Performance of stormwater detention tanks in an experimental catchment of northern Italy

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Abstract

The performance of stormwater detention tanks with alternative design configurations and operating conditions have been evaluated according to an integrated approach. Various performance indices have been adopted to describe the mitigation of the pollution impact to the natural environment, the reduction of the management and maintenance charges for the urban drainage system, the preservation of the normal purification efficiency, and the limitation of the costs at the treatment plant. A conceptual model based on the instantaneous unit hydrograph of a single linear reservoir system has been used to simulate the rainfall-runoff process and the pollutant dynamics on an experimental urban catchment and combined sewer network for a continuous run of events and inter event periods of one year. Stormwater detention tank combined with flow regulator demonstrates good performance with respect to environmental pollution: satisfactory performance indicators can be obtained with fairly low flow rate of flow regulator (1 L/s per hectare of impervious area) and tank volume of about 35-50 m^3 per impervious hectare. These solutions also ensure rather low number and duration of overflows. Intermittent emptying controls the volume sent for purification thus reducing the costs and the risks of impairment in the normal treatment efficiency of the plant. Dangerous anaerobic conditions can be avoided also for a considerable volume of the tank (i.e. 75 m^3/ha$_{imp}$) while adopting rather high emptying flow rate of the tank (i.e. 1-2 L/s/ha$_{imp}$).
Keywords: urban catchment, stormwater pollution, flow regulator, stormwater detention tank, numerical modelling.

WIT Transactions on The Built Environment, Vol 122,
www.witpress.com, ISSN 1743-3509 (on-line)
doi:10.2495/UW120241

1 Introduction

During rainfall events runoff waters collect urban surface pollution before entering in the sewer system (e.g. Ellis [1]; Pitt *et al.* [2]; Eriksson *et al.* [3]; Kim *et al.* [4]; Ballo *et al.* [5]). In most cases, when the system becomes saturated by runoff water, overflows directly discharge the polluted stormwater into the natural environment (e.g. receiving water bodies) without any treatment, severely polluting the downstream ecosystem (e.g. Borchardt and Sperling [6]; Even *et al.* [7]; Tixier *et al.* [8]; Todeschini *et al.* [9]). The first evidence of the impact of combined sewer overflow CSO on receiving water bodies came to light in the 1960s but it was not until 1990s that reducing the CSO became a concern (e.g. Marsalek and Kok [10]; Butler and Davies [11]). Consequently, international strategies on environmental pollution refer directly to urban stormwater discharges: the *U.S Clean Water Act* requires cities and states to reduce the pollution of CSOs; the *European Water Framework Directive* (Directive 2000/60/EC) implies that European countries should promote plans to suppress the most obvious sources of pollution, including CSOs, to restore their aquatic systems to a "good ecological status".

Throughout Europe and North America, stormwater detention tanks SWDTs are of particular importance in controlling the negative impact of storm sewer discharges (e.g. US-EPA [12]; Cabot Plè *et al.* [13]; Bertrand-Krajewski and Chebbo [14]; Calabrò and Viviani [15]). Also recent directions of Italian and Lombardia Region (Lombardia Regional Law 12 December 2003, N.26 and Regional Regulations 24 March 2006, N. 3 and 4) legislation on subject of urban stormwater management requires SWDTs in various situations both in residential and industrial catchments to safeguard the quality of the receiving environment (Todeschini [16]).

In this context, a precise understanding of the hydraulic and environmental behaviour of these structural works, widely used either in the urban drainage network or at the treatment plant, is of importance also for northern Italy. A previous study (Todeschini *et al.* [17]) investigated design and operating conditions of stormwater detention tanks on theoretical catchments. This research focuses on an instrumented urban catchment: the residential catchment of Cascina Scala in Pavia, Lombardia, northern Italy.

Consistent with previous studies on this subject (e.g. Harremoës and Rauch [18]; Welker *et al.* [19]; Wong *et al.* [20]), an integrated approach is adopted because of the interactions between the urban drainage system, the treatment plant and the receiving water.

A comparison among alternative design configurations and operating conditions is carried out using performance indexes describing the mitigation of the pollution impact into the natural environment (i.e. the limitation of maximum concentration of pollutant in overflow into the receiving water body and the entrapped pollutant mass), the reduction of the management and maintenance charges for the urban drainage system (i.e. the reduction of the emptying duration of the tank against odour emissions), the preservation of the normal purification efficiency, and the limitation of the costs at the treatment plant (i.e. the control of stormwater flow rate and volume sent to the treatment plant).

