutants in storm runoff is the consequence the accumulation of mass of a number of constituents during dry weather periods (the build-up phase) and the eventual detachment and transport of such constituents operated by storm water during rain events (the wash-off phase). The build-up phase is generally supposed to be linear or exponentially asymptotic with time (Huber and Dickinson, 1988). The Antecedent Dry Weather Period (ADWP) is a key variable in these approaches together with other parameters such as the accumulation rate in time and the dispersion coefficient, which are a function of urbanization, land use, and climate (Sartor et al., 1974; Alley and Smith, 1981; Bujon and Herremans, 1990).

During a storm event, the accumulated particles on impervious areas (street, kerbs, roofs) are washed off. Many variables are involved in this phenomenon: rainfall intensity, rain depth and duration, runoff peak and volume, topography, particles characteristics (Bertrand-Krajewski et al., 1993). Particles are washed off by rain drop impacts, thus the relevance of the rain intensity, and transported into the sewer system by the overland flow (Young and Wersma, 1973; Deletic et al., 1997).

Due to the complexity of the involved processes, the available numerical models are scarcely able to correctly reproduce the pollutant load associated with storm water runoff. A better understanding of the pollution generation mechanism requires that a reliable set of experimental data is collected about each individual process occurring at the surface of paved areas (Ashley et al., 1999). However, monitoring campaigns are usually characterized by measurements carried out at the watershed outlet, thus being representative of the combined effects of both the accumulation and transport of pollutants.

Considering the difficulties to single out each separate process the present paper aims at investigating the relationship between the hydrologic characteristics of rain events and the associated production of pollutants in storm runoff through reliable data measured at the outlet section of selected drainage areas. In the present work we assume that the pollutant generation process basically depends on the watershed rainfall-runoff response characteristics, rather than simply on the availability of constituents at the surface as a result of various accumulation processes occurring during dry weather periods.

1.1 Experimental sites and equipment

Since January 2002 the Department of Environmental Engineering of the University of Genoa has installed two pilot sites for sampling runoff quality parameters at an urban residential area and an auto recycler/dismantler facility.

Each monitoring station is basically equipped with an automatic sampler (24 PVC bottles with 0.5 l capacity for the residential area, 12 glass bottles with 0.95 l capacity for the production site) for water quality aspects and with a system for continuous flow monitoring designed according to the specific site characteristics. Both experimental sites are also equipped with a tipping bucket rain gauge (20 gr. bucket capacity).

The first experimental catchment is located in Villa Cambiaso, at the Faculty of Engineering of Genoa. The monitored site is an asphalt paved parking lot with an extension of about 1000 m². The sampling station is located just upstream the inflow into the municipal stormwater drainage system.

The second pilot site was installed within an auto recycler and dismantler facility located in Chiavari, in the vicinity of the town of Genova. The study area is about 4500 m² and consists of an external area, totally paved, used for the storage of scrap
vehicles and various metallic matters. The sampling station is installed inside the initial sedimentation chamber of a first flush tank. Stormwater drained into the tank is conveyed into a rectangular channel whose terminal section is equipped with a triangular weir.

1.2 Data and results
The following data are collected in both sampling stations: one minute rainfall and runoff data obtained from continuous measurements and runoff water samples automatically collected at five minutes intervals. The chemical-physical parameters investigated are Total Suspended Solids (TSS), Chemical Oxygen Demand (COD), ammonium nitrogen (NH$_4^+$), pH and heavy metals in dissolved form (Zn, Pb, Cu, Cd, Cr, Ni). Only for the production site, the total and linear aliphatic Hydrocarbons are also investigated (HC$_{tot}$). At the Villa Cambiaso site 12 rain events were monitored during the period 2002-2003, while 11 rain events were monitored at the auto dismantler facility in the period from February to December 2004.

