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Article

Combined Application of Real-Time Control and Green Technologies to Urban Drainage Systems

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Abstract: The increase in waterproof surfaces, a typical phenomenon of urbanization, on the one hand, reduces the volume of rainwater that naturally infiltrates the subsoil and, on the other, it determines the increase in speeds, flow rates, and outflow volume surface; at the same time, it causes a qualitative deterioration of the water. This study researched the optimal management of urban drainage systems via the combined application of real-time control and green technologies. A hydraulic model of the sewer system of the suburbs of Bologna (Italy) was set up using the Environmental Protection Agency (EPA) Storm Water Management Model (SWMM) to evaluate the reduction in water volume and the masses of pollutants discharged in water bodies. The combined application of these technologies allows significantly reducing both the pollutants released into the receiving water bodies and the overflow volumes, while optimizing the operation of the treatment plants. Green technologies cause an average reduction equal to 45% in volume and 53% of total suspended solids (TSS) sent to the receiver. The modeled cases represent only some of the possible configurations achievable on urban drainage systems; the combined use of different solutions could lead to further improvements in the overall functioning of the drainage system.

Keywords: real-time control (RTC); Best Management Practice (BMP); SWMM; sustainable drainage system

1. Introduction

In light of the results of numerous studies demonstrating an increase in in the frequency of extreme precipitations and floods [1] and of soil sealing due to urbanization [2] all over Europe, stormwater management is assuming a crucial role in the preservation of urban catchments in the face of two undesired phenomena: (i) pluvial floods and (ii) combined sewer overflows (CSOs) [3]. Engineers should provide solutions to minimize the impact of these phenomena which negatively affect human life, economic assets, and the environment [4] without forgetting sustainability [5]. In fact, the "sustainable management of water" is a pillar of the 2030 Agenda (https://sustainabledevelopment.un.org/).

In the last few decades, European, national, and local authorities addressed these problems promoting mainly the use of three families of solutions: (i) "end-of-pipe solutions" (EOPSs), (ii) "source control technologies" (SCTs), and (iii) "real-time control" (RTC). The first includes construction techniques used to reduce already formed volumes of water and contaminants such as tanks and detention ponds. They are normally implemented as the last stage of a sewer system before the water is discharged into a water body [6,7]. Because of the high cost of end-of-pipe stormwater management solutions and the lack of space in which to build them, particularly in highly urbanized urban basins, many water utilities are currently investigating the feasibility of reducing runoff with decentralized SCTs distributed throughout the urban watershed. This second family of solutions includes a range of approaches and techniques for local, on-site management and control of stormwater runoff at the point of rainfall [8,9]. Examples include green roofs, bioswales, rain gardens, permeable pavements, vegetated strips, wet/dry ponds, and others [10–12]. "Rainwater harvesting systems" can be considered a further example of SCTs. Despite being designed to meet other needs such as fighting water scarcity, reducing water withdrawal from traditional sources, or promoting water saving in buildings, they reduce and delay the peak of runoff conveyed into the sewer systems, thereby contributing to CSO reduction [13].

Approaches to water pollution control that focus on wastewater prevention and minimization should be given priority over traditional EOPS whenever possible [14]. In Italy, because of decades of design processes influenced by polices which incentivized the use of SCTs, most cities currently integrate both types of solutions. Moreover, there is also a third family of technologies, known as RTC, which allows minimizing overflows by optimizing water volumes stored in the sewer system. This group of technologies can be realized by efficiently operating the regulators of the system, such as pumps, gates, or others. RTC can be applied to manage the overall drainage systems including both EOPSs and SCTs. Most studies have been field-based and focused mainly on monitoring and then simulating a single type of technology at a site or a block scale. For example, some authors [15–17] built and monitored some green roofs to reduce peak flows, while other estimated the storm water mitigation potential of rainwater harvesting systems at the urban scale. Others have shown that permeable pavements were effective in retaining precipitation during storm events [18–21], that SCTs can alleviate water quality problems associated with diffuse pollution [22], that storm detention tanks are efficient even under rainfall variability due to climate change [6], and that RTC is not only a cost-efficient measure to mitigate the impact of CSOs but also a solution offering the most flexibility for further system upgrade [23]. No study has focused on evaluating the possible benefits deriving from the combined application of the technologies mentioned above simulated with long-time rainfall series. Therefore, the optimal management of a current urban drainage system cannot neglect the possibility of studying the influence of a complementary use of EOPSs, SCTs, and RTC in terms of reducing the volumes of water and masses of pollutants discharged by CSOs, as well as urban flooding. To address the abovementioned lack of knowledge, the long-term behavior of a small urban catchment (48 ha) was studied using a scenario-based approach. Runoff quantity and quality were modeled by means of the Environmental Protection Agency (EPA) Storm Water Management Model (SWMM). Simulations were carried out using 15 years of weather data (rainfall and air temperature data with a 15 min time step). Scenarios evaluated the single impact of the abovementioned technologies and of their combination.

2. Materials and Methods

2.1. Pilot Catchment and Datasets

The city of Bologna (44°29′38″ north (N), 11°20′34″ east (E)) is the county seat of the Emilia-Romagna Region, Italy. The sewer system of the city is mostly combined. A total area of approximately 5530 ha is drained by 728 km of sewer pipes. During dry weather, wastewater of 3.5×10^5 inhabitants goes to the wastewater treatment plant (WWTP) both via gravity and via the use of 14 pump systems. During wet weather, wastewater and stormwater are mixed and, when the sewage flow exceeds the WWTP capacity, 122 CSOs guarantee the overall hydraulic safety of the city and the WWTP efficiency by spilling the excess wastewater directly into receiving waters [24]. The "Fossolo" catchment (Figure 1), located in the southeastern suburbs of the city, is a densely urbanized residential area, monitored since 1995 for water quantity and quality aspects. For this reason, it was chosen as the study area. A total area of approximately 48 ha is connected to the drainage network, and wastewater (about 10,000 inhabitants) and rainfall are drained with a combined sewer system.