The performance of a SWDT is evaluated by modelling the rainfall-runoff process and the pollutant dynamics on urban surface and in drainage system by means of a conceptual model based on the instantaneous unit hydrograph of a single linear reservoir system (Todeschini *et al.* [9]).

2 Materials and methods

2.1 The experimental urban catchments

This study investigates the rainfall-runoff process and the pollutant dynamics on an instrumented urban catchment: the residential catchment of Cascina Scala, Pavia, northern Italy.

The Cascina Scala catchment is composed exclusively of residential use, supporting approximately 1500 inhabitants. The total contribution area is 12.7 ha, where 62% of the total area is impervious. The catchment is drained by a combined sewer system with a total length 2045 m; the pipe has average slope of 0.042 and all pipes are constructed of concrete. The physical characteristics of the catchment and drainage system, and the instrumental equipment are reported in Papiri *et al.* [21].

The numerical simulation of the catchment-sewer network is carried out for one year: from 1/08/2006 to 31/07/2007. Rainfall data belongs to SIAP tipping bucket rain gauges with 0.2 mm accuracy. According to EPA [22] studies rainfall events are selected on the basis of an inter event time *IET* of 6 hours. In such a way the independence between contiguous rainfall events is guaranteed at the level of each catchment-sewer network. Storm events with a precipitation depth less than 2 mm are set apart. Hyetographs are reconstructed with a discretization of one minute. The total precipitation depth in the examined period is 795.0 mm, while that of the 51 events selected on the basis of the previous criteria is 716.3 mm. The total duration of the selected storm events is equal to 502 hours. The year under examination exhibits an annual precipitation depth which is roughly that of the mean value of the annual precipitation height of Cascina Scala series from 1988 to 2007 (Papiri *et al.* [21]). Furthermore, all the alluvional plain (Pianura Padana) over northern Italy is characterised by the same precipitation pattern as Pavia.

The modelling of the system is carried out using a conceptual model based on the instantaneous unit hydrograph of a single linear reservoir system. Code parameters which influence the modelling processes (e.g. the accumulation of pollutants during dry weather on catchment surfaces; the removal of accumulated pollutants by runoff; the transport of pollutants due to drainage flows) have been tuned through experimental data measured during monitoring campaigns.

The monitoring activity and the main characteristics of monitoring storm events are well described in Barco *et al.* [23]. A total of 23 rainfall-runoff events were monitored and 281 wet-weather samples were analysed in a certified laboratory (*Analytica SRL*, Pavia, Italy) following the analytical methods of

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Italian Water Research Institute of National Research Council IRSA-CNR (2000). Barco *et al.* [23] present basic statistics of monitoring storm events, while Todeschini *et al.* [9] provide information on modelling of the system.

Pollutant dynamic refers to total suspended solids TSS as an indicator of overall stormwater quality parameters (e.g. Kayhanian *et al.* [24]). The procedure of calibration/validation of the model is accurately described in previous papers.

2.2 Stormwater flow regulators and detention tanks

The operation of flow regulators and stormwater detention tanks is modelled at the final reach of the combined sewer systems. The investigated design configuration is shown in Figure 1: SWDT with upstream flow regulator FR and by-pass device (BP). Different maximum flow rates per hectare of impervious area directed for treatment by FR (q_{FR}) and SWDT volumes per hectare of impervious area (V_{SWDT}) are considered. q_{FR} is assumed equal to 1, 1.5, and 2 L/s per hectare of impervious area. (In dry weather, mean daily flow rate is approximately equivalent to 0.5 L/s per hectare of impervious area, while peak daily flow rate is slightly lower than 1 L/s per hectare of impervious area.) V_{SWDT} is investigated in the range of 12.5-75 m^3 per hectare of impervious area in line with previous studies on this subject (e.g. Bertrand-Krajewski & Chebbo [14]; Calabrò & Viviani [15]; Todeschini *et al.* [17]) and to the prescriptions of Italian (D.Lgs. 152/2006) and Lombardia Region (Lombardy Regional Law 12 December 2003, N.26 and Regional Regulations 24 March 2006, N. 3 and 4) legislation on subject of urban stormwater management. (Lombardia Region represents a reference standard for the other Italian Regions as concerns environmental policies.)