In order to compare the overall runoff quality associated with each rainfall event, the Event Mean Concentration (EMC – flow-weighted average of constituent concentration) was evaluated. The EMC values for each parameter are shown in Table 1 where they are compared with the quality standards for direct outflows into the receiving water bodies (Annex 5 - Italian Decree by Law 152/2006 according to the EC Dir. 91/271).

<table>
<thead>
<tr>
<th></th>
<th>Residential site</th>
<th>Auto dismantler site</th>
<th>D.L.152/06</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSS (mg/l)</td>
<td>15</td>
<td>140</td>
<td>894</td>
</tr>
<tr>
<td>COD (mg/l)</td>
<td>11</td>
<td>281</td>
<td>1074</td>
</tr>
<tr>
<td>HC$_{tot}$ (mg/l)</td>
<td>n.a.*</td>
<td>n.a</td>
<td>5.3</td>
</tr>
<tr>
<td>Cu (µg/l)</td>
<td>0.1</td>
<td>53.3</td>
<td>7.2</td>
</tr>
<tr>
<td>Pb (µg/l)</td>
<td>6.1</td>
<td>23.3</td>
<td>1.9</td>
</tr>
<tr>
<td>Zn (µg/l)</td>
<td>27.7</td>
<td>123.4</td>
<td>76.1</td>
</tr>
<tr>
<td>Cr (µg/l)</td>
<td>-</td>
<td>-</td>
<td>0.8</td>
</tr>
<tr>
<td>Ni (µg/l)</td>
<td>-</td>
<td>-</td>
<td>7.7</td>
</tr>
<tr>
<td>Cd (µg/l)</td>
<td>-</td>
<td>-</td>
<td>0.4</td>
</tr>
</tbody>
</table>

* not available

Table 1 Observed Event Mean Concentration at the monitored sites compared with water quality standards for discharges directly entering the receiving water body (Italian D.L. 152/2006 according to the EC Dir. 91/271).

As regard the residential site, among heavy metals, Cu, Zn and Pb show significant concentrations, being indeed considered as the typical pollutants connected to vehicular traffic (Ball et al., 2000). Such values are representative of residential areas and low traffic sites according to the American and European studies reported in the literature (Barrett et al., 1995; Gromaire-Mertz et al., 1999). However, the EMC values for heavy metals are noticeably lower than those observed at the production site.

In order to investigate the delivery of mass, the wash-off process has been analysed using the dimensionless M(V) representation (reporting the cumulative fraction of total pollutant mass M vs. the cumulative fraction of total runoff volume V). In order to provide a quantitative measure of the first flush phenomenon, a first flush index FF$_{index}$...
has been evaluated as the ratio between the areas subtended by the M(V) curve and by the bisector; the first flush occurs when \( FF_{index} \) is greater than 1 (0 ≤ \( FF_{index} \) ≤ 2).

The elaboration of experimental data shows the occurrence of the first flush for TSS at both sites. At the auto dismantler facility the occurrence of the phenomenon was observed in 80% of the monitored events, while it was present in 70% of the rain events monitored at the residential area. The M(V) curves of COD do not show any significant first flush at the production site, while the phenomenon can be observed at the site of Villa Cambiaso. No clear behaviour emerges from the M(V) curves of Cu, Zn and Pb at both sites.

2 WASH-OFF PROCESS ANALYSIS

Data collected during the monitoring campaign result from the combined effects of the build-up and wash-off processes, thus focusing on one single process is not allowed based on such information. Also, no correlation emerges from the available data between ADWP and the EMC values of the mass of TSS (Gnecco et al., 2005b). Furthermore at the production site, the build-up process is strongly influenced by various factors related to the specific land use (such as the storage of various metallic materials), thus contributing to make full understanding of the build-up process quite difficult.