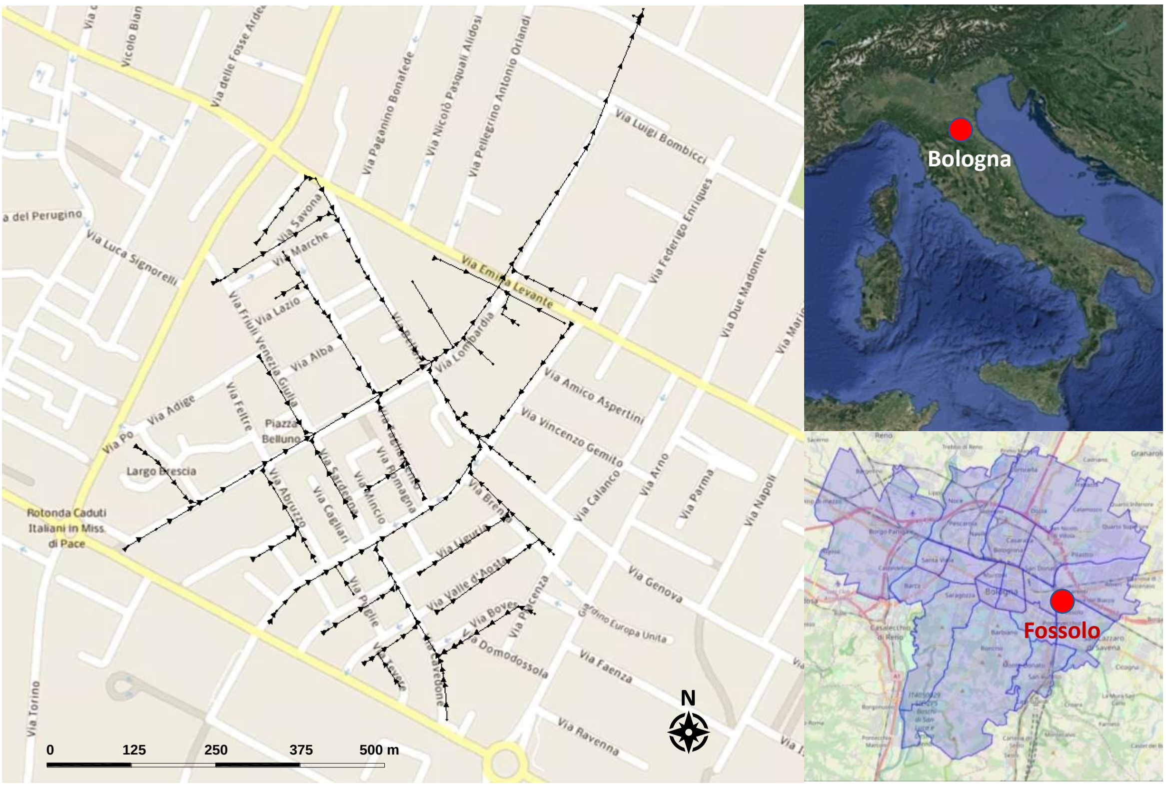


Figure 1. Catchment boundary and sewer layout for the pilot urban catchment.

Dominant land uses are residential, public service (civic), and commercial. The slope of the catchment goes from southwest to northeast and has an average value of 0.6%, ranging from 62.59 m above sea level to 54.13 m above sea level. The sewer system of the catchment (almost 5 km) was built in the 1960s; the final section was made by using bricks and adopting a polycentric section (1.44 m high and 1.80 m wide), while the remaining sections are mainly concrete egg-shaped pipes. The final conduit does not carry wastewater to a point of disposal; instead, it conveys the wastewater to a further polycentric conduit (1.92 m × 2.40 m). However, as the study was focused on volumes and mass reduction spilled by the catchment, a CSO (sized in agreement with local regulations) instead of the real geometry was considered. The site was equipped with two rain gauges, two flow meters, and an automatic sampling system to collect and later analyze wastewater quality during both dry and wet weather. Details on the monitoring campaign can be found on Marinelli et al. [25] and Calabrò et al. [26].

2.2. Hydraulic Model

For this small catchment, urban hydrodynamic models were set up in the Environmental Protection Agency (EPA) SWMM [27]. The model, initially set up by the University of Bologna and the Water Utility back in 2000 to gain a strategic understanding of the hydraulic behavior of the catchment, was recently updated to the 5.1.014 SWMM release. This model divides the area into 203 sub-catchments, connected with 203 nodes and 202 pipes (Figure 2a). As previously said, to disconnect the network from the downstream system, a CSO instead of the real node was modeled. It was composed of a weir, sized to activate when the flow rate exceeded five times the average dry weather flow rate. Excess of water was spilled by the CSO to a hypothetical receiving water body (Figure 2b,c).

The model was calibrated and validated on the basis of experimental data available [24,25] for both dry and wet weather. The model calibration and validation procedures are not presented on this study; however, the main calibration parameters obtained for both quantity and quality aspects are summarized in Table 1.

