Framework for Enhanced Stormwater Management by Optimization of Sewer Pumping Stations

D. Ganora[1]; S. Isacco[2]; and P. Claps[3]

Abstract: Control and reduction of pollution from stormwater overflow is a major concern to be addressed by municipalities in order to improve the quality of the receiving water bodies and the environment in general. In the European context, these actions are driven by the Water Directive 2000/60/CE. In this regard, assessment studies of the potential load from sewer networks recognize the need for adaptation and upgrade of existing networks with waterworks and management measures. In many cases this is done by building first-flush detention tanks that, however, present consistent practical and economical burdens. In this work, simple rules to manage existing pumping stations in combined sewer systems are proposed as a way to apply management rules that mitigate pollution load. Such rules can be easily implemented in real cases with minimal cost of activation and no need of additional infrastructures. The procedure is based on the previous knowledge of the precipitation forcing and of a quantity/quality model of the sewer network. The steps adopted are (1) use of a (long-term, high-resolution) sequence of rainfall events to compute a wide spectrum of flow conditions (hydrographs and pollutographs) to the pumping stations; (2) definitions of a pumping rule to apply to the whole sequence of events to filter the incoming flow toward the wastewater treatment plant, so to compute outflows; and (3) efficiency assessment of the pumping rule by cumulative frequency analysis of water volume, pollutant mass, and pollutant mean concentration. Rule optimization can be performed by iterating points (2) and (3). An example is proposed to show how two simple parameters (a discharge threshold on the inflow and a maximum pumping time) can control the management of water and pollutant fluxes. Numerical results show that a proper optimization allows one to reduce the pumped volumes (thus reducing energy requirements and increasing the treatment plant efficiency) without significant changes to the overall pollutant mass outflow. The new pumping rules can be implemented on real stations with minimal and economically sustainable interventions. **DOI: [10.1061/(ASCE)EE.1943-7870.0001220](#).** © 2017 American Society of Civil Engineers.

Author keywords: Sewer network overflow; Pumping stations; Alternative pumping rule; Optimization; Economically sustainable implementation.

Introduction

In a Smart City scenario, reduction of pollution from municipal stormwater is of major concern. For example, the European Union is strongly pressing Italy to converge to compliance with the Water Directive 2000/60/CE, using relevant economic sanctions as a main enforcement. Measures to mitigate the production of stormwater pollution and its leakage in natural streams are often targeted to the enhancement of processes at the treatment plants. However, the treatment plant is just the last element of a complex system of sewer channels, stormwater drains, weirs, pumping stations, etc., which may actually be reconsidered as a whole system to control the pollution formation and the subsequent conveyance to the plant (e.g., Todeschini et al. 2014). On the other hand, the cost of structural measures can be very relevant and not sustainable in medium or small sewer network systems.

Pollutant dynamics is a quite complex process to model in combined sewer systems, as stormwaters alter the dry-weather pollutant load to the wastewater treatment plant (civil effluents) by either increasing the pollution concentration, or decreasing it in longer storms. This is likely to occur in the presence of the so-called first-flush effect, which represents a disproportionate delivery of pollutants, either in terms of concentration or mass load, during the initial volume of the hydrograph (Sansalone and Cristina 2004; Bertrand-Krajewski et al. 1998). Such variability in load concentration challenges the plant management, as dilution of pollutants reduces the efficiency of the sewage treatment. In addition, a side effect is present at control weirs when peak flow in combined sewers causes the outflow of polluted water toward natural streams, lakes or, in general, to the surrounding environment. Such outflows are usually disregarded, but may affect the quality of stream water, as well as of the groundwater near urbanized areas due to the release of a significant mass of pollutants (De Martino et al. 2011).

In newly developed urban areas, a *distributed* optimization of the system is relatively easy to achieve, using Low Impact Development measures on drainage networks combined with Best Management Practices in planning (e.g., applied to rooftops, road pavement, parking lots, and so forth). These measures allow an improved management of stormwaters, although general conclusions on the relative efficiency of distributed and centralized measures are not obvious (Freni et al. 2010). However, the most common situation in many urban areas is that most of the drainage networks already exist, with evolution spanning dozens of years, and they

[1]Assistant Professor, Dept. of Environment, Land and Infrastructure Engineering, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy (corresponding author). ORCID: http://orcid.org/0000-0003-0605-6200. E-mail: daniele.ganora@polito.it

[2]Civil Engineer, Dept. of Environment, Land and Infrastructure Engineering, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy.

[3]Professor, Dept. of Environment, Land and Infrastructure Engineering, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy.

have been designed with a focus on water quantity rather than on water quality. The enhancement of existing systems is then usually proposed in terms of the building of detention tanks to properly modulate water and pollutant peak flows. This is the approach usually adopted in Italy where, however, the first-flush volume is defined a priori without acknowledging for specific at-site dynamics. Unfortunately, tanks cannot always be installed in the urban context, due to unavailable space or high costs.

The present work aims at delineating a systematic procedure to analyze existing sewer networks characterized by the presence of pumping stations using state-of-the-art methodologies in order to improve the whole system behavior with minimal changes to the infrastructure, and thus looking at economically-sustainable actions that can be easily implemented also by medium-small municipalities or local authorities that cannot afford high-cost actions. An example of application is presented, applied to a typical combined sewer network that can be exploited to control and modulate the flows at certain points of the network.

The authors propose to reframe pumping rules according to the typical incoming loads from the network using simple automated control rules, without any real-time management. With respect to real-time solutions, the proposed rules may be less efficient for individual events, but allow the enhancement of the system performances without structural actions on the sewer network. To strengthen the validity of the proposed approach the whole work is performed in a statistical framework, which provides a probabilistic description of the quantity/quality variables (Qin et al. 2013; Adams and Papa 2000). A motivation for the need of this analysis is that, as noted by Sansalone and Cristina (2004), the dynamic of pollution removal can be quite variable: The first-flush effect is present in *mass-limited* events, i.e., when most of the mass is removed early in the event due to a considerable runoff volume, but *flow-limited* events (the pollutograph and the hydrograph have similar shapes) may also be present. Moreover, each real rainstorm has a different duration, volume, temporal and spatial variability, etc., from the others. This requires a large number of events to validate a selected set of rules by evaluating the long-term performances of the system and not only the response to a few *design events*. Such information is fundamental to obtain robust information on the interaction between the sewer system and the receiving water body affected by the overflow (Lau et al. 2002; Andrés-Doménech et al. 2010).