In a previous study (Sansalone and Cristina, 2004) quality-quantity data collected from two small-size impervious watersheds constituted by highway sections were analysed to examine the first flush behaviour for suspended and dissolved solids. The observed events were classified into mass-limited high runoff volume events and flow-limited low runoff volume events, based on the measured mean flow per unit width of drainage area. Mass-limited events were characterized by high runoff volumes and disproportionately high delivery of mass in the early event, on the contrary flow-limited events were characterized by low runoff volumes and a more proportionate mass delivery with respect to the runoff hydrograph across the event (Sansalone et al., 1998; Cristina and Sansalone, 2003).

Following this approach, therefore assuming that the mass delivery behaviour is strongly related to the rainfall-runoff characteristics, the events monitored at both the residential and production site were examined and classified into mass-limited and flow-limited events. The first class is characterized by an exponential relationship between delivered mass and runoff volume while a linear relationship is typical of the second class of runoff events.

In this study it was observed that the most suitable parameter to discriminate between the different classes of mass transport is the maximum value of the average flow-rate \( Q \) calculated over a time window corresponding to the time of concentration \( t_c \) of the specific drainage system, hereinafter indicated as \( Q_{max(t_c)} \). This parameter is representative of the rainfall-runoff response characteristics of the specific watershed. Indeed, given the sites monitored in the present study, and in particular for the auto dismantler facility, it is evident that the specific land use has a strong influence on the hydrologic response and thus on the mass delivery behaviour. Also the adopted classification criterion, which is closely related to rain intensity, is consistent with previous results (Gnecco et al., 2005a) where a good correlation between the maximum rainfall intensity and the EMC of TSS was observed.

In Tables 2-3 the monitored rainfall events characterized by a mass limited behaviour are summarized in terms of the relevant hydrologic parameters, the total mass of suspended solids and the calculated first flush index.
As for the auto-dismantler site, after evaluating the eleven monitored rainfall events, five were classified as mass-limited processes, three as flow-limited ones and the remaining events were excluded from the investigation because of different reasons such as the limited number of samples available to describe runoff quality and the lack of sufficient rainfall data. The threshold value of the maximum flow-rate over the time of concentration, $Q_{\text{max}}(t_c = 15 \text{ min})$, was assumed equal to 2 l/s.

As for the residential site six events were classified as mass-limited process while two resulted rather flow-limited ones. The classification was based on the maximum value of the average flow-rate calculated over the time of concentration, $Q(t_c = 10 \text{ min})$, with a threshold equal to 0.5 l/s. As for mass-limited events an exception is the event of March 6th showing the lowest values of both the total runoff volume and the mass of suspended solids. Note that $Q_{\text{max}}(t_c)$ is close to the threshold value in this case.

At both monitoring sites mass-limited events generally exhibit a more pronounced first flush phenomenon. At the residential site this behaviour emerges quite clearly, probably due to the characteristics of the site whose main pollutants source is constituted by vehicular traffic: mass-limited events show a mean FFindex value equal to 1.3, while flow-limited events are close to 1 according to the quite linear M-V pattern. On the contrary, at the production site the occurrence of first flush is

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**Table 2** Hydrologic characteristics, total mass of suspended solids and FFindex for mass-limited events at the auto dismantler site.