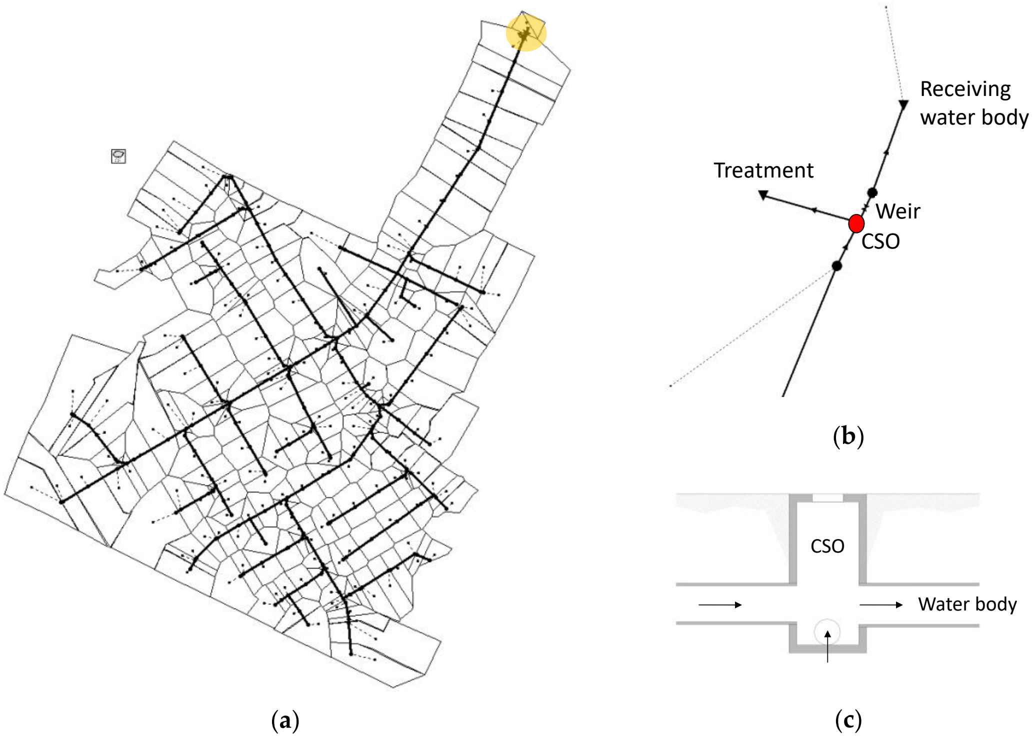


Figure 2. Model geometry: (**a**) Storm Water Management Model (SWMM) representation of the sewer network, where the yellow dot indicates the outfall of the system; (**b**) zoomed-in view of the model of the combined sewer overflow (CSO) located at the end of the system and (**c**) relative section.

Table 1. Main parameters obtained from model calibration in SWMM 5.1.014.

Type	Name	Description	Unit	Value
Quantity	N-imperv	Manning coefficient for impervious area	-	0.02
Quantity	N-perv	Manning coefficient for pervious area	-	0.16
Quantity	Dstore-perv	Depth of depression storage on pervious area	mm	3.0
Quantity	Dstore-imperv	Depth of depression storage on impervious area	mm	0.7
Quantity	% Slope	Average surface slope	%	1.7
Quality	DWF	Concentration of the pollutant in dry weather sanitary flow	mg/L	230
Quality	Max buildup	Maximum buildup	kg/ha/day	16
Quality	Rate Constant	Rate constant of buildup function	1/day	0.08
Quality	Washoff Coefficient	Washoff coefficient	1/mm	0.203
Quality	Exponent	Runoff exponent in washoff function	-	1.8

2.2.1. Input Data

Rainfall

The rainfall and air temperature regimes were analyzed using data recorded by the "Bologna Urbana" weather station, managed by the regional Agency ARPAE (https://www.arpae.it/). Rainfall data used for simulations ranged from 1 January 2005 to 31 December 2019 (15 years with a 15 min time step). Figure 3 shows the daily distribution of rainfall and the daily maximum and minimum air temperature, while Figure 4 shows the total and the average rainfall height over the simulation period. The rainiest year (977 mm) was 2005, while the driest was 2011 (488.5 mm). The average annual rainfall was 727 mm. The number of days with precipitation greater than 1 mm was 1182, corresponding to about 79 wet days per year. Figure 5 shows the cumulative frequency curve of the daily rainfall. Four events with a frequency value over 0.0025, 21 events with a frequency value over 0.013, and 139 events with a frequency value over 0.089 exceeded 60, 40, and 20 mm/day, respectively. About 77% of the events had a daily height of precipitation below 10 mm/day.

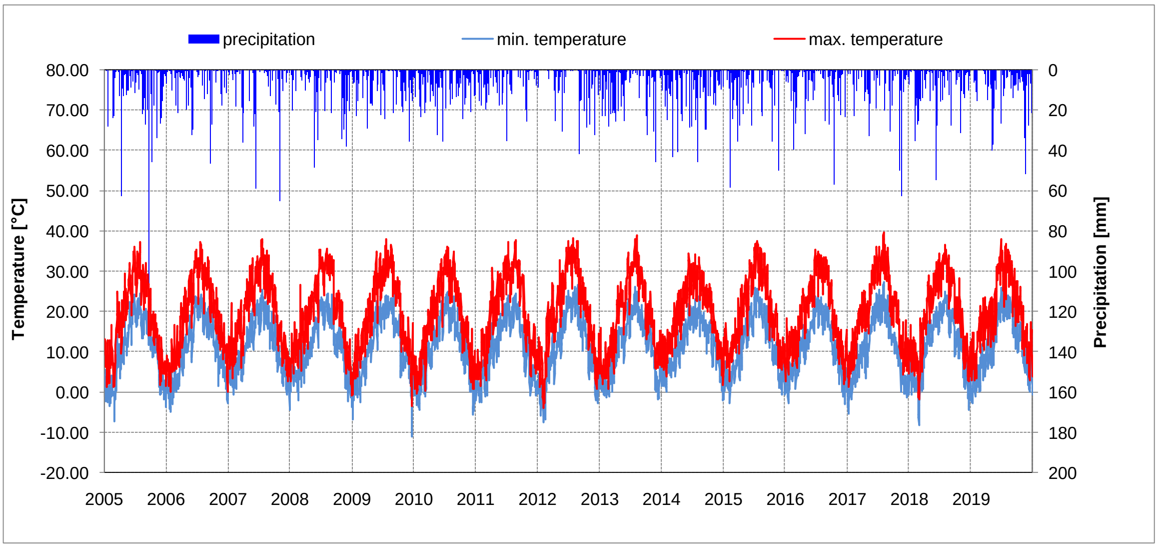


Figure 3. Histogram of the daily cumulative precipitation, and maximum (red) and minimum (light blue) daily air temperature values from 2005 to 2019.

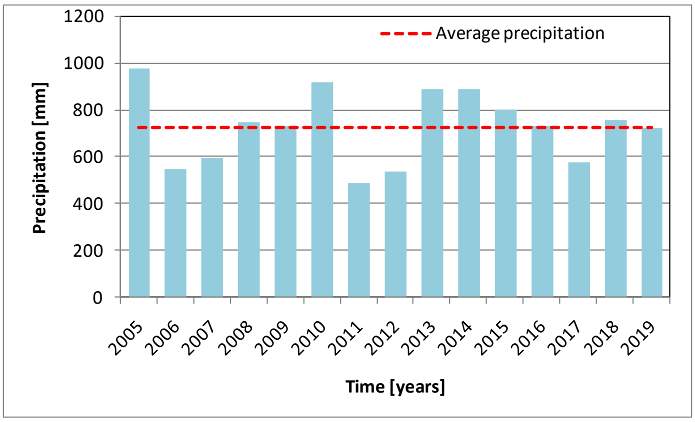


Figure 4. Histogram of the annual precipitation (light blue) and average value (red line) from 2005 to 2019.