Methods

Assessment of Pump Settings

Pumping stations are widely used in plains areas to work around the topographic flatness. Their structure may be more or less complex, but they basically consist of a tank, a set of pumps, and an overflow device. Usually, pump activation is automatically regulated by the level within the tank (optimized for the dry-weather flow); during rainstorm events, as water volume increases, pumping rate changes and, if insufficient, the volume excess within the tank is diverted through the overflow device (e.g., a weir) toward the surrounding environment. This rule is common to pumping systems, as they are usually designed for the primary control of water volumes and not for pollutant control.

For a generic wet-weather event [Fig. 1(a)] the pumping station will deliver a certain flow [Fig. 1(c)] toward the wastewater treatment plant (WWTP) or another point on the network, following the standard pumping rule (SPR) based on levels in the tank (not shown). The example refers to a station with three equally-sized

pump units that may work all together, on the basis of the level within the tank, increasing the diverted flow proportionally. Depending on the incoming flow and tank capacity, an overflow may occur [Fig. 1(e)]. The incoming pollutant mass can be split between pumped flow and outflow although the buffer effect of the tank may be significant. Clearly, in combined systems, the flux of pollutants is a combination of dry-weather load and pollutants flushed by the catchment surface by the rainstorm.

A main drawback of the SPR is that flow toward downstream nodes (or to the WWTP) remains significant until the rain event is over, implying a considerable volume of pumped flow with low concentration of pollutants. One can recognize that this protocol uses energy proportionally to the overall incoming flow and not to the incoming mass of pollutants, producing inefficiency in the treatment plant that again corresponds to the volume of the storm exceeding the first flush.

With respect to the preceding standard pumping rule, the proposed alternative pumping rule (APR) is expected to pump toward the WWTP the volumes with (on average) the higher pollutant concentration (which also deliver most of the pollutant mass), while diluted volumes are partially released out of the system. This is achieved by simply turning on all the available pumps (or a fraction of pumping power defined a priori) for a maximum time duration D_{PM}. The SPR is, however, still used depending on the inflow discharge: When a fixed discharge threshold Q_{TH} is exceeded (see the reference time windows TW in Fig. 1), the system switches to the APR, otherwise the original SPR remains active. During the APR period:

- If $Q_{inflow} \leq Q_{PM}$ and pumping time $\leq D_{PM}$, all the inflow is pumped and the available pumping capacity is not completely exploited. No overflow is possible;
- If $Q_{inflow} > Q_{PM}$ and pumping time $\leq D_{PM}$, the maximum flow is pumped by the station. The overflow occurs with incoming discharges larger than the pumping capacity; and
- For any Q_{inflow} and pumping time $> D_{PM}$, pumps are turned off and all the inflow leaves the tank toward the environment.

The APR condition can be easily implemented in real networks as it simply requires a sensor for the inflow discharge or, alternatively, a measure of level in the pipeline upstream from the pumping tank. Simple electrical controls can be used to manage the maximum pumping duration. The proposed approach is particularly suitable for systems that exhibit a first-flush behavior in most of the events, as it delivers to the WWTP the first part of the hydrograph (i.e., the volumes expected to have the higher concentration containing most of the mass transported in the whole event). However, a precise definition of *first-flush* is not needed here, as the proposed pumping rule operates only on the basis of the inflow discharge/level threshold and the rule efficiency is indeed evaluated a posteriori, by assessing the amount both of the pollutant mass and of the concentration delivered to the WWTP and to the receiving water body.

Analysis Setup

The study and optimization of the system requires three preliminary elements: (1) a reliable hydrodynamic model of the network, (2) a reliable quality model of the system, and (3) a set of rainfall events to feed the quantity/quality model in order to check the actual behavior of the pumping station. These elements may be available with different degrees of accuracy, depending on the case study at hand. Here, it is considered that the whole procedure can be implemented if:

- A reliable (i.e., properly calibrated) quantity/quality model of the whole sewer network is available. This condition is usually
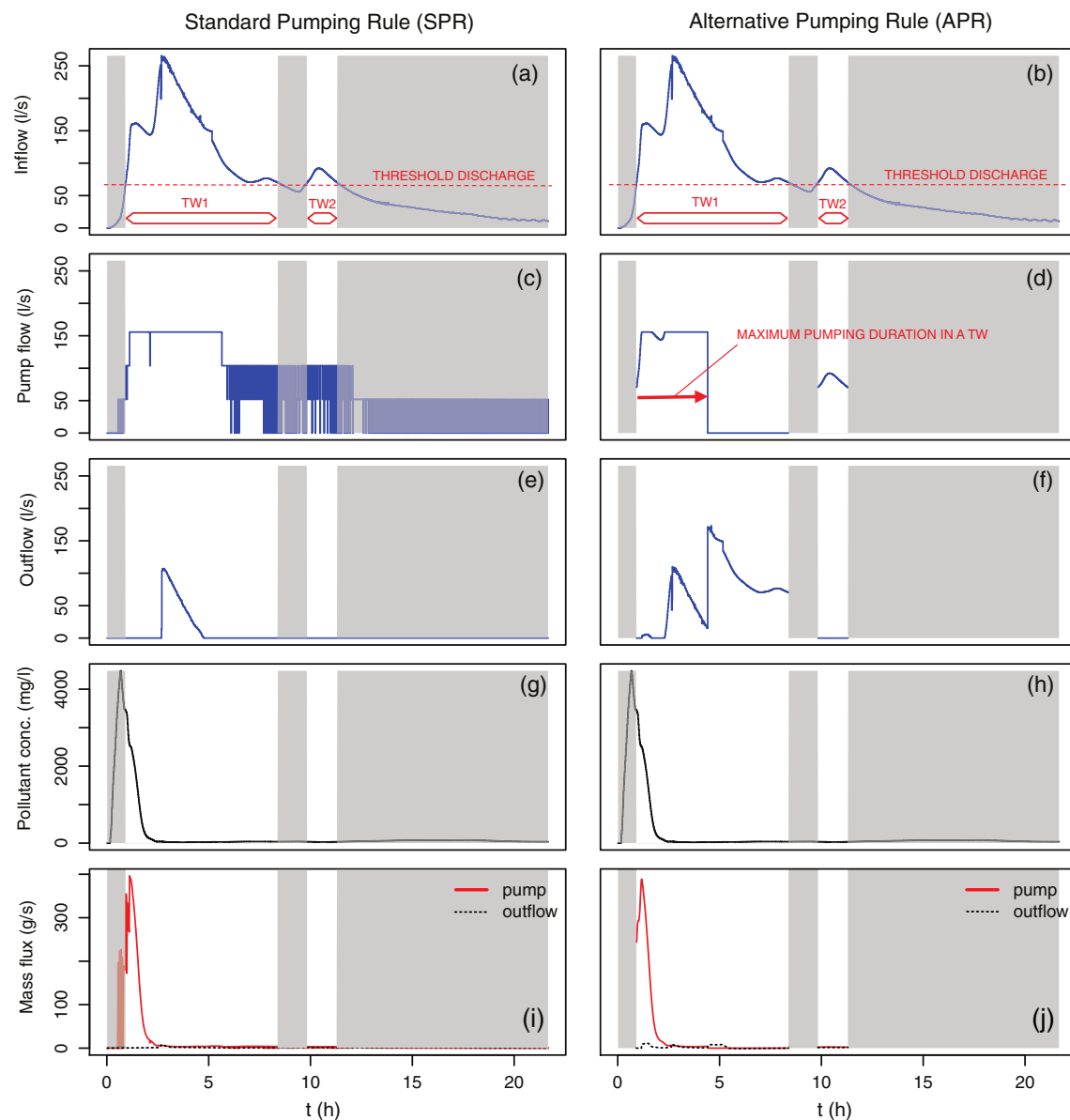
Fig. 1. Example of behavior of pumping station-overflow node with SPR (a, c, e, g, and i) and APR (b, d, f, h, and j) for same event: (a and b) inflow; (c and d) pumped flow; (e and f) outflow; (g and h) inflow pollutograph; (i and j) pumped/overflow mass flux; shaded areas correspond to periods where only SPR operates, as discharge is below APR's activation threshold

