Catchment-wide validated assessment of Combined Sewer Overflows (CSOs) in a Mediterranean coastal area and possible disinfection methods to mitigate microbial contamination

Paolo Crocetti [1], Anna Laura Eusebi [1,*], Cecilia Bruni [1], Enrico Marinelli [1], Giovanna Darvini [2], Claudio Bernardo Carini [3], Cristiana Bollettini [3], Virginia Recanati [3], Çağrı Akyol [1,*], Francesco Fatone [1]

[1] *Department of Science and Engineering of Materials, Environment and Urban Planning-SIMAU, Marche Polytechnic University, 60131, Ancona, Italy*

[2] *Department of Civil and Building Engineering and Architecture, Marche Polytechnic University, 60131, Ancona, Italy*

[3] *CIIP SpA – Cicli Integrati Impianti Primari – Water Utility - Viale della Repubblica, 24 - 63100 Ascoli Piceno, Italy*

*Corresponding authors (A.L. Eusebi; Ç. Akyol)

Phone: +390712204911

E-mails: a.l.eusebi@staff.univpm.it; c.akyol@staff.univpm.it

ABSTRACT

The first phase of this study aimed to evaluate the environmental impact of combined sewer overflow (CSO) events originated from 35 spillways on the Rio Vallescura catchment (Central Italy) and to understand their contribution to the deterioration of the coastal bathing water quality. A specific analytical campaign was carried out in the sewer system and a dynamic rainfall-runoff simulation model was developed and integrated with a water quality model and further validated. The simulations led to identify the most critical spills in terms of flow rate and selected pollutant loads (i.e. suspended solids, biochemical oxygen demand, chemical oxygen demand, total Kjeldahl nitrogen, *Escherichia coli*). Specifically, the *E. coli* release in the water body due to CSO events represented almost 100% of the different pollutant sources considered. In the second phase, the applicability of various disinfection methods was investigated on the CSOs introduced into the catchment. On site physical (UV) and lab-scale chemical (peracetic acid (PAA), performic acid (PFA), ozone) disinfectant agents were tested on microbial indicators including *E. coli* and intestinal enterococci. PFA and ozone were more effective on the removal of both bacteria (above 3.5 log units) even at low concentration and with short contact time; whereas, PAA showed a moderate removal efficiency (around 2.5 log units) only for *E. coli*. The highest removal efficiency was achieved in the on-site UV unit and none of the indicator bacteria was detected in the final effluent after the sand filtration and UV treatment. Finally, potential scenarios were developed in comparison to the baseline scenario for the management and treatment of CSOs where a mitigation of *E. coli* loads from 28% to 73% was achieved on the receiving water body, and a comparative cost assessment of the disinfection methods was provided for *in situ* treatment of the most critical spillway.

Keywords: combined sewer overflow; disinfection; *Escherichia coli*; microbial contamination; modelling; bathing water quality

1. Introduction

Most older town and city centers are drained by combined sewer systems, which raises concerns regarding combined sewer overflows (CSOs) for many metropolitan cities in Europe and the US (Gasperi et al., 2010; Lund et al., 2014). In combined sewer systems, municipal wastewater and rainwater are collected and carried to wastewater treatment plant (WWTP) in a single network. In the event of intense precipitation, the flow of this line might exceed the capacity of the sewer system and consequently the excess flow, so called CSO, is directly discharged into water bodies (Botturi et al., 2020).

Contaminations due to CSO events can be originated from the dilution of sewage by rainwater, internal contribution by in-sewer sediment re-suspension and external contribution by runoff (Madoux-Humery et al., 2013). Pollution loads in CSOs are mainly characterized by solids, organic matter, nutrients, metals, organic compounds and pathogenic microorganisms (Montserrat et al., 2013). Main CSO impacts on receiving water bodies include: (i) oxygen depletion due to the biodegradation of organic matter carried by the untreated wastewater, (ii) elevated turbidity that causes the reduction of photosynthetic primary production, (iii) increase in the concentration of some organic micropollutants and metals, and (iv) pathogenic microbial contamination (Passerat et al., 2011). In fact, during intense rain periods, a sudden microbial contamination may occur due to untreated CSO releases (Jalliffier-Verne et al., 2016), resulting in an increment of more than a 2 log factor in the concentrations of *Escherichia coli* and enterococci in the receiving water bodies (Al Aukidy and Verlicchi, 2017). Passerat et al. (2011) estimated that sewer sediments were responsible to contribute to about 75% of the solid matter, 10-70% of the *E. coli*, and 40-80% of the intestinal enterococci that were discharged by CSO events. Enteric viruses are stable in aquatic environments and they can be transported over long distances with storm water runoff after rainfall events (Hata et al., 2014). Currently, a method for the quantitative calculation of the occurrence and impact of storm water overflows at EU or Member State level does not exist (Milieu, 2016). However, there are different methods typically applied at the local scale like the Blue Flag (Foundation for