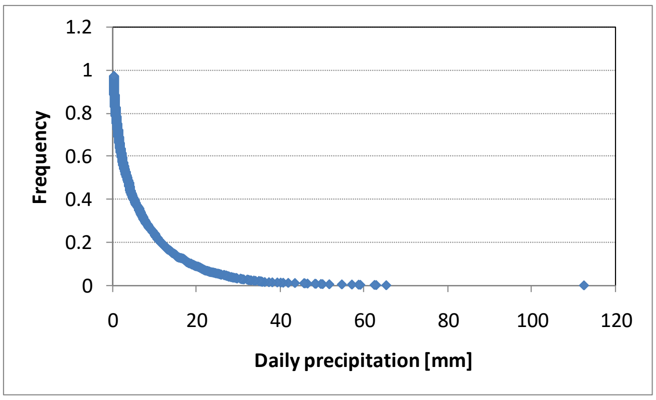


Figure 5. Frequency distribution of daily rainfall for the period 2005–2020.

Dry Weather Flow

The baseline dry weather inflow of catchments was calculated on the basis of their number of inhabitants. The time pattern, illustrated in Figure 6, whose factors adjust the baseline inflow on a daily basis, was obtained by dry weather calibration.

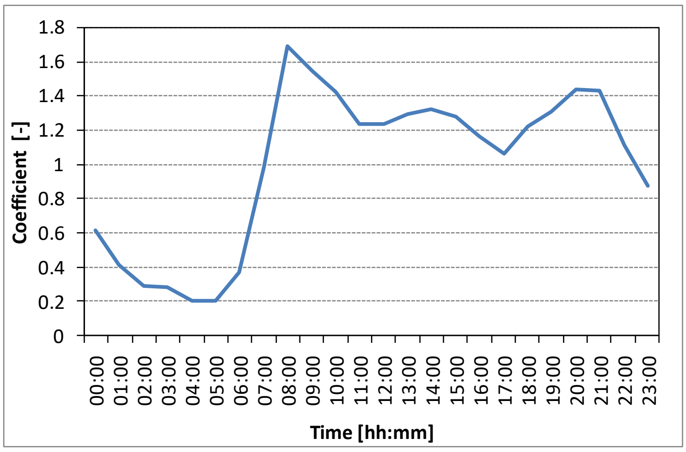


Figure 6. Wastewater daily patterns.

2.2.2. Green Roofs

Green roofs, also known as vegetated roof covers or living roofs, are a complex multilayer structure. They are mostly used in the case of retrofitting of existing buildings due to their low weight and minimal maintenance requirements. The long-term modeling of green roofs was carried out following the guidelines and the parameters presented by Cipolla et al. [16]. An extensive green roof package with 15 cm of substrate was located above the roof building. Evapotranspiration was modeled using the maximum and minimum daily air temperature and following the Hargreaves–Samani formulation [28].

2.2.3. Rainwater Harvesting Systems (RWHSs)

RWHSs allow the collection and the reuse, for nonpotable purposes, of rainwater; thus, their first goal is the reduction of conventional water withdrawal. However, as they retain important volumes of precipitation, they also pursue a secondary goal which consists of the reduction of runoff. In this study, RWHSs were sized according to the Italian UNI/TS 11,445 regulation [29], while their long-term behavior was modeled according to the procedure proposed by Cipolla et al. (2018a) [30]. As recommended by Cipolla et al. (2018b) [31], cisterns, to be economically sustainable, must recover at least 60% of water needed to meet nonpotable consumption.

2.2.4. End-of-Pipe Solutions: Storm Detention Tanks

A storm detention tank detains rainwater for a limited period and releases it in a controlled manner. The detention volume is created because inflows to the detention facility exceed the controlled outflow rate, and runoff accumulates in the designated detention area until inflow rates decrease. It represents a last line of defense in dealing with stormwater runoff and helps to prevent urban flooding. For new development, it is common practice to require detention storage so that peak flow rates for the proposed development do not exceed predevelopment peak flow rates. In the context of redevelopment or infill development in urban areas, the goal of detention often is to ensure that runoff from the development site does not exceed the capacity of the existing conveyance system or exacerbates existing flooding problems. This study used two sizing criteria differing according to the specific storage volume of the detention tank. Specific volumes were assumed equal to 10 m^3 (Case a) and 50 m^3 (Case b) per hectares of impervious surface drained by the upstream network, while the outflow was assumed to be 3 L/(s·ha) for both cases. This led to the inclusion of six offline tanks located along the network. Each of them was modeled by adding a lateral threshold and a storage node which was emptied by means of a pump with a constant flow rate. The volume of the storage node and the pump flow rate depended on the sizing criteria and surface of the upstream catchment.

2.3. RTC Strategy Design

The RTC system design is usually based on two main steps: (1) the identification of controllable sub-basins, relative interconnections, and control locations, and (2) the design of control algorithms [32].

2.3.1. Identification of Control Locations

Before identifying the links where RTC controllers must be installed, some preliminary actions are required. The first is the manual definition of the system's most downstream node, which, in this case, coincided with the CSO (Figure 2). From this point forward, the terms CSO and "end node" are considered synonymous. CSO was used as the starting point for further network analyses, and any hydraulic structures downstream were ignored. The remainder of the procedure involved a detailed analysis of all the links upstream of the CSO, the related sub-basins, and the storage capacity. The literature shows that the identification of the conduits or node in which the installation of an RTC system is advisable can be done by using different approaches. For example, Vonach et al. [33] provided a procedure for the identification of the most suitable links for the installation of a monitoring system using a heuristic approach. Kroll et al. [32] proposed a methodology for the automated design of RTC strategies for combined sewer systems using graph theory applied to sewer systems. According to the approaches proposed by the abovementioned studies, seven control sections were identified, with their positions shown in Figure 7. Sluice gate 1 (S.g.1) was located at the end of the system, immediately before the CSO, and six gates were located on the subnets [34].