met as state-of-the-art software can support this task; the pollution management component of the model, which is usually affected by larger uncertainties, may require further investigations (e.g., field measurements and sensitivity analysis); and

- A large spectra of discharge/pollutograph events can be simulated, thus requiring long-term rainfall sequences to feed the model. Although this step can take significant computational time (depending on the model details, the network extent, the rainfall sequence duration, and the available computational power), using a comprehensive set of events is crucial for the reliability of results, as the sewer network system has a very complex behavior and a small set of events may be not sufficient to properly study its overall performance.

Under these requirements, a reference set of simulations can be performed with the SPR, based on a large number of events. The APR can be implemented as a *filter* applied to the simulated reference set of hydrographs/pollutographs, providing a different pumped/overflow flow ratio with respect to the *original* SPR. This filter can be easily coded in *Matlab*, *R*, or other software for numerical analysis. Although the APR filter simplifies the real behavior of the system (for instance, the buffer effect of the pump tank in this version of the model has not been considered), its feasible computational burden, even for large sets of rainfall events, make it suitable for sensitivity analysis and optimization [see e.g., Freni et al. (2008) and van Daal-Rombouts et al. (2016), for discussions about the complexity of models for sewer network analysis].

Case Study

Vercelli-Cappuccini Sewer System

The study focuses on the combined sewer system of the Cappuccini area, a suburb of the city of Vercelli, located in northwestern Italy (Fig. 2). The catchment can be studied independently on the
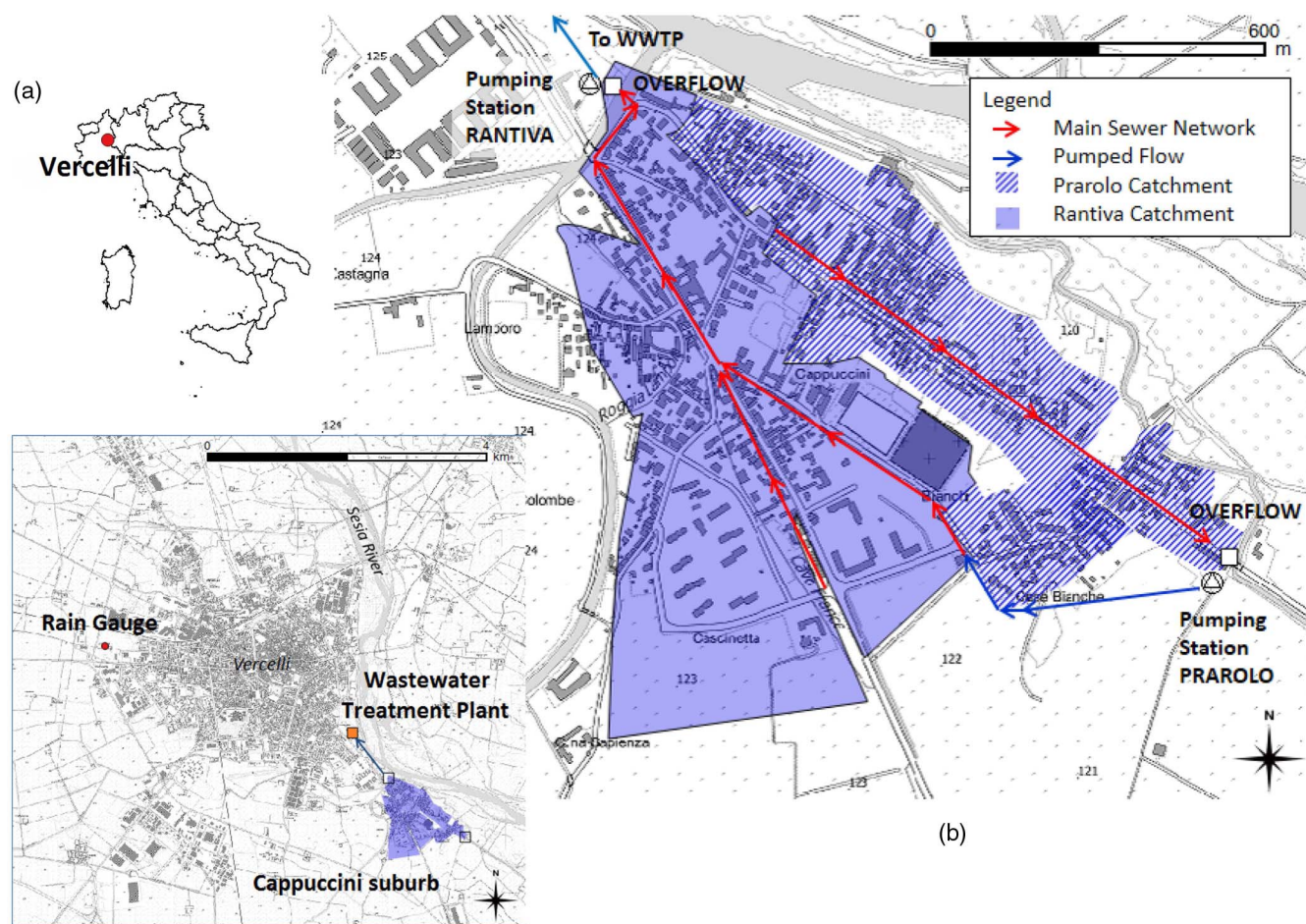
Fig. 2. Location of studied catchment (a) and its structure (b) existing pumping stations and combined sewer overflows are reported on map