Environmental Education) in Italy. Since the pollutant loads originated from CSOs are one reason to exceed threshold values of these local guidelines, states and municipalities need to make greater efforts to develop storm water management strategies to reduce them (Tondera et al., 2019; Venditto et al., 2020) and carry out specific water safety plan (Carducci et al., 2020). All above mentioned reasons create a high-priority need to minimize the environmental risks of CSO events, which represents a great challenge for public utilities due to the high number of CSOs in urban catchments (Launay et al., 2016). Finally, the last assessment of the EU Urban Wastewater Treatment Directive (271/91/EC) has highlighted the critical impact related to CSOs which are responsible for discharging to the EU water bodies loadings of BOD, N, P and coliforms much higher than 5 million population equivalent (PE).

The occurrence of overflow events are particularly damaging the urban catchments in Mediterranean countries with low river flow patterns, unable to dilute the undesired inputs (Montserrat et al., 2013). In fact, the Mediterranean region is foreseen to suffer from elevated CSO events in the next years as most climate change models conclude that the Mediterranean countries will be more affected by summer droughts, severe storms and higher flood frequency (Murla et al., 2016). In Italy, only few regions set out guidelines for the management of rainwater and these guidelines differ between the regions. For instance, Lombardia Region (North Italy) requires local treatment systems or specific storage tanks for every overflow (Lombardia Regional Regulation n°6, 2019). The Emilia-Romagna Region (North-East Italy) also suggests collecting and treating the first 2.5-5 mm of rain on the impervious surface. Similarly, the Marche Region (Central Italy) recommends to separately collect and treat the first rainfall of 5 mm uniformly distributed on the entire draining surface. The regional regulation of Marche states that the discharge into the sea must happen off the coast defense works parallel to the coast, or in the shoreline, but only if there are no defense works at less than 400 m (Piano Tutela Acque, 2010). Meanwhile, recent studies revealed that extreme precipitation events showed no positive nor negative trends related to the annual maximum rainfall in the Marche Region (Gentilucci et al., 2019; Soldini and Darvini, 2017). Hence, the unpredictability of extreme

precipitation regimes eventually increases the risk and impact of CSOs in those regions and requires taking action on the management of such pollution loads.

Up to date, only few conventional monitoring campaign has provided knowledge on the level of pollutant loads in urban CSO events (Copetti et al., 2019), while the collected data are often used without any consideration of the large uncertainties in the environmental measurements (Marchis et al., 2013). Moreover, no specific indication is given in cases where the CSO is directly released into the sea. While few comprehensive studies exist in the literature focusing on big catchment areas (Fong et al., 2010; Quijano et al., 2017), small catchments should not be overlooked since they may have the most drastic effect on the coastal bathing water quality. In a study took place in a coastal area of the Emilia-Romagna Region, 5 CSO events were characterized with respect to hydraulic and pollutant loads (Al Aukidy and Verlicchi, 2017). It was found out that the modest water volume discharged by all CSO outfalls contains 90% of the microbial load. One of the alternatives to assess the impact of pollutant loads on receiving water bodies can be water quality modelling, that is a useful approach to address mitigation and management of CSOs. The fate and effect of pollutants within the river catchment can be simulated using hydraulic modelling limits (Björklund et al., 2018; Morales et al., 2017; Taghipour et al., 2019). This approach can help to understand the role of CSOs to alter the hydrodynamics and water quality of receiving water bodies under different precipitation events (Quijano et al., 2017) and further complement monitoring and addressing the limitations of analytical methods to some extent (Björklund et al., 2018). Furthermore, the integrated models need to be properly calibrated/validated with focus on the impacts, which should be mitigated (Riechel et al., 2016). While developing an overflow scenario, the knowledge and the integration of different parameters enable a better and deeper comprehension on the real mechanism that could have impacts on the environment. Four different levels were identified by (Malgrat, 2013) based on the quantity and quality of the data available for CSO control policies. The application of hydrologic/hydraulic models allow to reach only a "desirable" N2 level; whereas the integration of the quality data (spilled concentration) together with hydraulic models represent a "good" N3 level. In order to reach the

"optimum" level, the assignment of the intermittent concentration in receiving water must be implemented. The outputs of these models can help to develop pollution mitigation scenarios and to obtain the best performance configuration for a further scale-up and application.