As concerns filling operation, a widely circulated classification distinguishes between capture and transit SWDTs: in the first type only the first part of the hydrograph is entrapped in the tank (commonly a by-pass device stops the filling

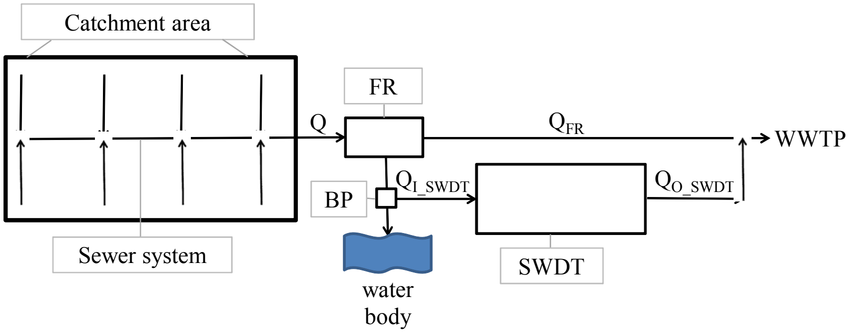

Figure 1: Scheme of the catchment and design configurations. BP: by-pass device; FR: flow regulator; SWDT: stormwater detention tank; WWTP: waste water treatment plant; Q: stormwater flow rate; Q_{FR}: flow rate of FR; Q_{I_SWDT}: filling flow rate of SWDT; Q_{O_SWDT}: emptying flow rate of SWDT.

once the tank is full), while in a transit SWDT the first and the second part of the hydrograph mix in the tank. Regarding emptying cycles both continuous and intermittent operation of the tank is feasible. The choice among alternative emptying rules is a crucial point both for a correct operation of the downstream system (sewer network or treatment plant) and the quality safeguard of the receiving water. A proper operation of the downstream system implies that the emptying flow rate of the tank does not exceed the flow capacity of the downstream network and that the influent flow to the wastewater treatment plant avoids a breakdown of the plant capacity (e.g. loss of clarifier sludge blanket). Environmental safeguard is related to the definition of a criterion establishing when two rainfall events should be considered distinct for collecting the first flush in the tank. If the dry time preceding a rainfall event is short the quality of runoff is presumably rather good (i.e. the accumulation of pollutants on the catchment surfaces is probably scarce) and water storage in the tank is not required. In contrast, a long dry period implies more polluted runoff and, consequently, collection is necessary.

This research focuses on capture SWDTs with intermittent emptying at the end of stormwater runoff. The filling of the tank occurs during a rainfall event but, when the SWDT is full, the filling is stopped thanks to a by-pass device (BP) and all the incoming flow rate exceeding Q_{FR} is discharged to the receiving water body. The emptying of the SWDT begins when the flow rate upstream of the tank (Q_{I_SWDT}) becomes less than 0.1 L/s and stops when Q exceeds 0.2 L/s (this use of different flow rates governing the emptying of the tank guarantees system stability). Emptying flow rate of SWDT per hectare of impervious area (q_{O_SWDT}) is assumed equal to 0.5-1-2 L/s per hectare of impervious area. A new filling of the tank is possible only when the SWDT has completed its emptying cycle.

The choice of capture SWDT is due to two main reasons: 1. during a rainfall event the initial volume of runoff on urban catchments contains the highest pollutant levels (e.g. Barco *et al.* [23]); 2. national legislation requires SWDTs able to store only the first part of the runoff (i.e. the first flush). Intermittent emptying is examined because a previous investigation concerning northern Italy (Todeschini *et al.* [17]) shows that this operating condition reduces the volume sent for purification (and subsequently the costs and the risks of impairment in the normal treatment efficiency of the plant), while ensuring a quite low number and duration of overflows, and a rather short empting duration of the tank.

3 Results and discussion

Numerical simulations allow a rational analysis of the behaviour of design configurations and operating conditions of FRs and SWDTs described in Section 2. A comparison among these alternative solutions is carried out thanks to performance indexes PIs describing the mitigation of pollution impact on the natural environment, the reduction of management and maintenance charges for the urban drainage system, the preservation of normal purification efficiency, and the limitation of costs at the treatment plant.

