Sediment transport in sewers

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Abstract

Solid transport in combined sewers is characterized by a succession of two phenomena: erosion of sediment from the pipe bottom and deposition of solid matter transported by the flow during the sequential phases of a storm wave.

The alternation of these phenomena in a combined sewer network causes the deposition of sand and organic material during the time between two successive storm waves.

Dry weather flow generally cannot activate near-bed solids transport, so that the sediment remains in sewer trunks until the first storm flow occurs.

After long periods of permanence at the sewer pipe bottom, especially during summer, organic material can undergo a process of decomposition. In this case, wet weather flow created by the first storm event often causes erosion and transport of solid material in a decomposed state to the receiving aquatic systems, with the risk of anoxia.

This phenomenon is being analysed in two different hydrographic basins in Rome, with on-site monitoring of two combined sewer networks, whose dry weather flow and first storm flow, according to designed dilution ratios, is conveyed to the Roma Nord wastewater treatment plant and whose combined sewer overflow (CSO) spills are received by the river Aniene, one of the main tributaries of the river Tevere.

This experimental activity is aimed at both locating, characterizing and quantifying sediment deposits in such sewer networks, and defining a sediment transport model to predict the position of sewer trunks with high probability of deposit and to estimate mean values of sediment volume.
Keywords: combined sewerage, sewer sediments, transport model, water quality.

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1 Introduction

The increasing sensitivity towards problems in the solid transport phenomenon at international level, has given rise to: the development of experimental studies aiming to define self-cleaning design criteria for different types of sewer pipes; the definition of predictive models to localise and quantify sediment deposit in sewer networks, aiming to support the management of the whole system.

However, the analysis of solid transport in sewers is still characterised by a significant uncertainty related to the high number of variables on which the phenomenon depends; the location and type of sewerage, the nature of solid material, the granulometric composition, the presence of cohesion, the size, shape, material and slope of sewer pipes, are but few variables indispensable for a detailed description of the system.

The movement of solid material in sewer trunks is the result of different forms of transport by flow, all contributing to a global solid flow. The different types of solid transport can be simplified into the following three phases (Crabtree et al [1], Gent et al [2]):

- suspended transport of middle and small-sized particles, generally at the same rate or slightly slower than the flow rate;
- a dissolved phase transport of very small particles, at the same rate as the flow rate and completely diluted in flow;
- bed and near bed transport, characterised by middle and large-sized particles, which move under the effect of higher flow conditions.

Although it is possible to classify such phenomenon as shown, varying the instantaneous flow conditions (i.e. altering the energetic content), a single solid particle can pass from one type of transport to another. The great range of sizes and materials of common particles, as well as the high flow variability over time, are all elements that contribute to making the real boundaries between different phases even less definable.

Recent studies, aimed to adapt classical solid transport models for natural channels to sewer systems, have highlighted the significant dissimilarity between the two cases. Such difference makes the classical transport models of the first half of the twentieth century practically inadequate to approach the analysis of solid transport in sewerage.

The main differences between the two cases include characteristics such as:

- composition, size and nature of transported materials; in particular, the presence of cohesion strongly influences the resistance of solid deposit to abrasion;
- flow characteristics, which can change rapidly especially in combined sewer pipes;
- shape and size of pipe sections; large rectangular river sections can be considerably different from sewer sections, which are often small and circular or egg-shaped;
- action on flow by macro roughness of sewer beds.

Experimental results have also shown how the granulometry of sediments in sewer beds highly influences the amount of eroded and re-suspended material under fixed flow rates. The presence of granular matter in beds composed of fine solid material, for example, can increase erosion thanks to the abrasive action of sand in motion, by reducing the cohesion created by clay particles (Tait et al [3]).

The great variability of such factors is the main cause of a remarkable uncertainty in qualitative and quantitative solid transport analysis. A proper description of this phenomenon requires a complex model and an appropriate calibration of its input data, based on experimental studies and a high number of on-site measurements. Solid transport problems in natural basin drains are here analysed thanks to a simplified simulation method which represents a valid compromise between a realistic description of transport phenomena and quick data processing. Such an approach is based on the relation between transport capacity by different flow rates and quantity of solid material conveyed by storm water into sewer pipes from the whole basin surface.