remainder of the network because it is not directly connected to the other city subcatchments, being located in an area with a lower elevation than that of the wastewater treatment plant. The catchment is a low-density urban area of about 103 ha, with about 30% of impervious surface. It is characterized by two nested subcatchments: The first one drains southward to the Prarolo pumping station, and the second one drains northward to the Rantiva pumping station. The latter station pumps directly to the WWTP of the city. Both pumping stations are equipped with an overflow device. Although this case study does not present critical elements in its configuration and operation, it is a representative example of many other sewer systems, so that the applied procedure is likely to be applicable in other locations.

Model Calibration

The case study catchment has been previously structured in standardized elements to build a hydraulic model using the Storm Water Management Model (SWMM), available from the U.S. Environmental Protection Agency (Rossman 2010). Topological and geometrical data of the network have been made available by the sewer system managing authority (ATENA s.p.a.), including all the information about pipes, manholes, weirs, pumping stations, and so on. However, no direct measurements of discharge and water quality at the catchment outlet, nor within the catchment have been used, as common in almost all practical cases.

Calibration of the model has been performed by considering (1) the results of a previous detailed field analysis performed in

the whole Vercelli catchment and in a neighboring subcatchment with some quantity and quality observations; and (2) the official start/stop rate of the pumps during the dry weather period in the Cappuccini catchment, as provided by the management authority. The authors recognize that transfer of calibration parameters between different catchments carries some uncertainties and a dedicated measurement campaign would be preferable; however, for the aim of this work this is not of primary importance.

Concerning the rainstorm input, continuous observation at 10-min resolutions from the Vercelli rain gauge (784 mm of average annual precipitation) operated by the ARPA Piemonte (Regional Environmental Agency) has been used to test the model. The rain gauge is located about 3.5 km from the centroid of the catchments (Fig. 2).

Concerning the pollutants dynamics, only the total suspended solids (TSS) concentration has been considered, thus being easy to measure and often resulting in correlating to other pollutants (e.g., Ciaponi et al. 2006). Other pollution constituents may also be present, for instance, dissolved solids and substances determining pH variations (e.g., Ying and Sansalone 2010; Sheng et al. 2008). These have not been considered here, as no quantitative data were available for the case study. The build-up and the wash-off processes have been described with the exponential models used also by Di Modugno et al. (2015) with parameters Accu = 10.4 kg ha^{-1} d^{-1}, Disp = 0.08 d^{-1}, Arra = 0.03 mm^{-1}, and Wash = 1.6, which have been obtained with the support of a measurement campaign on nearby catchments. These parameters fit well with typical literature values for similar Italian catchments [for further

details the reader is referred to Artina et al. ([1997])] and can be considered suitable for the present application. However, note that for more detailed analyses, due to the large uncertainty related to the pollutant dynamics, it is advisable to run different scenario-based simulations of the sewer system to test the sensitivity of the results to the variability of build-up/wash-off parameters. A dry-weather pollutant concentration of 250 mg/L has been considered with an average discharge of about 7 L/s for the whole catchment. The discharge has been calibrated according to the application of the SPR declared by ATENA s.p.a. in dry periods.

Rainfall Data for Extended Simulations

As noted in the section, "Analysis Setup," long-term simulations are necessary to provide reliable statistically based results to support a probabilistic design of the measures to enhance water quality. To this aim, a long sequence of rainfall observation at the Vercelli rain gauge has been used. Observations span from 1994 to 2011 (18 full years) with a 10-min resolution (measurement sensitivity 0.2 mm). The whole sequence has been filtered to extract a set of individual rainfall events. Two events can be considered as independent if they are separated by at least 12 h of no rain. Hence, a generic event can have dry periods, but always shorter than the interevent time duration of 12 h. Events with less than 2 mm of rain volume have also been discarded. Finally, a total of 775 events were used in the application.

It is worth noting that high-resolution rainfall observations are commonly available but in general are underexploited because most of the analyses carried out by practitioners are based on single-event design hyetographs. Long-time series are often underexploited due to difficulties in managing large data sets and simulation runs, but they can be profitably used to obtain statistically based results that carry much more information than analyses based on just a few *representative* rainfall events. The design events commonly used in sewer design are indeed based on the theory of extreme precipitations and are used for hydraulic design in high-flow conditions. This approach turns out to be not completely useful, if not misleading, when one studies the pollutants dynamics, as significant pollution overflows can occur and may be critical also for nonextreme events.

The use of a wide data set of rainfall events is thus a necessary condition to obtain reliable results in the analysis of overflow pollutant fluxes. The most critical hydrometeorological conditions that force the sewer system emerges only after the analysis of the pollutant yield and transport; in general, they do not depend only on the rainfall intensity, but also on the event duration, volume, and on its prior dry-weather period. As a consequence, the efficiency of mitigating actions should be considered in a stochastic analysis framework.

System Simulation and Optimization

The standard simulation performed with the fully equipped SWMM model has been run considering the initial setup of the system. All the succeeding results presented here will be referred to the Rantiva pumping station, as the Prarolo one (located upstream from the Rantiva) did not generate significant overflow during the whole period of analysis. Thus, the Prarolo station has been set to the SPR rule for the whole simulation time. The inflow hydrograph (at the Rantiva station) for each event has been filtered according to the methodology described in the section, "Methods," earlier in this article, for different values of discharge threshold Q_{TH} and maximum pumping duration T_{PM}.