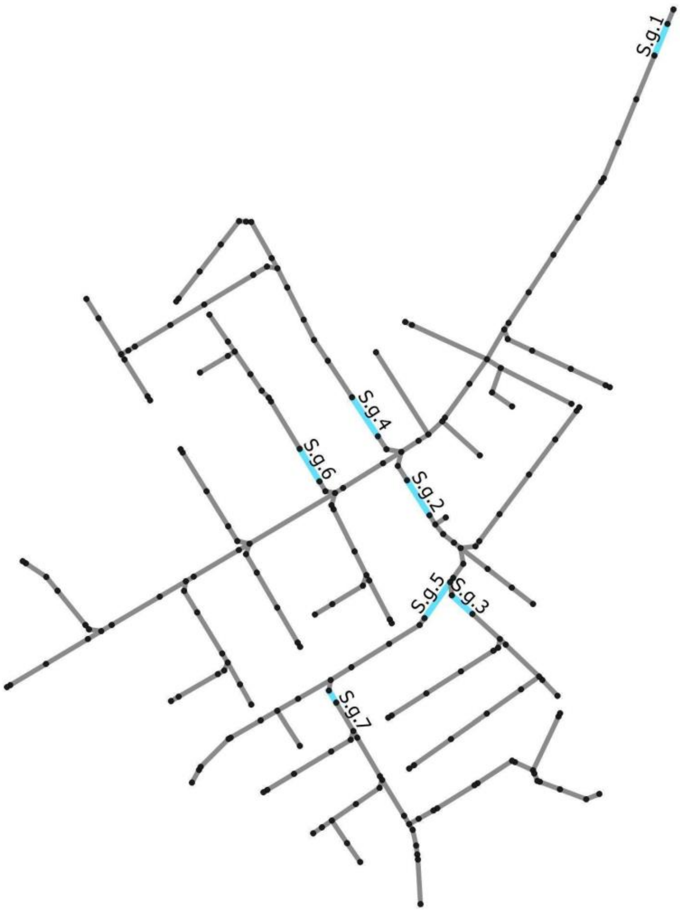


Figure 7. Network scheme with sluice gate positioning.

Sluice gates 2, 4, and 6 controlled three of the four main sub-basins that comprised the main catchment, while S.g.3 and S.g.5 were located upstream of S.g.2. Table 2 summarizes the main characteristics of the sub-basins controlled by each gate.

Table 2. Characteristics of the sub-basins controlled by each sluice gate.

Name	Drained Area (ha)	Upstream Sluice Gate
S.g.1	43.14	S.g.2, S.g.3, S.g.4, S.g.5, S.g.6, S.g.7
S.g.2	14.24	S.g.3, S.g.5, S.g.7
S.g.3	2.27	-
S.g.4	4.40	-
S.g.5	8.16	S.g.7
S.g.6	2.13	-
S.g.7	5.52	-

2.3.2. RTC Modeling

Once the position in which to install the sluice gate was identified, a local RTC system to reduce peak and system surcharge and optimize the utilization of existing storage volumes was implemented for each of them. The overall RTC systems were managed by PID (proportional–integral–derivative) controllers. PID "standard" controllers send to the regulators proportional (P), integral (I), or derivative (D) movement signals or a combination of these types. Each sluice gate was modeled in SWMM as two orifice links to regulate the flow rate. Orifices, in fact, are used to model outlet and diversion structures in drainage systems, which are typically openings in the wall of a manhole, storage facility, or control gate. The principal input parameters for an orifice include the following: (i) conduit's cross-section shape (rectangular or circular), (ii) dimensions, (iii) configuration ("side" or "bottom"), and (iv) discharge coefficient. The flow through an orifice is computed on the basis of the area of its opening, its discharge coefficient, and the head difference across the orifice. As the drainage system was combined, two orifices for each sluice gates were needed (Figure 8). The former was a bottom-type orifice link; its role was to intercept and regulate the dry weather flow rate following a control rule. The other was a side-type orifice link, controlled by a PID, used to regulate wet weather flow.

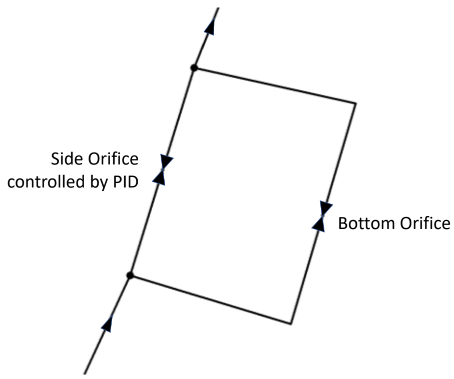


Figure 8. SWMM representation of the two orifices "side" and "bottom".

In this context, the PID controller was used to adjust the opening on a gated orifice to maintain a target flow rate in a specific conduit. As recommended by Campisano et al. [35], the PID needs to be calibrated to reduce the numerous errors.

A standard PID controller (Equation (1)) has the following form [27]:

$$m(t) = K_p\left[e(t) + \frac{1}{T_i}\int e(\tau)d\tau + T_d\frac{de(\tau)}{dt}\right], \quad (1)$$

where $m(t)$ is the controller output, K_p is the proportional coefficient (gain), T_i is the integral time (minutes), T_d is the derivative time (minutes), $e(t)$ is the error (difference between set-point and observed variable value), and t is the time.

The performance of a general PID controller is determined by the values assigned to the coefficients K_p, T_i, and T_d. Because link settings are relative values (with respect to the full opening height of the sluice gate), the error $e(t)$ used by the controller is also a relative value. It is defined as the difference between the control variable set-point x^* and its value at time t, $x(t)$, normalized to the set-point value.

$$e(t) = \left(\frac{x^* - x(t)}{x^*} \right). \tag{2}$$

The control variable used in this study is the water level in the upstream node of a sluice gate. It must be noted that, for direct action control, where an increase in the link setting causes an increase in the controlled variable, the sign of K_p must be positive. For reverse action control, where the controlled variable decreases as the link setting increases, the sign of K_p must be negative. K_p was adjusted to maintain an upstream water level, and it was considered a reverse action with negative sign (see Table 3).

The action clause of each sluice gate was the storage capacity of the upstream node. Its maximum storage capacity was set in the range 80–85%. K_d, T_i, and T_d values were calibrated in order to allow a gradual opening of the gate, trying to keep the filling of the upstream node in the range and to minimize the sudden opening and closing of the operating device. The values of the calibrated parameters are shown in Table 3.