<table>
<thead>
<tr>
<th>Event Date</th>
<th>Rainfall Depth (mm)</th>
<th>Mean Intensity (mm/h)</th>
<th>$i_{\text{max}}$ at 5' (mm/h)</th>
<th>ADWP (d)</th>
<th>Runoff Depth (mm)</th>
<th>Mean Flow Rate (l/s)</th>
<th>$Q_{\text{max}}(t_c)$ (l/s)</th>
<th>TSS Mass (kg)</th>
<th>FFindex</th>
</tr>
</thead>
<tbody>
<tr>
<td>05/08/04</td>
<td>7.2</td>
<td>5.4</td>
<td>19.2</td>
<td>29.3</td>
<td>1.9</td>
<td>2.90</td>
<td>4.75</td>
<td>3.572</td>
<td>1.27</td>
</tr>
<tr>
<td>16/09/04</td>
<td>12.2</td>
<td>14.6</td>
<td>72.0</td>
<td>1.3</td>
<td>1.3</td>
<td>4.47</td>
<td>8.75</td>
<td>2.756</td>
<td>1.15</td>
</tr>
<tr>
<td>14/10/04</td>
<td>7.8</td>
<td>5.9</td>
<td>16.8</td>
<td>3.4</td>
<td>1.4</td>
<td>1.90</td>
<td>3.72</td>
<td>1.619</td>
<td>1.6</td>
</tr>
<tr>
<td>18/10/04</td>
<td>3.0</td>
<td>1.8</td>
<td>9.6</td>
<td>3.9</td>
<td>1.0</td>
<td>0.66</td>
<td>2.48</td>
<td>1.573</td>
<td>1.34</td>
</tr>
<tr>
<td>25/12/04</td>
<td>10.8</td>
<td>5.6</td>
<td>36.0</td>
<td>8.8</td>
<td>1.0</td>
<td>0.74</td>
<td>2.13</td>
<td>1.167</td>
<td>1.23</td>
</tr>
</tbody>
</table>

**Table 3** Hydrologic characteristics, total mass of suspended solids and FFindex for mass-limited events at the residential site.

<table>
<thead>
<tr>
<th>Event Date</th>
<th>Rainfall Depth (mm)</th>
<th>Mean Intensity (mm/h)</th>
<th>$i_{\text{max}}$ at 5' (mm/h)</th>
<th>ADWP (d)</th>
<th>Runoff Depth (mm)</th>
<th>Mean Q (l/s)</th>
<th>$Q_{\text{max}}(t_c)$ (l/s)</th>
<th>TSS Mass (kg)</th>
<th>FFindex</th>
</tr>
</thead>
<tbody>
<tr>
<td>06/03/02</td>
<td>3.6</td>
<td>4.3</td>
<td>14.4</td>
<td>18</td>
<td>0.7</td>
<td>0.29</td>
<td>0.57</td>
<td>0.079</td>
<td>1.27</td>
</tr>
<tr>
<td>14/03/02</td>
<td>6.2</td>
<td>8.1</td>
<td>16.8</td>
<td>7</td>
<td>2.1</td>
<td>0.70</td>
<td>1.94</td>
<td>0.208</td>
<td>1.13</td>
</tr>
<tr>
<td>17/10/02</td>
<td>4.6</td>
<td>11.0</td>
<td>16.8</td>
<td>5</td>
<td>1.7</td>
<td>0.44</td>
<td>1.74</td>
<td>0.294</td>
<td>1.27</td>
</tr>
<tr>
<td>01/03/03</td>
<td>11.4</td>
<td>5.3</td>
<td>24.0</td>
<td>29</td>
<td>2.8</td>
<td>1.29</td>
<td>2.78</td>
<td>0.665</td>
<td>1.23</td>
</tr>
<tr>
<td>24/07/03</td>
<td>14.6</td>
<td>28.3</td>
<td>72.0</td>
<td>19</td>
<td>6.0</td>
<td>3.33</td>
<td>7.41</td>
<td>2.034</td>
<td>1.35</td>
</tr>
<tr>
<td>28/09/03</td>
<td>8.8</td>
<td>6.2</td>
<td>19.2</td>
<td>3</td>
<td>1.4</td>
<td>0.40</td>
<td>1.02</td>
<td>0.136</td>
<td>1.44</td>
</tr>
</tbody>
</table>

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associated with less significant differences between mass and flow-limited events, whose FF\textsubscript{inaw} values are generally greater than one. The rainfall-runoff response and the pollutant load are strongly dependent on the total amount and the type of stored material respectively.