Figs. 3–5 report the results obtained for two different combinations of Q_{TH} and T_{PM}. These results provide essential information for a comprehensive management of such types of sewer network and related infrastructures, with particular reference to overflows and WWTP inflows. The first example (Fig. 3) reports the empirical cumulative distribution function (ECDF) of the most relevant variables involved in the analysis. The use of the ECDF is possible as the simulation is based on a large set of events, and it is also a powerful tool to study the behavior of the system on a long-term perspective. In fact, using a large sample of events allows one to identify critical conditions that cannot be visible if a small number of synthetic events is used to test the system. The high variability of the range of the considered variables (e.g., Fig. 3) highlight the importance of a statistical treatment of the event characteristics, as already suggested by Qin et al. ([2013]).

Fig. 3 shows on the first row of panels the variables relative to the outflow from the Rantiva station, while the second row concerns the pumped flows (to the WWTP). From left to right the columns reproduce respectively: The total water volume; the total pollutant mass; and the event mean concentration (EMC), computed as the ratio between total pollutant mass and total water volume. Each panel shows three curves: The inflow curve represents the volume, mass or EMC produced by the whole catchment (inflow to the pumping station), the SPR curve is relative to the standard pumping rule, while the APR curve represents the alternative pumping scenario. Note that all the reported values are computed only over the reference time windows identified for each event (see the TWs in Fig. 1), i.e., during the period in which the alternative pumping rule can be operated; in this way, the values are directly comparable, being referred to the same time span.

In the first example, described in Fig. 3, the discharge threshold has been set to three times the dry-weather wastewater discharge and the maximum pumping duration to 5 h. Taking the inflow line as a reference, the relative position of the SPR and APR lines provides insights about the behavior of the system under the standard and the alternative scenarios. [Fig. 3(a)] shows that the frequency distribution of the outflow volume is significantly affected by the APR as, in this case, most of the inflow volume leaves the system as outflow. About 80% of the events produce outflow with the APR while this occurs for just 25% of the events with the SPR. This can be recognized through the closeness of the APR curve to the inflow curve; a corresponding result is reported in [Fig. 3(d)] in terms of pumped volumes. By using the SPR almost all the incoming volume is pumped, while with the APR only a relatively small fraction of volumes reach the WWTP. As shown in [Figs. 3(b and e)], one can see the effects of the different pumping scenarios on the distribution of total pollutant mass. In this case, both the APR and the SPR results resemble the inflow curve for the pumped mass, meaning that the distribution of the pumped mass to the WWTP with the APR remains similar to that of the SPR. On average, about 98% of the total incoming mass is pumped with the SPR and about 84% with the APR. Finally, Figs. 3(c and f) show the distribution of the EMC for the outflow and pumped fluxes: The EMC depends on both the mass and the volume and is a useful indicator of the *importance* of the load of each event. The inflow EMC is reproduced in both [Figs. 3(c and f)], so it can be used as a comparison. In [Fig. 3(c)], relative to the outflow fluxes, both the APR and the SPR cases fall on the left of the reference line, thus meaning that the flow outside the system has a lower (average) pollutant concentration than that of the incoming flow. On the other hand, the pump flux shown in [Fig. 3(f)] for the APR is on the right of the reference curve, showing that the average concentration of the pumped pollutant is greater than that of the incoming one. The SPR curve, instead, is practically overlapping the reference one.
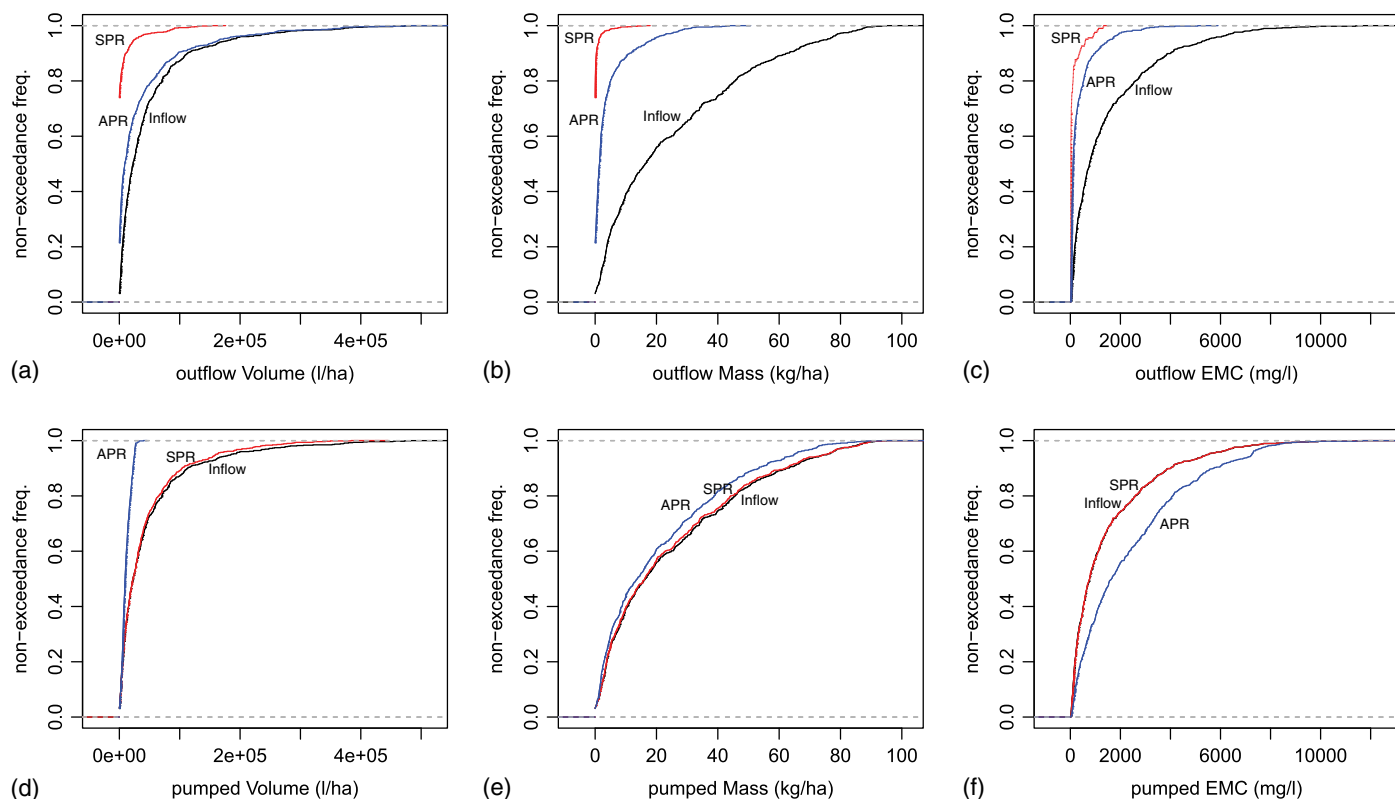
Fig. 3. Long-term statistical characteristics of fluxes at Rantiva pumping station represented through empirical cumulative distribution function of events volume, mass, and EMC; (a–c) shows variables relative to overflow, while (d–f) represents pumped flow; reference condition is labeled inflow, standard pumping rule SPR, and alternative pumping rule APR; results have been obtained with $Q_{th} = 3 \times Q_{dry\,weather}$, $D_{PM} = 5$ h, and $Q_{PM} = 156$ L/s
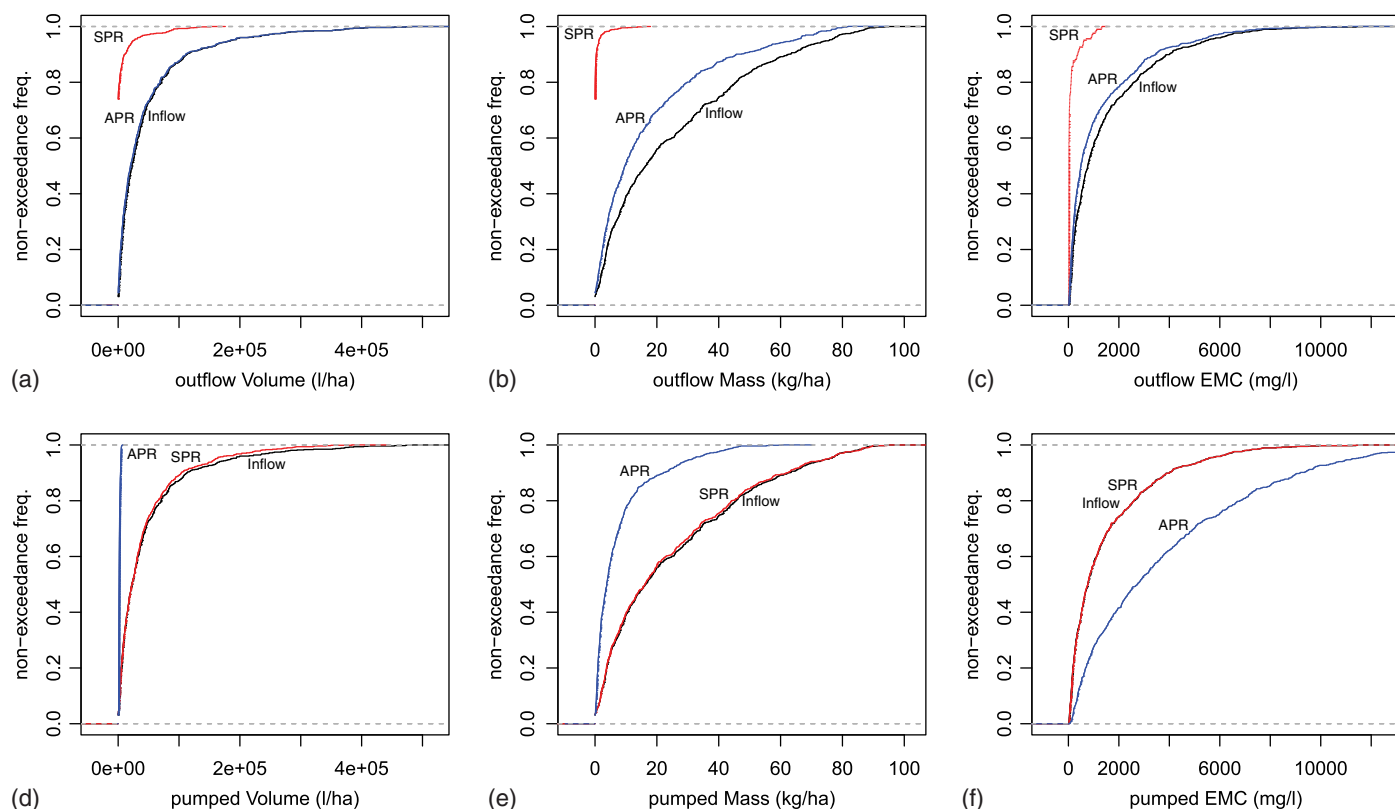