In fact, the bathing water quality can be maintained by instant disinfection of inflowing CSO water (Chhetri et al., 2016). To date, various disinfection methods at lab- and/or pilot-scale were proposed for the removal of pathogens from CSOs, such as peracetic acid (Chhetri et al., 2016), performic acid (Chhetri et al., 2014; Tondera et al., 2016), hypochlorite (McFadden et al., 2017), ozone (Tondera et al., 2015) and UV (Gibson et al., 2017, 2016). However, the applicability and frequency of a disinfection method applied for CSOs are often site-specific due to high variability of the pollution load in CSOs and therefore need optimization to assess the effectiveness of the chosen disinfectant agent.

The present study integrated and further experimentally validated dynamic rainfall-runoff simulation and water quality models to create a CSO pattern of a small catchment (Rio Vallescura in the Municipality of Porto San Giorgio - Marche Region, Italy) based on different precipitation scenarios and pollutant loads. 35 spillways were characterized that were responsible for the CSO events in the catchment area. Most critical spillways were further identified which cause most of the fecal bacteria contamination and loss of excellent bathing water quality in Porto San Giorgio. Based on the simulations, chemical and physical disinfection methods were proposed and *in situ* and *ex situ* tested in order to eliminate microbial contamination. In the final step, possible mitigation scenarios were developed for the most critical spillways to minimize their impact on the receiving water body. While the existing literature has mostly focused on either modelling or treatment of CSOs, hereby in this paper we presented a comprehensive assessment that can help to to provide technical support and data for controlling CSOs and further support regulatory and policy decisions.

2. Materials and methods

2.1. Study area

The Rio Vallescura is a small-medium canal located in the Marche Region, in Central Italy, which corresponds a river catchment of 9.16 km² at an average height above sea level of 118 m. The length of the canal is more than 8 km, starting from the upstream from Fermo old town until it reaches the coastal area of Porto San Giorgio and flows directly into the Adriatic Sea. The average meteorological pattern during the sampling days was as follows: temperature: 24±5.8 °C, precipitation: 0 mm, humidity: 61.8±16.5%, pressure: 1014.6±4.3 atm.

In addition to its own catchment area drainage, the study area receives critical CSOs that serve urban and agricultural areas. The existence of few industrial sources with low environmental impact (i.e. car washing) do not represent any major contributions in terms of pollutant loads, so the wastewater is mainly originated from domestic sources. The drainage system works by gravity, without any use of pumping, and conveys the sewer into a principal collector placed to Rio Vallescura, in which secondary pipelines arriving from the nearby hills are also connected and ends up in Lido di Fermo WWTP. The WWTP has a design capacity of 50,000 PE coming through three main collectors, one from Vallescura that includes approximately 7,227 PE, another one from the south that collects flow of Porto San Giorgio and the last one from the north of Lido di Fermo. Wastewater treatment scheme is composed of preliminary treatment units, conventional activated sludge process, secondary sedimentation, filtration and finally disinfection; while the sludge section includes thickening, aerobic digestion and dewatering processes.

Each CSO infrastructure was analyzed in terms of design characteristics to understand how these overflows work: the overflow occurred thanks to a circular side opening in the sewer well. Only the spillways with ratios lower than 2, between pulling water before overflow and internal diameter of outgoing pipeline, were considered for the modelling phase. The environmental impact of CSOs occurred from 35 spillways in the drainage system was further identified as shown in **Fig. 1**. The degree of incidence due to overflows for each selected pollutant was evaluated, while utmost importance was given to fecal bacteria contamination leading to the loss of excellent bathing water quality in Porto San Giorgio.