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PIs referred to annual wet-weather duration including both sewage and storm water are:

- annual number of overflows (n);
- annual duration of overflows/annual duration of stormwater runoff (d);
- annual wet-weather pollutant mass sent to treatment/annual wet-weather pollutant mass (ε);
- annual wet-weather volume sent to treatment/annual wet-weather volume (η);
- annual maximum SWDT emptying time (t_{max}).

3.1 Insertion in the drainage network and volume of the tank

The modelling results show decreasing annual number (n) and duration (d) of overflows for increasing volume of the tank and flow rate of the FR (Tables 1 and 2). The volume of the tank is more effective at reducing both the number and duration of overflows than the flow rate of the FR. However, for the highest volumes (i.e. 50 and 75 m^3/ha_{imp}) the duration of overflows is almost the same for all the examined flow rate of the FR. The values (especially those referred to the lower volumes of SWDT and flow rates of FR) are typically greater than those found by Todeschini *et al.* [17] on theoretical catchments because this study investigates a combined sewer system while in the previous research only stormwater was modelled.

Table 1: Annual number of overflows (n) for increasing volume of SWDT per ha_{imp} (V_{SWDT}) and flow rate of FR per ha_{imp} (q_{FR}). q_{O_SWDT} 0.5L/s/ha_{imp}.

q_{FR} [L/s/ha_{imp}]	V_{SWDT} [m^3/ha_{imp}]			
	12.5	*25*	*50*	*75*
1.0	39	33	25	23
1.5	38	31	24	22
2.0	36	30	23	20

Table 2: Annual duration of overflows/annual duration of stormwater runoff (d) for increasing volume of SWDT per ha_{imp} (V_{SWDT}) and flow rate of FR per ha_{imp}(q_{FR}). q_{O_SWDT} 0.5 L/s/ha_{imp}.

q_{FR} [L/s/ha_{imp}]	V_{SWDT} [m^3/ha_{imp}]			
	12.5	*25*	*50*	*75*
1.0	0.40	0.34	0.27	0.26
1.5	0.29	0.26	0.21	0.20
2.0	0.25	0.19	0.18	0.17

As concerns captured volume and pollutant mass, simulation outcomes exhibit a positive tendency with the volume of the tank and flow rate of the FR (Figure 2). The percentages of annual wet-weather pollutant mass sent to treatment are appreciably higher than those found by Todeschini *et al.* [17] on a storm sewer system because of the significant contribution of sewerage pollutant mass sent to treatment in wet-weather. Simulation outcomes show that it is possible to achieve a captured TSS mass greater than 80% with alternative configurations (i.e. flow rate of FR q_{FR} = 1 L/s/ha$_{imp}$ and volume of SWDT V_{SWDT} ≥ 34.0 m^3/ha$_{imp}$; q_{FR} = 1.5 L/s/ha$_{imp}$ and V_{SWDT} ≥ 24.2 m^3/ha$_{imp}$; q_{FR} = 2 L/s/ha$_{imp}$ and V_{SWDT} ≥ 21.0 m^3/ha$_{imp}$). These solutions imply different stormwater volumes sent to the WWTP, and consequently they require different costs and charges to the purification as rainwater causes many problems to the normal operation of the treatment plant (e.g. wash-out for the sedimentation tank; bulking-foaming; increase of the sludge volume index). For this reason, it is crucial to minimize the stormwater volume sent to treatment for a given environmental purpose. For the previous examined solutions annual wet-weather volume sent to treatment represents the 38.5, 40.9 and 43.9 respectively of annual wet-weather volume. Captured wet-weather volume decreases with decreasing volume of the SWDT and increases with increasing flow rate of the FR, thus suggesting fairly low flow