Fig. 4. Same as in Fig. 3 but with smaller pumping duration ($Q_{th} = 3 \times Q_{dry\,weather}$, $D_{PM} = 1$ h, and $Q_{PM} = 156$ L/s)
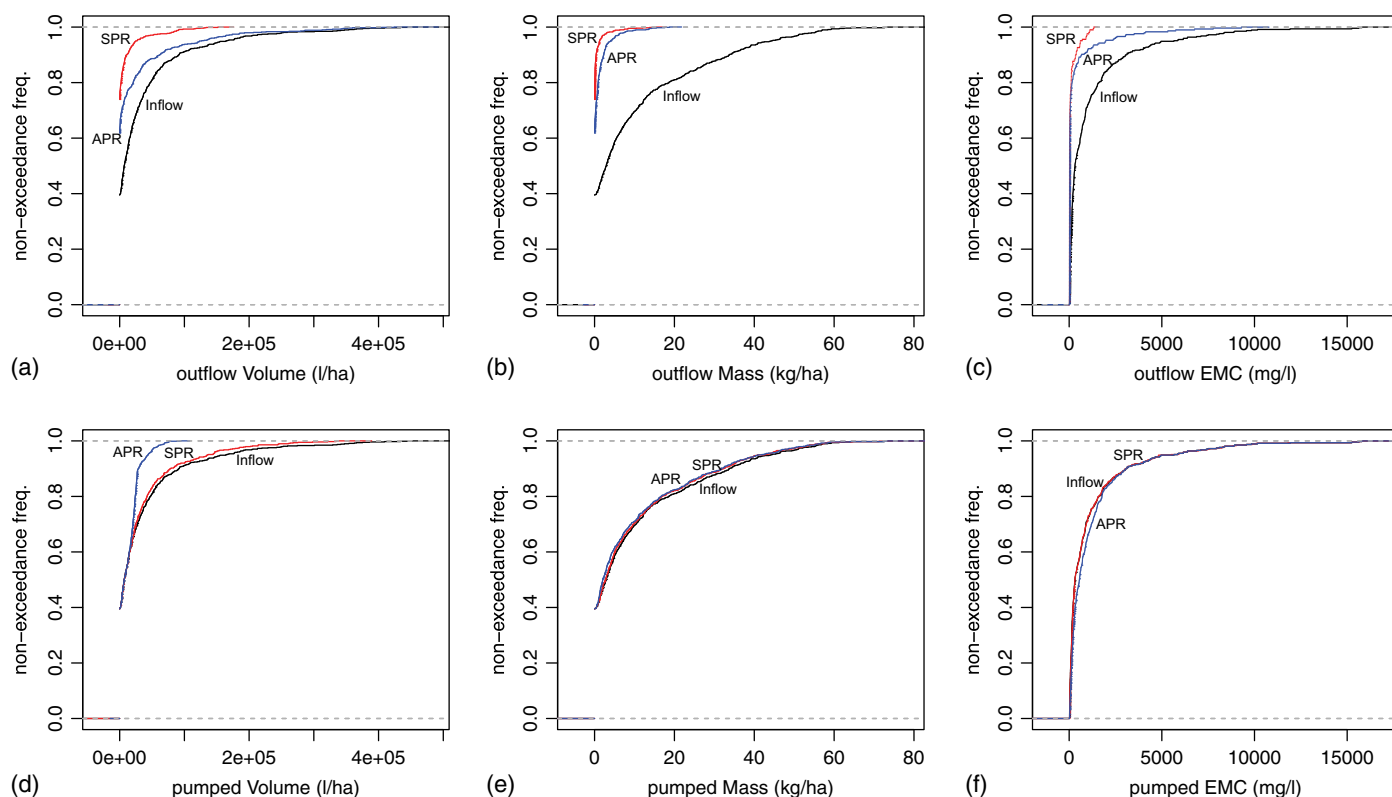
Fig. 5. Same as in Fig. 3 but with higher discharge threshold ($Q_{\text{th}} = 10 \times Q_{\text{dry weather}}$, $D_{\text{PM}} = 5$ h, and $Q_{\text{PM}} = 156$ L/s)