2.2. Water quality modelling

The assessment of hydraulic operation of the drainage system was done using the Storm Water Management Model (SWMM), the open-source software developed by United States Environmental Protection Agency (EPA). SWMM is used for planning, analysis, and design related to stormwater runoff, combined and sanitary sewers, and other drainage systems (EPA, 2020). This dynamic rainfall-runoff simulation model is widely used to evaluate the runoff quantity and quality for single event or long-term simulation (Rossman, 2015). A quantitative assessment was conducted in the preliminary phase by implementing the urban drainage network that included the setting of hydraulic structure (i.e. pipes dimension) as well the knowledge of river basin hydrological characteristics. In order to verify the data accuracy, the calibration of the model was required both in dry and wet periods. This evaluation was done by comparing the measured values to the results extrapolated by SWMM. A flow meter was placed in the point S282 (as indicated in **Fig. 1**) to provide hydraulic influent daily flow into the sewage system. The average value of 1506 m³/d was obtained from the specific elaboration of the data meter during the period considered (from 4th June to 12th June 2019), that identified a specific influent flow value of 136 liters per person per day. The latter provided the total discharged flow by 7,227 PE, inserted as input in SWMM, and specific simulation was run to verify the correspondence between flow meter data and output model. Qualitative calibration was performed by entering the concentrations measured during the sampling campaign in the four most upstream points (S272, W409, S276, S280) in SWMM and then checking that the model output in the downstream spillway (S282) could be compared to the laboratory analysis values. Regarding the wet period evaluation, that took place in March-April 2019, the same procedure was applied considering that the flow meter was in another point (S273) and provided an average value of 1791 m³/d.

Model evaluation was carried out using percent bias (PBIAS) that compares the simulated data with the observed one, providing information about overestimation (positive PBIAS) and underestimation

(negative PBIAS) of the calibrated model (Gupta et al., 1999). The calculation was done applying the following equation:

$$PBIAS = \frac{(Y_{OBS} - Y_{SIM})}{Y_{OBS}} * 100$$

where PBIAS = deviation of pollutant concentration and mass [percentage]; Y_{OBS} = mean value measured in field [expressed as mg/l for concentration and as kg/d for mass]; and Y_{SIM} = output value simulated by SWMM [expressed as mg/l for concentration and as kg/d for mass]. COD and TKN concentration and mass results assure the accuracy of the following simulations with PBIAS values between 5.06% - 7.30%, a rating performance lower than the 10% that can be considered "very good" (Moriasi et al., 2007).

2.3. Simulations conditions

The impact of the pollutants in the environment was considered as composed of three main sources: CSO loads, load of the users not connected to the sewer system and WWTP effluent. The simulations under dry and wet conditions were carried out also using pollutant loads determined for CSOs as well as the influent of Lido di Fermo WWTP. The rainfall data were obtained from the database of the "Centro Funzionale Multirischi della Protezione Civile" which manages the monitoring network of Marche Region. The rainfall amount collected by drainage system was evaluated considering the historical storm events of the territory and data extrapolation concerning the closest rainfall monitoring stations located in Fermo and Porto Sant'Elpidio. The data were downloaded from the "Portale del Sistema Informativo Regionale Meteo-Idro-Pluviometrico Sirmip on-line" (Regione Marche, 2020). Three return times (RT) were considered for rainfall height calculation, representing the probability that a harmful event occurs in each area within a specified period. These rainfall heights are equal to 12.8 mm for RT = 1 y, 41 mm for RT = 5 y and 48.7 mm for RT = 10 y. To have a continuously rainfall scenario, a "typical year" was calculated through a statistical evaluation. Accordingly, all the precipitation data from 1999 to 2019 (**e-Supplementary file**) were analyzed to identify the most representative year that deviated less than the average value of the period

considered. In addition to the rainfall statistical evaluation, the seasonal variability of pollutant loads between the summer and winter periods as well as physical-chemical characterization of the rainfall events was also considered. Typical concentrations of runoff water were evaluated both for the entire precipitation event and for the first flush (initial surface runoff of a rainstorm) as given in **Table 1**. The impact of storm water runoff linked to dwellings that are not connected to the public sewage system (4% of the total users in the basin) was also considered and modelled.

Table 1. Main pollutants concentration in runoff water for both first flush and entire rainfall event, estimated and elaborated from different references.