Table 3. Proportional–integral–derivative controller (PID) constants set in SWMM 5.1 as control rules for the Fossolo network model.

Smart Gate	K_p	T_i (Minutes)	T_d (Minutes)
S.g.1	−10	0.1	0
S.g.2	−10	0.1	0
S.g.3	−10	0.1	0
S.g.4	−1	0	0
S.g.5	−10	0.01	0
S.g.6	−1	0	0.01
S.g.7	−10	0.1	0

2.4. Scenario Development

Following the purpose of evaluating the effectiveness of different technologies (EOPSs, SCTs, RTC, and RWHSs) and their combination, in preventing combined sewer overflows, a scenario-based analysis is presented. A benchmark scenario and 11 alternative scenarios were developed, and a short description, the acronym, the type of technology, and the allocation of RTC are described below for each scenario (Table 4). The sequence for developing alternative scenarios started with using only SCTs (green roofs, permeable pavements, rainwater harvesting systems) with and without RTC, and eventually including EOPSs (detention tanks), starting from easy installations to more difficult options, and moving from systems that do prevention to those that manage already formed problems. The benchmark scenario ($C1_{real}$) was the real sewer network without any installation in the sewer and consisted of 52% (24.7 ha) impervious areas, while the remaining (22.8 ha) could be considered pervious (public and private gardens).

The first alternative scenario ($C1_{RTC}$) represented installation of control sluice gates on seven conduits of the network, according to the RTC strategy design previously illustrated. From this point forward, all scenarios that derived from the C1 sewer model are denoted by the "real" subscript, while those equipped with the RTC system are denoted by the "RTC" subscript, using the network of the C1 scenario as a starting point. The second scenario (Case 2) represented installation of green roofs on all suitable private or public-owned roofs. It resulted in 8.4 ha of impervious roofs which were replaced by 15 cm thick extensive green roofs. The third scenario (Case 3) represented installation of porous pavements on driveways and paved parking lots, an alternative to the Case 2 scenario. The imperviousness of each subcatchment (roofs excluded) was decreased by 15%, resulting in 7.12 ha of permeable surface homogeneously distributed on the urban basin. The fourth scenario (Case 4) represented installation of seven rainwater harvesting systems located above the control sections. It resulted in 6450 m^3 of privately owned tanks which, allowed reducing the water supply consumption by at least 60%. The last scenario, Case 5, represented installation of six detention basins, an alternative to the previous scenario. The overall capacity of the detention basins was designed to receive runoff from the drainage area to store 10 m^3/ha and 50 m^3/ha for cases 5a and 5b, respectively.

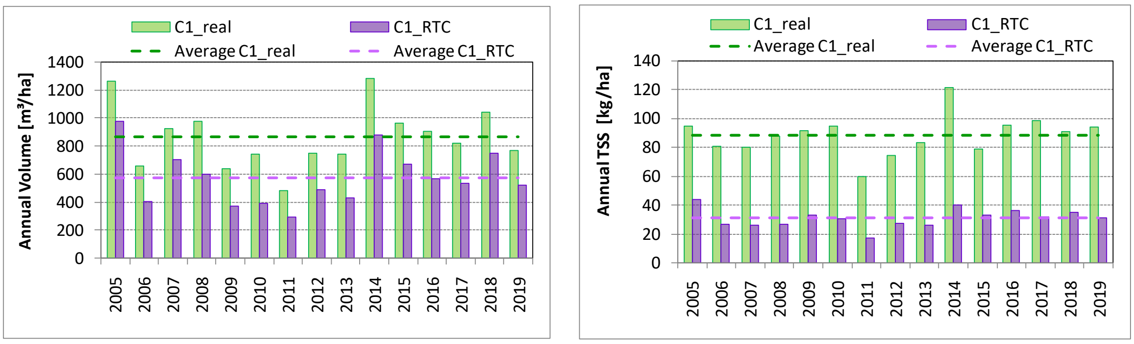
Table 4. Conditions simulated for each scenario, including end-of-pipe solution (EOPS), source control technology (SCT), and real-time control (RTC) systems.

N	Case	Description	Acronym	EOPS	SCT	RTC
1	Case 1	Benchmark network	$C1_{real}$			
2	Case 1	Benchmark network with RTC	$C1_{RTC}$			x
3	Case 2	Green roofs with RTC	$C2_{RTC}$		x	x
4	Case 2	Green roofs	$C2_{real}$		x	
5	Case 3	+15% pervious surfaces with RTC	$C3_{RTC}$		x	x
6	Case 3	+15% pervious surfaces	$C3_{real}$		x	
7	Case 4	7 rainwater harvesting tanks + RTC	$C4_{RTC}$		x	x
8	Case 4	7 rainwater harvesting tanks	$C4_{real}$		x	
9	Case 5a	6 detention tanks (10 m^3/ha) + RTC	$C5a_{RTC}$	x		x
10	Case 5a	6 detention tanks (10 m^3/ha)	$C5a_{real}$	x		
11	Case 5b	6 detention tanks (50 m^3/ha) + RTC	$C5b_{RTC}$	x		x
12	Case 5b	6 detention tanks (50 m^3/ha)	$C5b_{real}$	x		

3. Results and Discussion

Twelve scenarios with different green, gray, and RTC installations were modeled under 15 years of rainfall and temperature data. Simulations results were evaluated with respect to the $C1_{real}$ benchmark scenario in terms of runoff volumes (m^3) and total suspended solids (TSS) (kg) spilled by the CSO into the receiving water body. Long-term simulation results were analyzed on an annual basis and divided by the total surface. This allowed analyzing specific values of runoff volume (m^3/ha) and TSS (kg/ha). The CSO specific volume and TSS of overflow spilled into the river, computed as the medium values over the 15 years, were fairly significant, ranging from 864 m^3/ha to 24 m^3/ha and from 88 kg/ha to 1 kg/ha, respectively.