The model here illustrated has been calibrated for the sewer system of Cesarina catchment, a large basin located east of the centre of Rome, on the right side of the river Aniene (2015 ha).

2 The model

The solid material heterogeneity, as well as the high variability of hydrodynamic flow conditions during a storm wave, implied the need for a simplified model founded on the separation between hydrodynamic simulation of the sewer network and analysis of solid transport development.

Starting from such a hypothesis, all calculations are based on the following consequential steps:

- characterisation of hydrodynamic conditions into sewer pipes during storm waves (U.S. EPA [4]);
- evaluation of the amount of solid material accumulated on the basin surface (Alley and Smith [5]);
- evaluation of flow transport capacity for each storm event (Verbanck [6, 7]);
- estimation of deposited solid material according to a balance between entering solid material and transport capacity in each sewer trunk (Silvagni et al [8]).

This balance, continuatively developed over time and space, is aimed to quantify solid transport during different phases of a storm wave, as well as deposits on pipe bottoms.

2.1 Hydraulic modelling of the sewer network

The flow capacity to re-suspend particles deposited on the pipe bottom, and to transport them within the water solution, is strictly related to the flow shear stress on the pipe walls and to the mean flow velocity in each pipe section.

Therefore, to simulate the alternation of erosion and deposit phenomena, it is fundamental to know how hydrodynamic characteristics of flow vary in the sewer network over time and space. For the examined sample basin, the hydrodynamic SWMM engine [4] has been used with the Horton infiltration model to solve the complete De Saint Venant equation under the hypothesis of mono-dimensional flow conditions.

The analysed sewer network is mainly composed of egg-shaped pipes (3.0x3.75 m and 4.50x5.04 are the sizes of the final segments) with an inferior semi-circular cunette, while the final trunk's section is box-shaped, 3.80x4.90 m, with a trapezoidal-shaped bottom. This last segment, 300 m long, ends with a Combined Sewer Overflow (CSO) chamber which is connected downstream to the Roma Nord wastewater treatment plant. Calibration is based on field data collected in the terminal section of the main egg-shaped pipe, where a level gauge and an automatic water sampler have been installed. First results show a substantial agreement between computed and registered data (fig. 1 and 2).

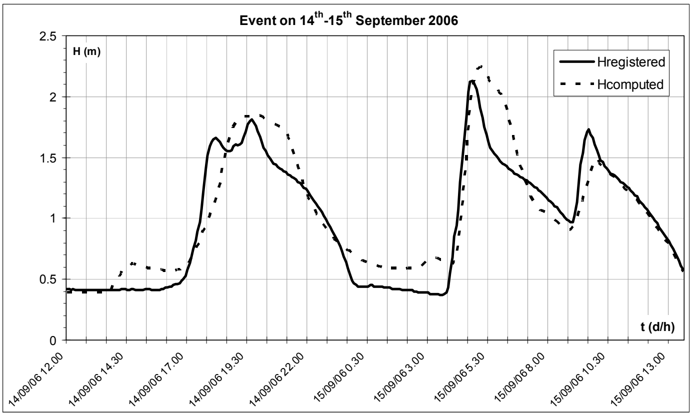

Figure 1: Event on 14th-15th September, 2006 – hydraulic model's calibration.

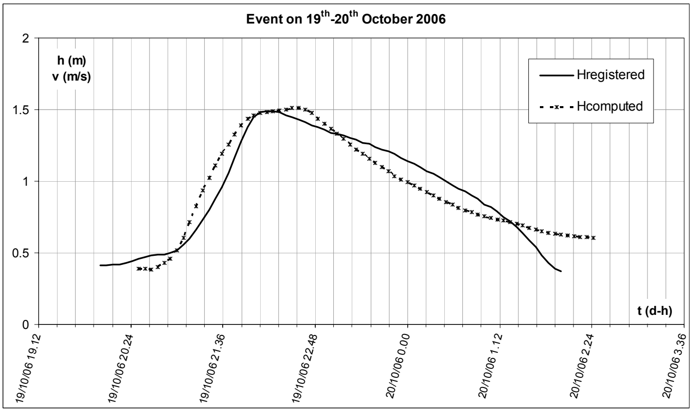

Figure 2: Event on 19th-20th October, 2006 - hydraulic model's calibration.