To deeper understand the delivery behaviour for suspended particles at both monitoring sites the equation describing mass-limited wash-off processes have been analysed. The mass-limited events can be described with an exponential law in terms of mass delivery as a function of the runoff volume:

\[
\Delta M_t = M_0 (1 - e^{-k_1 t})
\]

where \(\Delta M_t\) is the cumulative mass delivery, \(V_t\) the cumulative runoff volume, \(k_1\) the first order wash-off coefficient and \(M_0\) the mass limiting parameter. In the present study it is assumed that \(M_0\) actually accounts for the maximum mass available for detachment and transport by runoff during each specific rainfall event. This parameter does not represent the total mass of pollutant accumulated on the surface with time during the antecedent dry weather period as employed in traditional studies. Indeed the observed correlation between \(M_0\) and the ADWP is very scarce (see below). The \(M_0\) parameter therefore depends on the specific rainfall characteristics and is the actual limiting factor of the wash-off process for this class of events.

The exponential parameters \(M_0\) and \(k_1\) were calculated for all mass-limited events at both sites.

In order to investigate the correlation between the mass-limited events and the hydrologic characteristics a simple regression analysis was carried out for the following hydrologic parameters: average and maximum rainfall intensity, total rain depth, total runoff depth, mean runoff flow rate, maximum value of the average flow-rate over the time of concentration and antecedent dry weather period. The results of the elaboration are reported in Figures 1 and 2 for both experimental sites.

The \(M_0\) coefficient provided good correlation with the runoff flow rate (\(Q_{\text{mean}}\) and \(Q_{\text{max}}(t_c)\)) at both the residential and productive site. On the contrary, good correlation with rainfall characteristics in terms of maximum intensity only emerges for the residential site of Villa Cambiaso. This different observed behaviour can be related to the influence of land use on the rainfall-runoff response: at the auto-dismantler facility the hydrological response strongly depends on the specific conditions of the watershed (e.g. amount of stored material) thus masking the influence of the rainfall characteristics.

As for the \(k_1\) coefficient, results seem to be less homogenous between the two sites, even if a good correlation emerges with runoff characteristics in terms of mean and maximum flow rate and runoff depth. From data collected at the production site a good correlation with the mean rainfall intensity was observed.

From the findings of the elaboration it emerges that the pollution generation process seems to be controlled by rainfall-runoff response parameters. However the assumptions adopted in this study need to be validated against a wider data set in terms of both the number of monitored events and the type of sites with different land-use/activities.

In spite of the limited data set available, starting from an empirical approach based on the monitored data it seems promising to investigate further under a hydrological perspective the correlation observed at both experimental sites.
CONCLUSIONS
Data from two monitoring campaigns were analysed in order to investigate their suitability to fit the two main classes of flow-limited and mass-limited wash-off processes that were recently proposed in the literature. A first attempt was made to correlate parameters deriving from the mathematical description of the second class of processes with suitable hydrologic variables. It was found that the value of the average maximum flow discharge calculated over the time of concentration of the drainage basin, which is a measure of the hydrological response of the system,
provides good correlation at least with $M_0$, the total mass of pollutant that is made available for wash-off at the paved surface of each site. Weaker correlation was observed between the first-order wash-off coefficient $k_1$ and the investigated hydrological parameters, with a different behaviour between the two monitoring sites. Despite the preliminary promising results, the data set available to the present study was limited in various aspects. Due to the limitation in time of the monitoring campaign the class of monitored events in terms of their hydrological characteristics was confined at quite short duration events -- the range of runoff responses is therefore far from being comprehensive. Finally, the experimental sites were limited in number, only covering two different types of land use. The above considerations stimulated the need for improved monitoring capabilities within the urban environment, with special interest on production sites of various characteristics.

LIST OF REFERENCES


Gnecco, I., Berretta, C., Lanza, L.G. and La Barbera, P. (2005b) Quality of stormwater runoff from paved surfaces of two production sites. 10th Int. Conf. On Urban Drainage, Copenhagen, Denmark (published on CD-rom).