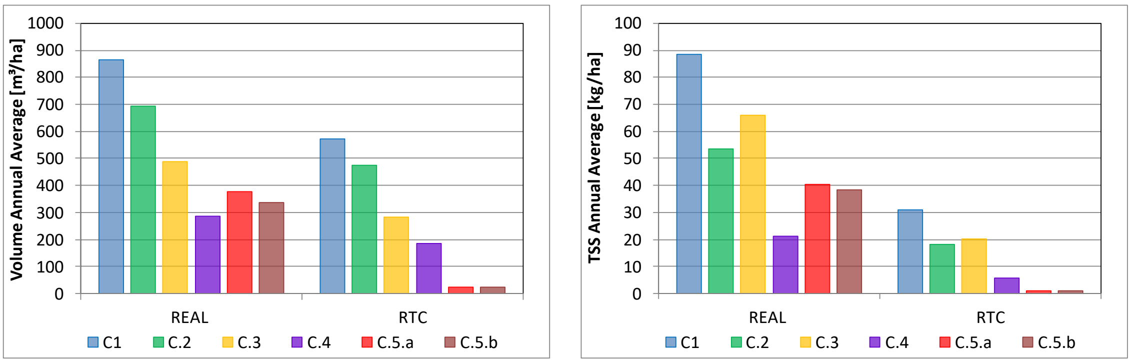
Compared to the benchmark scenario ($C1_{real}$), the $C1_{RTC}$ scenario reduced runoff and TSS by 34% and 65%, respectively, and confirmed the possibility of increasing the efficiency of the wastewater treatment system to which the most polluted water is sent (Table 5). Figure 9 shows, year by year, the reduction in both runoff volume and TSS [36].



(**a**) (**b**)

Figure 9. Annual specific runoff volume (**a**) and specific total suspended solids (TSS) (**b**) spilled by the CSO into the receiving water body under C0 (benchmark scenario) and C1 (benchmark scenario + RTC) scenarios.

Figure 10 depicts a bar chart of the simulation results, in terms of specific average runoff volume (a) and TSS (b), for all scenarios considered, while Table 5 shows the corresponding numerical values.



(**a**) (**b**)

Figure 10. Annual average specific runoff volume (**a**) and annual average specific TSS (**b**) discharged by the CSO.

Table 5. Simulation results in terms of specific annual average runoff volume and TSS spilled by the CSO into the receiving water body and relative percentage of reduction using $C1_{real}$ as the benchmark scenario.

Case	Volume Annual Average (m^3/ha)	TSS Annual Average (kg/ha)	Volume Reduction Compared to $C1_{real}$ (%)	TSS Reduction Compared to $C1_{real}$ (%)
$C1_{real}$	864	88	/	/
C_{RTC}	571	31	34%	65%
$C2_{real}$	692	54	20%	39%
$C2_{RTC}$	474	18	45%	79%
$C3_{real}$	489	66	43%	25%
$C3_{RTC}$	283	20	67%	77%
$C4_{real}$	285	65	67%	76%
$C4_{RTC}$	186	21	78%	93%
$C5a_{real}$	376	40	56%	54%
$C5a_{RTC}$	24	1	97%	99%
$C5b_{real}$	336	39	61%	56%
$C5b_{RTC}$	24	1	97%	99%

The $C2_{real}$ scenario (green roof) reduced runoff by 20% and TSS by 39% compared to the baseline scenario. The increased percentage of porous pavement in the $C3_{real}$ scenario reduced stormwater runoff by 43% and TSS by 25%, as compared to the $C2_{real}$ scenario because the $C3_{real}$ scenario increased infiltration of stormwater runoff. Figure 11 shows the differences in terms of the total volumes of water infiltrated, drained, and lost through evapotranspiration for cases C1, C2, and C3. In the green roof scenario (C2), 27% of the rain evaporated, 40% infiltrated, and the remaining 33% drained to the sewer system. In scenario C3, however, the predominant phenomenon was that of infiltration (65%), followed by drainage (25%) and evapotranspiration (10%). The ability to infiltrate great volumes of water, typical of the permeable pavements used in the C3 scenario, allowed reducing volumes drained by the sewer system and, therefore, those spilled by the CSO toward the water body. However, these technologies, unlike the green roofs present in the $C2_{real}$ scenario, are unable to filter the water. This is the reason why TSS removal was more pronounced in scenario $C2_{real}$ (39%) than in scenario $C3_{real}$ (25%). In both cases (C2 and C3), the additional presence of the RTC system determined a marked improvement in performance in terms of volume runoff. Furthermore, since the presence of an RTC system optimizes the storage capacity of the network and, therefore, increases the volumes of wastewater sent to depuration, the $C3_{RTC}$ scenario could guarantee a clear improvement in terms of TSS removal respect to $C3_{Real}$. In fact, there was a decrease in the difference in TSS removal between the C2 and C3 scenarios, which went from an average of 14% to 2% in the real and RTC configurations, respectively. Figure 12 shows, year by year, the differences in volumes and TSS among $C1_{real}$, C2, and C3 cases for both configurations (real and RTC).

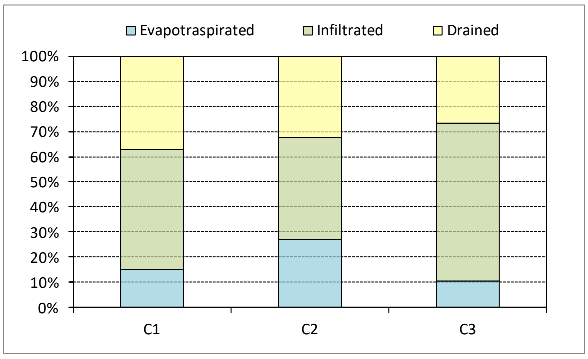
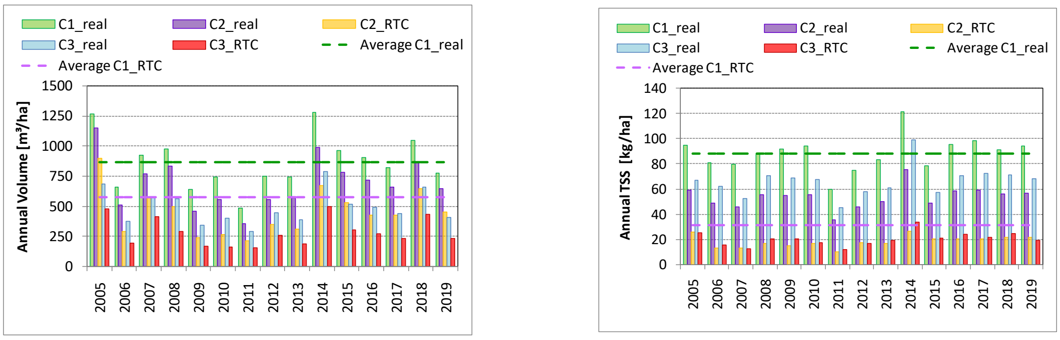


Figure 11. Graph related to the percentages of infiltrated, lost (due to evapotranspiration), and drained water with respect to rainfall, in cases C1, C2, and C3.