2.2 Superficial solid storage and transport capacity

The main sources of solid material transported by combined sewer flow during a storm event are both particles deposited on the basin surface during a dry period, and re-suspended particles deposited on sewer beds during the decreasing phase of the previous storm wave, scarcely eroded by dry weather flow.

Referring to experimental studies conducted by Alley and Smith [5], storage of solid material on the basin surface was evaluated with the following expression:

$$M_{acc} = M_{acc,lim}\left(1 - e^{-\frac{Disp \cdot \Delta t_s}{24}}\right) + M_r e^{-\frac{Disp \cdot \Delta t_s}{24}} \qquad \text{(kg)}. \qquad (1)$$

where: *Accu*, accumulation rate of solid material which depends on basin urbanisation (kg/ha/d); *Disp*, dispersion coefficient given by 0.08 d^{-1}; *S*, basin surface (ha); *Peim*, percentage of impermeable area; M_r, residual mass on the basin surface at the end of the last storm event (kg).

The experimental activity on the road drains conducted in the land of Comune di Roma during the 1999 – 2002 biennium (Silvagni [10, 11]), as well as the first experimental results of field study in the sewer system, allowed the definition of characteristic accumulation rates for the analysed network.

Table 1: *Accu* and *Peim* values.

Basin	Peim	Accu (kg/ha/d)
Cesarina stream	15%	6
Cinquina stream	40%	6
Urban	65%	10

The catchment, with a global surface of 2015 ha, is composed of two large non-urbanised areas (Cesarina basin, 1200 ha; Cinquina basin, 640 ha) and of a densely populated urban area (175 ha).

Under the hypothesis of isolated and sufficiently intense storm events, it is assumed that solid material deposited on the basin surface is completely washed away, and eroded material reaches the sewer trunks with the modulating action of road drains. Such a global mass of conveyed material equals the following limit:

$$M_{acc,lim} = \frac{Accu}{Disp} Peim \cdot S \qquad \text{(kg)}. \qquad (2)$$

Under this hypothesis, the concentration in flow of solid material washed away from the basin surface and introduced in the sewer system during a storm event equals:

$$C_s = \frac{M_{acc,lim}}{V_{ev}} \qquad (\text{kg/m}^3). \qquad (3)$$

where V_{ev} is water volume globally introduced into the sewer through road drains of an examined segment during the storm event (m^3).

A sensitivity analysis of characteristic variables, conducted on a wide range of experimental studies, allowed the selection of the Verbanck [6, 7] formulation for solid transport capacity, deduced for sewer pipe shapes and sizes comparable to the ones in the Cesarina network.

The concentration of suspended solids transported by flow (C_v), under the hypothesis of non-cohesive material, can be evaluated with the following expression, using sedimentation velocity w_s (m/s), hydraulic radius R (m), gravitational acceleration g (m/s^2), relative density of sediments in water Δ, and tangential velocity on the bed of sediments $u_{*,b}$ (m/s):

$$C_v = \frac{1}{5.16}\frac{u_{*,b}^3}{g\Delta w_s R} \qquad \text{(adm).} \qquad (4)$$

$$u_{*,b} = \frac{u_m}{\frac{1}{k}\ln\left(\frac{12H}{\varepsilon_{tot}}\right)} \qquad \text{(m/s).} \qquad (5)$$

where H is the depth of flow (m); u_m the mean flow velocity (m/s); k the Von Karmann constant, 0.40; ε_{tot} the global pipe roughness (mm).