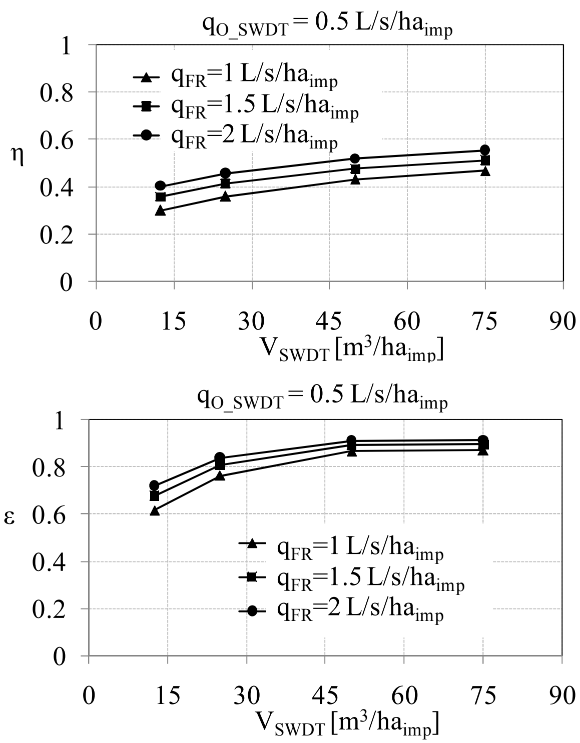

Figure 2: Annual wet-weather volume sent to treatment/annual wet-weather volume (η) and annual wet-weather pollutant mass sent to treatment/annual wet weather pollutant mass (ε) for increasing volume of SWDT per ha$_{imp}$ (V_{SWDT}) and flow rate of FR per ha$_{imp}$(q_{FR}).

rate of the FR (1 L/s/ha$_{imp}$) and rather high stormwater detention tank volume (35-50 m^3/ha$_{imp}$) for both good environmental performance and limitation of the risk of impairment in the normal treatment efficiency.

3.2 Empting rule of the tank

Regarding the management and maintenance charges for the urban drainage system an interesting feature is the time required for a complete emptying of the tank. In fact, the operation of the modelled SWDT with an intermittent emptying rule starting at the end of stormwater runoff requires a totally empty tank for a new filling cycle. The probability of unavailability for a new filling cycle increases for increasing volume of the tank and decreases for increasing emptying flow rate. As previously explained the admitted unavailability is strictly related to the definition of a criterion establishing when two rainfall events should be considered distinct for collecting the first part of their hydrograph in the tank. The Lombardia Region (Regional Law 12 December 2003, N.26 and Regional Regulation 24 March 2006, N. 4) imposes an unavailability limit for a SWDT of 96 hours.

Simulation results exhibit an annual maximum SWDT emptying time significantly lower than the Regional limit for all the adopted solutions. For example, for a flow rate of the FR of 1 L/s/ha$_{imp}$ and emptying flow rate of the tank of 0.5 L/s/ha$_{imp}$, the maximum emptying duration is about 26 hours for a SWDT of 25 m^3/ha$_{imp}$ and 62 hours for a SWDT of 75 m^3/ha$_{imp}$ (Figure 3). Even if all the examined solutions complied with the Regional limit rather high emptying flow rate of the tank (i.e. 1-2 L/s/ha$_{imp}$) should be taken while adopting a considerable volume of the tank (i.e. 75 m^3/ha$_{imp}$). This shrewdness guarantees rather short maximum emptying durations avoiding dangerous anaerobic conditions, putrefaction phenomena and offensive odorants also for the highest volumes of the tank (Kabir *et al.* [25]). Figure 3 also shows that the interval between mean emptying time (continuous line) and emptying time without interruption of a full SWDT (broken line) increases with increasing volume of the tank. This result indicates a decreasing number of storms filling completely the tank with increasing tank volume.

4 Conclusions

Stormwater detention tanks represent a useful environmental tool against stormwater pollution. However, design configurations and operating conditions significantly affect the extent of the ecological benefit, investment and maintenance costs, and functionality of the urban drainage system and the wastewater treatment plant. An integrated approach is required for the performance assessment of alternative solutions in large urban areas.

This research shows for an experimental catchment of northern Italy (the residential catchment of Cascina Scala, Pavia) that good performance against environmental pollution can be attained by coupling flow regulator and stormwater detention tank.