(**a**) (**b**)

Figure 12. Graphs related to the annual volume (**a**) and TSS (**b**) sent to the receiver when comparing the real scenario C.1_{real} with scenarios C2 and C3 with and without the RTC system.

The $C4_{real}$ and $C4_{RTC}$ scenarios (rainwater harvesting systems) reduced runoff by 67% and 78% and TSS by 77% and 93%, compared to the baseline scenario. These systems stored varying volumes of precipitation which were then used by people for nonpotable purposes. In fact, they reduced the volumes of rain entering the sewer system, and this reduction led to less volume and mass spilled from CSO. The efficiency of these systems depended greatly on the type of rainy events; well-distributed low-intensity events led to a higher efficiency than a few very intense rainfall events. The use of 15 years of rainfall data allowed us to evaluate the average behavior, including the frequency of heavy rainfall. Simulation results showed that rainwater harvesting systems are a valuable technology not only to reduce potable water consumption but also to prevent CSO spills. Furthermore, in this case, the presence of an RTC system contributed significantly to lowering the peak flow rate below the threshold of the CSO and, consequently, the volume of runoff and the mass of TSS discharged.

Case C5a and C5b scenarios were those equipped with 450 and 2245.5 m^3 of detention ponds, respectively, which guaranteed the hydraulic safety of the catchment. Compared to $C1_{real}$, $C5a_{real}$ reduced stormwater runoff and TSS mass by 56% and 54%, respectively, while $C5b_{real}$ reduced stormwater runoff and TSS mass by 61% and 56%, respectively. This means that increasing the holding volume by five times increased the system performance by only 5% for volume and 2% for TSS mass. On the contrary, the inclusion of an RTC system in scenario C5a led to a net improvement in performance. In fact, $C5a_{RTC}$ showed a reduction of 97% for volume and 99% for TSS. This means that the joint insertion of detention systems of 10 m^3/ha and an RTC system practically eliminated all CSO spills. With scenario $C5b_{RTC}$, there were identical results.

The results of the simulations showed that the inclusion of an RTC system led to a significant hydraulic and environmental benefit, both in the base scenario and in all scenarios equipped with SCT or EOPS technologies. In particular, the simulation results showed that RTC systems are better at reducing the mass of TSS than the volumes. However, it should be noted that the use of RTC technology requires an important economic and management effort on the part of multiple utilities and does not lead to secondary benefits such as biodiversity, hydrological regeneration, or reduction in water withdrawal. The realization of an RTC system requires a high level of technology in terms of sensors, alarm systems, and controls. Furthermore, the technological complexity of these systems leads to a need to create detailed maintenance plans. EOPSs have proven to be an excellent tool for reducing outflows; however, their ability to remove TSS is adequate and they do not provide any further ecosystem services. On the other hand, SCTs show different behavior depending on the predominant mechanism. In fact, from the comparison of C2 and C3, it emerged that technologies such as permeable pavements, in which infiltration is predominant, have better performance in terms of a reduction in outflows, while those in which evapotranspiration predominates remove TSS better. This is mainly attributable to the vegetation that filters the water by retaining the particles of pollutants. In addition to the hydraulic benefits measured using the model, it is important to underline how these solutions also contribute to the increase in biodiversity, the creation of public spaces, the mitigation of the heat island effect, hydrological regeneration, etc. [37–39]. On the other hand, these spaces are generally private; thus, the maintenance and construction operations fall on a single individual and not on multiple utilities, which can represent both an advantage and a disadvantage linked to the difficulties in controlling efficiency over time. Of all the technologies analyzed, rainwater harvesting systems appear to be the most efficient in terms of both volume reduction and TSS mass removal. These systems also make it possible to create onsite water supply sources by reducing the withdrawal from the traditional water supply. They, therefore, contribute to reducing the consumption of precious water resources while increasing the resiliency of the entire supply system. Furthermore, in this case, the costs of such interventions are often borne by individual citizens, and it is difficult to monitor the functioning status of these plants over time. While many local authorities promote their use through incentives, there is often no way to verify that these remain in place and, without incentives, the cost of water is often so low that it is not possible to reach the breakeven point of the investment in a reasonable time.

4. Conclusions

This study provided and illustrated a modeling tool for analyzing the outcomes of installing EOPSs, different types of SCTs, and RTC to reduce the amount of volume and TSS mass spilled into the receiving body during CSO events. The case study referred to a small catchment located in the first suburbs of the city of Bologna (Italy). Starting from a numerical model of the drainage system, calibrated and validated on the basis of experimental measures for both water quality and quantity, different technologies were inserted such as green roofs, permeable pavements, rainwater harvesting tanks, and detention tanks with and without RTC systems. This resulted in 12 different scenarios. Simulations were carried out continuously using 15 years of precipitation and temperature data as the input. The model was shown to be an excellent tool for evaluating the long-term behavior of these technologies. In particular, the use of long series of precipitation and temperature data allowed simulating the real cycles of filling and emptying of the reservoirs, as well as the evapotranspiration phenomena that greatly influence the behavior of technologies equipped with vegetation. In general, all systems showed a good ability to reduce volume and TSS mass. EOPSs appear to be very efficient; however, they do not come with secondary benefits. The model was also shown to be a valuable tool to optimize the size of storage tanks, as emerged from the comparison of scenarios C5a and C5b. Among the SCT technologies, rainwater recovery systems proved to be the most efficient in terms of volume and mass reduction. They were also capable of increasing the resilience of the city by providing an unconventional source of water supply. RTC systems are a promising tool if applied to all the technologies analyzed. In particular, the possibility of exploiting the maximum reservoir capacity of the sewer system makes it possible to significantly act on the spilled masses.

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