2.3 Balance

For a certain storm event, the hydrodynamic simulation allows the calculation, for each segment, of the flow rate $Q(t)$, the depth of flow $H(t)$ and the mean flow velocity $V(t)$; in particular, the model takes into consideration the hydraulic conditions at the terminal section of each segment, considered more representative of solid transport capacity.

Solid material accumulated on the basin during the dry interval between two significant storm events and solid transport capacity by flow, are calculated with relations (2) and (4), under the simplifying hypothesis of non-cohesive material and immediate system response in terms of erosion and deposit. It is also assumed that solid flow entering one of the initial segments of the sewer network equals, at every time step, the expression:

$$Q_{s,ing}(t) = C_s \cdot Q(t) \qquad \text{(kg/s).} \qquad (6)$$

where C_s corresponds to solid material concentration of flow accessing the segment and it is considered constant during the same storm event, eqn. (3). When a sewer trunk downstream of the initial segments is analysed, solid flow conveyed from the upstream network is added to the solid rate coming from the road drains belonging to the said trunk.

The instantaneous balance of solid mass present in each sewer trunk was so computed, by calculating the amount of solid material deposited in each trunk, at the i time step, as:

$$M_{dep}(i) = M_{t=0} + \sum_{j=0}^{i}\left[Q_{s,ing}(j) - Q_{s,usc}(j)\right]\cdot \Delta t \qquad \text{(kg).} \qquad (7)$$

where $M_{t=0}$ is the solid mass present on the pipe bottom before a storm event occurs (kg) and $Q_{s,usc}(j)$ is the solid flow (kg/s) pouring out of the analysed segment, transported downstream. The latter equals flow transport capacity, eqn. (4), when there is storage of deposited material to erode, otherwise it is lower.

This function can be expressed as:

$$Q_{s,usc}(i)=\begin{cases} Cap_s(i) \ \ when \ \ M_{t=0}+\sum_{j=0}^{i}\left[Q_{s,ing}(j)-Q_{s,usc}(j)\right]\cdot\Delta t+Q_{s,ing}(i)\cdot\Delta t > Cap_s(i)\cdot\Delta t \\ \dfrac{M_{t=0}+\sum_{j=0}^{i}\left[Q_{s,ing}(j)-Q_{s,usc}(j)\right]\cdot\Delta t+Q_{s,ing}(i)\cdot\Delta t}{\Delta t} \ \ otherwise \end{cases} \quad (8)$$

where $Cap_s(i)$ is the solid rate that can be transported by flow, given by:

$$Cap_s(i)=C_v(i)Q(i)\cdot\rho_s \qquad \text{(kg/s)}. \quad (9)$$

with ρ_s specific weight of solid material (kg/m^3).

Therefore, for each examined sewer segment it is possible to draw, over the duration of considered storm events, the patterns of the following functions:

- water flow $Q(t)$, depth of flow $H(t)$ and mean flow velocity $V(t)$;
- global solid transport capacity $Cap_s(t)$;
- entering solid flow $Q_{s,ing}(t)$ and solid flow conveyed downstream $Q_{s,usc}(t)$;
- instantaneous amount of deposited solid material along the whole analysed segment.

3 Initial results

Surveys conducted in the terminal trunk of the Cesarina sewer (box-shaped section 3.80x4.90 m) highlighted the presence of temporary deposits of solid material during dry periods between sequential storm events, whose maximum depth reached the sidewalk level (about 0.80 m).

The deposit is mainly made of non-cohesive sand, which is normally re-suspended and conveyed downstream by significant storm waves. The effect of foul flow on deposits of solid material has not been taken into account in this study.

The model is rapidly self-calibrated: in particular, under the initial hypothesis of sewer pipes completely free of deposits, after simulating the effect of the second storm event on the system, the M_{dep} output values become compatible with measured ones.

The relatively high CSO weir, which allows the storage of a large first storm water volume, as well as water pouring back into the CSO chamber from the river Aniene during major flood events, are causes of flow velocity decrease and a sudden reduction of solid transport capacity during both peak and minimum flow.