	COD	BOD$_5$	N-NH$_4$	TKN	TSS	*E. coli*	Coliform	Reference
	mg/l	mg/l	mg/l	mg/l	mg/l	mpn/100ml	mpn/100ml	
First flush	112.98	20.89					55976	(Maestre et al., 2004)
	210	680.5			737.5			(Papiri and Barco, 2003; Papiri, 2015)
			0.8		70.96			(Maestre and Pitt, 2005)
Mean ± standard deviation	161 ± 69	351 ± 466	0.8		404 ± 471		55976	
Entire rainfall	65.92	12.53					46238	(Maestre et al., 2004)
	176	10.3		1.4	173		6879	(Ciaponi et al., 2014)
	56.5	9			84		5500	(Metcalf & Eddy)
	111.1	140.5			222.1			Papiri and Barco, 2013; Papiri, 2015)
	46.45	8.05	0.52		44.36	1750	4062	(Maestre and Pitt, 2005)
Mean ± standard deviation	91 ± 53	36 ± 58	0.52	1.4	131 ± 81	1750	15670 ± 20411	

2.4. Disinfection tests

Different disinfection agents were selected and *ex situ* or *in situ* tested to reduce the microbial pollution in CSOs. Chemical disinfection was conducted at lab-scale by using performic acid (PFA), peracetic acid (PAA) and ozone; meanwhile UV-treatment system was tested on-site.

The influent wastewater was taken from Lido di Fermo WWTP and diluted at a ratio of 1:4 (v:v) to simulate the most critical CSO conditions according to the regional legislations which introduce a minimum permitted ratio (P ratio) between peak flow in rainy weather and average dry flow, equal to 4 (Piano Tutela Acque, 2010). The disinfection tests included: i) PAA at a concentration of 2, 4 and 6 mg/L with contact time of 5, 10 and 20 min; ii) PFA at a concentration of 2 and 4 mg/L with contact time of 5, 10 and 20 min; iii) ozone at a concentration of 10 and 20 mg/L with contact time of 7 and 15 min.

The on-site disinfection test was carried out using two filtration units in parallel followed by a small UV system (illustrated in **Fig. 2**) to remove TSS and to increase UV transmittance. The sand filter consisted of a rigid PVC cylinder, with 150 cm high, and a nominal diameter of 20 cm and at the bottom, PVC sleeve attached to the side outlet of the effluent (HRT = 8-10 min). The cylindrical tube was filled with sand up to 120 cm, a type of sand with an average diameter of 1 mm and range of dimensional variability between 0.8 and 1.2 mm. At the end of the cylinder coarse gravel was placed to avoid the compaction of the sand on the bottom and to dissipate the energy of the jet of the influent flow. The belt filter consisted of a rigid PVC cylinder for temporary containment of the influential and a nylon filter disc with a mesh size of 250 μm. Following the filtration units, a UV lamp was placed (Viqua, model D4) with the dimension of 50 cm of height, 10 cm of diameter and a working volume of 2.85 l. The UV disinfection tests included: i) sand filtration and UV dose of 85, 128 and 256 mJ/cm² with contact time of 34, 51 and 103 sec, respectively; ii) belt filtration and UV dose of 85 and 256 mJ/cm² with contact time of 34 and 103 sec, respectively. The treatment efficiencies were determined by log removals of *E. coli* and intestinal enterococci.

2.5.Analytical methods

All physical-chemical analyses were carried out according to the Standard Methods for the Examination of Water and Wastewater (APHA, 2012). Microbiological analyses were conducted in accordance with the official analytical methods of the Italian legislation, issued by the IRSA-CNR Institute for Water Research of the Italian National Research Council Agency for the Protection of the Environment and Technical Services (IRSA-APAT, 2003). In particular, *E. coli* was analyzed according to Method 7030F, and intestinal enterococci were done according to Method 7040C.

2.6.Statistical analysis

The statistical significance between the disinfectant concentration and the contact time in the disinfection tests was determined using one-way analysis of variance (ANOVA). The level of significance was taken as $p < 0.05$.

3. Results

3.1. Output of the calibrated model

The calibration was done by using the data only obtained from the dry period, since the data from the wet period result much lower than those one sampled in the dry period due to the increase in the flow rate following of a storm event, that causes a dilution effect. All the data measured in the samples taken from the influent and effluent of the WWTP and in the points (S282-S280-S276-W409-S272) are given in the **e-Supplementary file**. In order to obtain an average wastewater characterization under the same conditions, the flow rate peak ratios at every concentration was applied. The average values for the measured pollutant concentrations in the $WWTP_{inf}$, $WWTP_{eff}$ and at the spillways are given in **Table 2**.

Table 2. Mean value and standard deviation of the data measured in the samples taken from the influent ($WWTP_{inf}$) and effluent ($WWTP_{eff}$) at the WWTP and at the spillways inside the sewerage (S282-S280-S276-W409-S272).