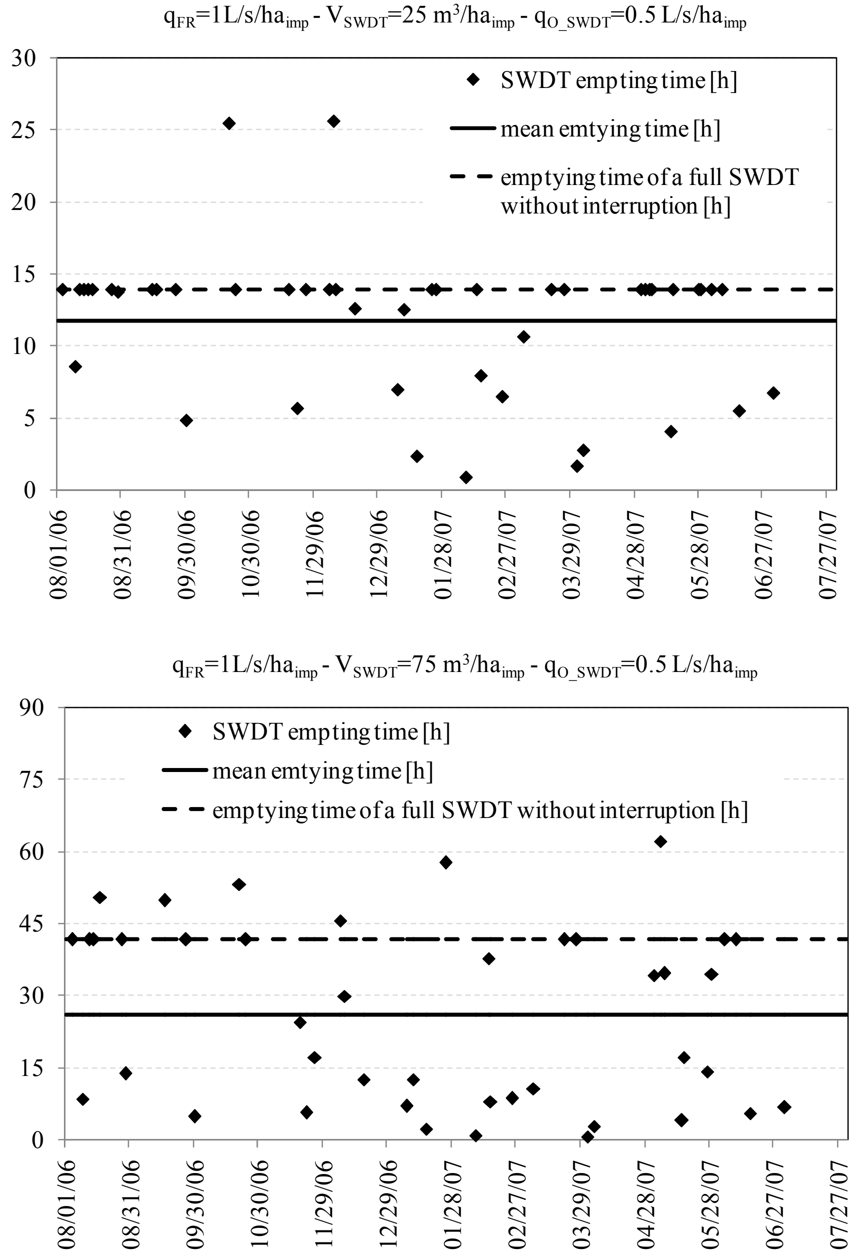

Figure 3: Emptying duration of SWDT for increasing volume of SWDT per hectare of impervious area ha$_{imp}$ (V_{SWDT}).

Among alternative combinations providing an adequate pollutant interception, fairly low flow rate of flow regulator (1 L/s per impervious hectare) and volume of the tank of about 35-50 m^3 per hectare of impervious area should be preferred because these design criteria ensure good environmental performance (i.e. suitable annual pollutant mass entrapped) and at the same time reduce stormwater volume sent for purification thus diminishing the costs and the risks of impairment in the normal treatment efficiency. (Rainwater causes many problems to the normal operation of the treatment plant: wash-out for the sedimentation tank, bulking-foaming, increase of the sludge volume index.)

These solutions also ensure rather low number and duration of overflows. Intermittent emptying controls the volume sent for purification, thus reducing the costs and the risks of impairment in the normal treatment efficiency of the plant. Dangerous anaerobic conditions, putrefaction phenomena and offensive odorants can be avoided also for a considerable volume of the tank (i.e. 75 m^3/ha_{imp}) while adopting rather high emptying flow rate of the tank (i.e. 1-2 $L/s/ha_{imp}$).

An important issue to deal with in future research is to consider other experimental catchments also with different urban typology (e.g. production catchment) for the performance assessment of stormwater detention tanks. Also the pollutant abatement at the wastewater treatment plant should be considered for the evaluation of the total pollution load discharged into the natural environment.

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