Results from Fig. 3 can be interpreted as follows: In a first instance, both the APR and the SPR can be considered reliable solutions as they are able to properly *filter* the incoming flow by delivering most of the pollutant load to the WWTP rather than to the water bodies outside the system. However, the two scenarios have very different behaviors: The APR delivers a more concentrated load to the WWTP with respect to the SPR, as shown by the larger shift of the APR curve of [Fig. 3(f)]. In general, APR also delivers much smaller water volumes to WWTP [Fig. 3(d)]: The present case study results show that the APR pumped volume is 25% of the SPR pumped volume, thus allowing a notable energy saving. The delivered mass is, however, comparable to that of the SPR [Fig. 3(e)]. This result highlights the positive effect of the APR with respect to the WWTP, as the WWTP is not overloaded with large volumes of water with diluted pollutants.

It must be said, however, that the overflow pollutant mass is subjected to an increase if the APR is operative, as shown in [Fig. 3(b)]. This is due to the increased number of events that produce overflow in the APR with respect to the SPR, even if not necessarily presenting an increase in instantaneous concentration in the course of events. A typical example of these events is reported in Fig. 1; during the time window TW1, the APR switches on the pumps for a fixed time then allows a full overflow of the incoming flux in the last part of the window. In this last period, the pollutant concentration is low, as the first-flush effect is no longer evident and the dry-weather load is heavily diluted by the rainstorm flow.

All these conclusions are supported in a quantitative way by use of frequency distributions to describe the variables of interest. This allows one to quantify the costs and benefits of different pumping rule approaches by a balanced analysis of the fluxes toward the WWTP and the surrounding environment. Hence, a real-world final analysis must include information about both the optimal concentration and volumes that can be treated by the WWTP, and the

maximum possible concentration of overflow water tolerable by the receiving water body. For instance, it is worth remarking that usually a control weir is present just before any WWTP, which could possibly flush out the pollutants pumped from the pumping station controlled by the SPR.

The preceding results refer to a realistic, but illustrative, case study. Information about the WWTP and the receiving environment are not accounted for in this study because they are out of the scope of the paper. However, it is interesting to see how the results may change for a different set of parameters. In this regard, Fig. 4 shows an APR with the same discharge threshold as Fig. 3 (i.e., equal to three times the dry weather flow), but with a shorter duration (1 h instead of 5 h). Although the setup of the APR is quite similar, results appear substantially different: The pumped mass is significantly smaller than that of the SPR [Fig. 4(e)], meaning that the pumping rule is not able to properly deliver most of the pollutants to the WWTP. Moreover, most of the mass is diverted out of the system, as clearly visible from Fig. 4(b), where the APR line is closer to the inflow one (incoming mass). Finally, overflow has an EMC similar to the incoming one, meaning that the pumping system is not able to properly *select the right part* of the pollutograph. One must conclude that a too short pumping time can degrade the quality of results.

A further example is reported in Fig. 5 with a different set of parameters (Q_{TH} equal to 10 times the dry weather flow and T_{PM} equal to 5 h). In this simulation, the APR affects mainly the pumped/overflow volumes, but the actual pumped/overflow mass is very similar to the SPR case. Also, the EMC distributions are rather similar for the two scenarios. This example highlights a case in which the discharge threshold is so high that the APR is activated only for short time periods during the most heavily peaked events. Hence the global behavior of the system is not really influenced by the APR versus the SPR operation.

© ASCE

J. Environ. Eng.

Conclusions

A detailed analysis of pollutant overflow from sewer systems is needed in many cases, in order to be compliant with water quality requirements of current regulations. The complexity of the sewer systems and the large uncertainty involved, especially regarding the assessment of pollutants, may undermine these analyses. However, the availability of long and detailed rainfall series makes it possible to explore new management solutions.