Under the hypothesis discussed above, considering for solid material the specific weight ρ_s= 1500 kg/m^3 and a sedimentation velocity w_s = 0.006 m/s, the following graphs show model's results for the terminal sewer trunk of Cesarina system, during the storm events on 14th-15th September 2006 (fig. 3), 19th October 2006 (fig. 4), 1st and 12th November 2006 (fig. 5 and 6).

In particular, simulated values for the amount of deposited material M_{dep}, whose patterns over time (t) are here shown, substantially match experimental data.

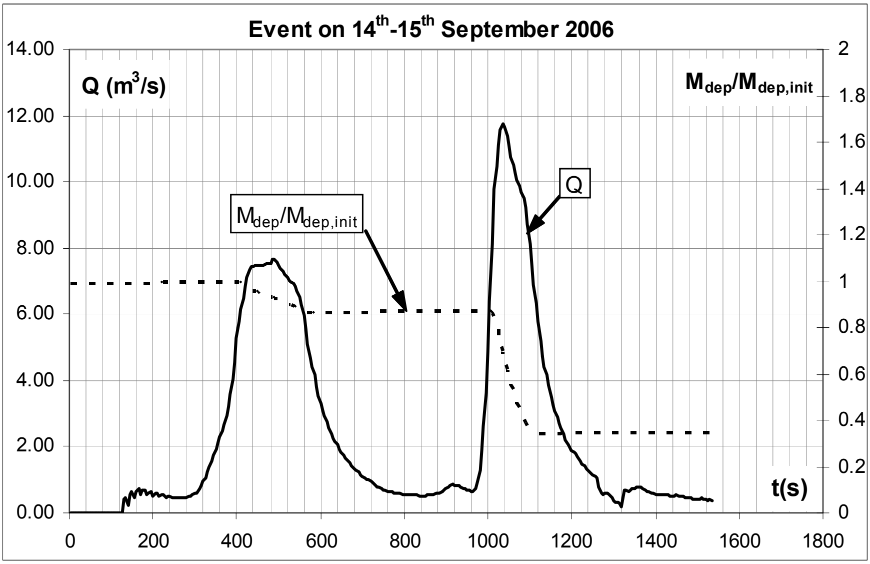

Figure 3: Event on 14th-15th September 2006 – Q(t) and $M_{dep}/M_{dep,init}(t)$ pattern.

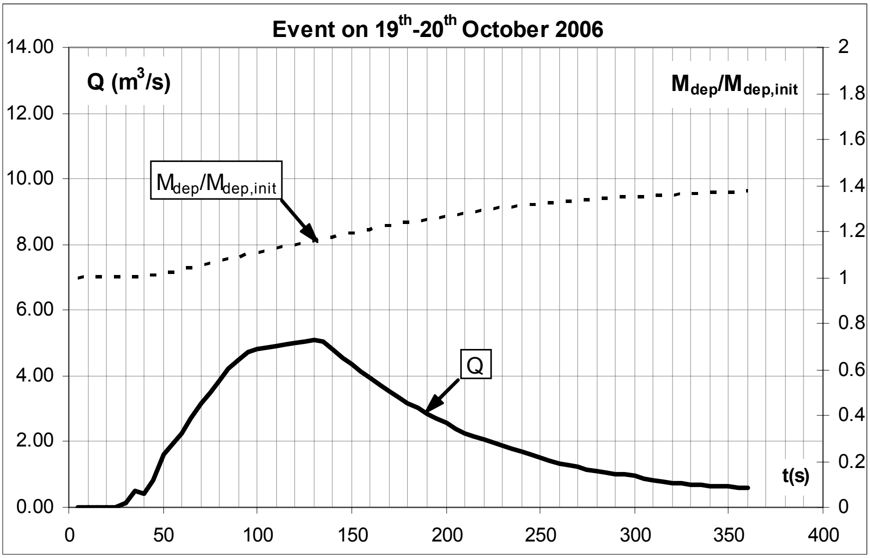

Figure 4: Event on 19th-20th October 2006 – Q(t) and $M_{dep}/M_{dep,init}(t)$ pattern.

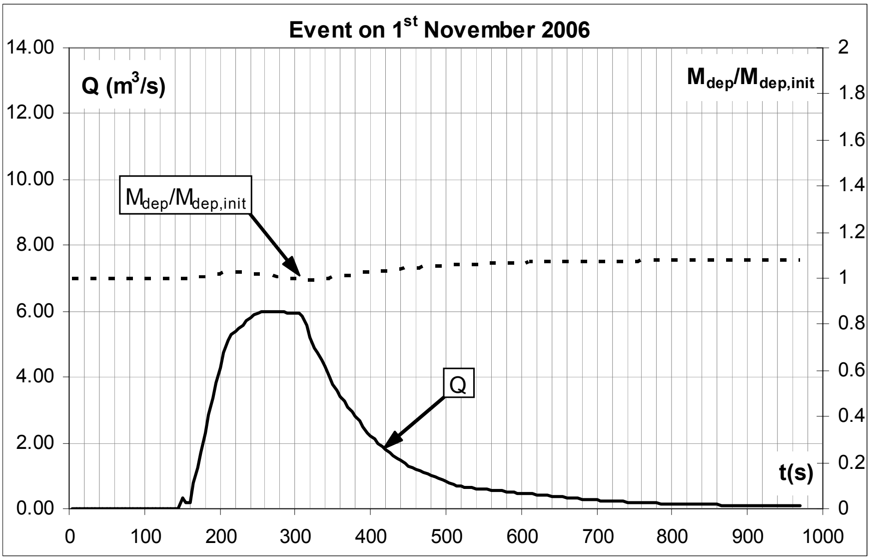

Figure 5: Event on 1st November 2006 – Q(t) and $M_{dep}/M_{dep,init}(t)$ pattern.

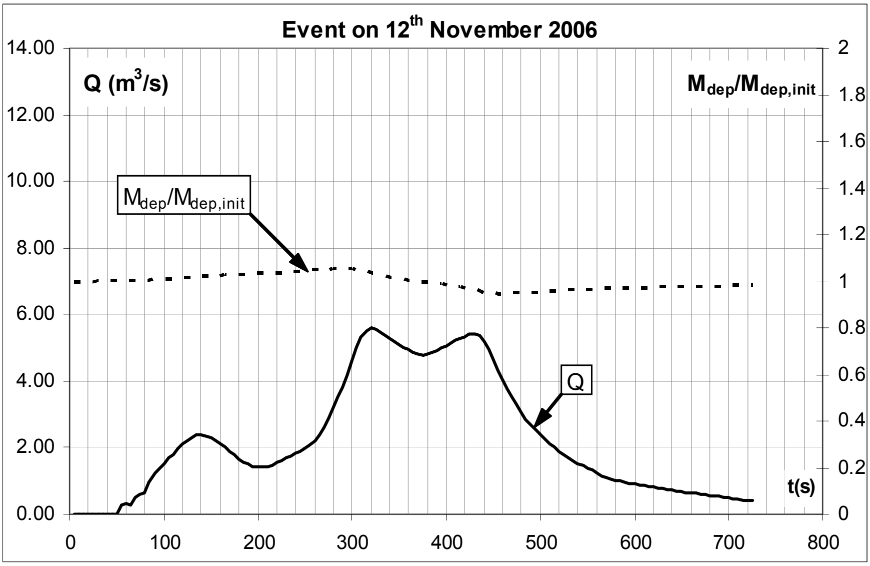

Figure 6: Event on 12th November 2006 – Q(t) and $M_{dep}/M_{dep,init}(t)$ pattern.

4 Conclusions

Solid transport in sewers has been studied thanks to a simplified model which, through the hydrodynamic simulation of a sewer network and the evaluation of flow transport capacity varying hydraulic characteristics, allows the location of all segments of the sewer network with the highest probability of deposit phenomena.

The practical application of such analysis to the sewerage of the Cesarina basin allowed the quantification of the effects of solid material deposit in the terminal trunk of the network, substantially confirmed by the results of on-site experimental research.

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