In this work, a framework to optimize the management of existing pumping stations to improve the general behavior of the system is proposed. The approach is particularly suitable for plains areas where pumping stations are a key element of the network. The basic idea is to modify the pumping rules, which are usually dependent of the water level in the pump tank. Alternative pumping rules are devised, based on the inflow discharge; all (or some of) the available pumps are turned on as soon as the inflow exceeds a certain threshold of discharge, then, pumps work for a fixed time duration. When the inflow returns below the threshold, pumps switch to the standard rule based on the levels in the tank (dry weather conditions).

The proposed framework can be easily implemented in real-world cases as it simply requires a discharge/level gauge and some electrical equipment to control the pumping duration. The optimization of the parameters (activation threshold and pumping duration) can be effectively performed using a simplified hydraulic model, without resorting to the full hydrodynamic model of the sewer network. This allows the analyst to perform a sensitivity analysis to study the effect of the more uncertain parameters.

Results obtained from a case study show that the alternative pumping rule can significantly reduce the water volume pumped to the wastewater treatment plant, thus avoiding loss in the treatment efficiency due to the high pollutant dilution and saving energy. On the other hand, the overall pumped polluted mass can approach the total of the incoming mass, thus ensuring the treatment of most of the pollutant load. Overflow from the pumping station to the surrounding environment is generally larger than with the standard pumping rules, so that the overflow pollutant concentration should be carefully verified. However, it is also worth noting that a control weir is commonly located upstream from the wastewater treatment plant, acting as an overflow device when incoming fluxes exceed the plant capacity. This is a factor in the optimization that should be explicitly considered in future studies.

A great advance in pollution management can be obtained by framing the analysis in a statistical context, using a long-term, high-resolution rainfall sequence (often available but underutilized). This can produce reliable results when combined with currently available quantity/quality hydrodynamic models of the sewer network, so that the large spectrum of events can provide a statistical description of the behavior of the system. This aspect is of primary importance, as water quality issues typically depend also on nonextreme events (in contrast with problems related only to the conveyance capacity of the network) and thus the approaches typically used for the design of the networks are not adequate for pollution control.

In conclusion, the proposed framework appears to be easily applicable to real systems, with the final aim of minimizing the overall pollutant flux toward the environment and maximizing the efficiency of wastewater treatment plants during rainstorm conditions. The efforts in developing models and optimization procedures can then produce tangible benefits in terms of more efficient and even simpler infrastructure management.

Acknowledgments

References

Adams, B. J., and Papa, F. (2000). *Urban stormwater management planning with analytical probabilistic models*, Wiley, Hoboken, NJ.

Andrés-Doménech, I., Múnera, J. C., Francés, F., and Marco, J. B. (2010). "Coupling urban event-based and catchment continuous modelling for combined sewer overflow river impact assessment." *Hydrol. Earth Syst. Sci.*, 14(10), 2057–2072.

Artina, S., et al., eds. (1997). *Sistemi di Fognatura. Manuale di Progettazione*, CSDU, HOEPLI, Milano, Italy (in Italian).

Bertrand-Krajewski, J. L., Chebbo, G., and Saget, A. (1998). "Distribution of pollutant mass vs. volume in stormwater discharges and the first flush phenomenon." *Water Res.*, 32(8), 2341–2356.

Ciaponi, C., Papiri, S., and Todeschini, S. (2006). "Analisi e interpretazione della correlazione tra alcuni parametri inquinanti nella rete fognaria di Cascina Scala in tempo di pioggia." *Proc., XXX Convegno di Idraulica e Costruzioni Idrauliche*, IDRA, Roma (in Italian).

De Martino, G., De Paola, F., Fontana, N., Marini, G., and Ranucci, A. (2011). "Pollution reduction in receivers: Storm-water tanks." *J. Urban Plann. Dev.*, 10.1061/(ASCE)UP.1943-5444.0000037, 29–38.

Di Modugno, M., et al. (2015). "Build-up/wash-off monitoring and assessment for sustainable management of first flush in an urban area." *Sustainability*, 7(5), 5050–5070.

Freni, G., Maglionico, M., Mannina, G., and Viviani, G. (2008). "Comparison between a detailed and a simplified integrated model for the assessment of urban drainage environmental impact on an ephemeral river." *Urban Water J.*, 5(2), 21–31.

Freni, G., Mannina, G., and Viviani, G. (2010). "Urban storm-water quality management: Centralized versus source control." *J. Water Resour. Plann. Manage.*, 10.1061/(ASCE)0733-9496(2010)136:2(268), 268–278.

Lau, J., Butler, D., and Schütze, M. (2002). "Is combined sewer overflow spill frequency/volume a good indicator of receiving water quality impact?" *Urban Water*, 4(2), 181–189.

MATLAB [Computer software]. MathWorks, Natick, MA.

Qin, H., Tan, X., Fu, G., Zhang, Y., and Huang, Y. (2013). "Frequency analysis of urban quality in an urbanizing catchment of Shenzhen, China." *J. Hydrol.*, 496, 79–88.

Rossman, L. A. (2010). "Storm water management model user's manual version 5.0." *EPA/600/R-05/040*, U.S. Environmental Protection Agency, National Risk Management Research Laboratory-Office of Research and Development, Cincinnati.

Sansalone, J. J., and Cristina, C. M. (2004). "First flush concepts for suspended and dissolved solids in small impervious watersheds." *J. Environ. Eng.*, 10.1061/(ASCE)0733-9372(2004)130:11(1301), 1301–1314.

Sheng, Y., Ying, G., and Sansalone, J. (2008). "Differentiation of transport for particulate and dissolved water chemistry load indices in rainfall-runoff from urban source area watersheds." *J. Hydrol.*, 361(1–2), 144–158.

Todeschini, S., Papiri, S., and Ciaponi, C. (2014). "Stormwater quality control for sustainable urban drainage systems." *Int. J. Sus. Dev. Plann.* 9(2), 196–210.

van Daal-Rombouts, P., Sun, S., Langeveld, J., Bertrand-Krajewski, J. L., and Clemens, F. (2016). "Design and performance evaluation of a simplified dynamic model for combined sewer overflows in pumped sewer systems." *J. Hydrol.*, 538, 609–624.

Ying, G., and Sansalone, J. (2010). "Transport and solubility of heterodisperse dry deposition particulate matter subject to urban source area rainfall-runoff processes." *J. Hydrol.*, 383(3–4), 156–166.