Sample	T	pH	COD	N-NH$_4$	TKN	N-NO$_2$	N-NO$_3$	Total N	TSS	BOD$_5$	Total P	P-PO$_4$	Cl	SO$_4$	E. coli	Intestinal enterococci
	°C	-	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	UFC/100 ml	UFC/100 ml
$WWTP_{inf}$		7.3 ± 0.2	320 ± 131	48 ± 12	62 ± 18	0	0.24 ± 0.5	62 ± 18	188 ± 53	270	6.7	15.6 ±20	117.5 ±23	66 ± 31	3046667 ± 3514902	900000 ± 989949
$WWTP_{eff}$				0	0	0	6	0				0	150	74		
S282	20 ± 1.29	7.5 ± 0.08	551 ± 318	50 ± 15	76 ± 27	0	0.34	77 ± 26	371 ±197	370 ±220		4.3 ± 2.6	98 ± 39	50 ± 12	9280000 ± 8084058	3250000 ± 1626345
S280	23 ± 1.2	7.7 ± 0.15	453 ± 115	66 ± 4.7	86 ± 12.6	0	0.97 ± 1.1	87 ± 13	257 ± 71	380 ± 42		4.4 ± 1.1	115 ±13.6	49 ±6.8	7700000 ± 4794789	
S276	24 ± 1.9	7.5 ± 0.2	362 ± 67	40 ± 5.9	55 ± 13	0	0.49 ± 0.8	56 ± 14	240 ±102	280 ±28.3		2.9 ± 0.9	137± 14	62 ±15.2	4966667 ± 702377	
W409	25 ± 1.8	7.6 ± 0.3	444 ± 68	40 ± 8.2	54 ± 6.7	0	0.68 ± 0.1	55 ± 6.6	216 ±130	295 ± 78		1.8 ± 2.5	81 ± 18	38 ± 17	3600000 ± 4101219	
S272	24 ± 0.8	7.5 ± 0.1	495 ± 164	39 ± 1.1	56 ± 1.4	0	0.72 ± 1.0	57 ± 0.4	324 ± 54	335 ±91.9		3.5 ± 1.6	191 ±0.15	45 ± 19	2050000 ± 2050609	

The extrapolation of the results by SWMM provided indications on both quantitative and qualitative overflows relative to their impact on the environment. It was possible thanks to simulation scenarios referred to a return time of one year, five years, ten years and the typical year. For all these scenarios, the real P ratio was simulated to verify the accomplishment of the regional regulation (see **e-Supplementary file)**. Hydraulic impact on the sewer system for great RTs (5 y and 10 y) implied a flooding for 44% and 50% of the all 153 wells, respectively. Differently, for a return time of one year this portion remained at 3%, hence the greatest events with return times of five and ten years, the flooded volume was included in the CSO volume. This means that for strong events (5 y and 10 y of RTs), the sewer is not sufficient. In order to avoid underestimation of the total impact, the flooded flow was considered as an overflow. The results highlighted the activation of 14 in 35 spillways for smallest return time, while that of were 25 for the other two return times. The *E. coli* were mainly originated from the discharge of the utilities connected to the sewer (10^{14} UFC/d), even if the value associated to the runoff of the rainwater turned out to be still high (10^{11} UFC/d). The cumulative discharge load in terms of TSS was greater than the quantity to be treated in WWTP for all return times. For COD and BOD_5, this happened only for very critical situations of return time of five and ten years. The overflow load mainly affected COD (46%-84%), TSS (57%-89%) and BOD_5 (29%-69%) coming from storm water runoff on impermeable surfaces. Instead, TKN and *E. coli* loads had an impact with at a range varying from 7% to 35% and were derived mainly from utilities connected to the sewer. Considering that in the typical year there were about 201 rain events (including minor events) there were several activations of the spillways that went from a minimum of once to a maximum of 69 times per year, with an average of 24 active spillways per year. The flows and concentrations coming from the CSOs are shown in **Fig. 3**. Among the 24 active spillways only 4 of these were identified as the most harmful in terms of volume and pollutant discharges, as follow: S277 (25.3% of volume and 29% of *E. coli* load); S279 (9.1% of volume and 8.4% of *E. coli* load); S280 (8.5% of volume and 15.5% of *E. coli* load); S283 (13% of volume and 33.8% of *E. coli* load).

The contribution of the other pollutants was also significant in these four spillways, corresponding to 74.4%, 57.7%, 56.3% and 59.7% for TKN, COD, TSS and BOD_5, respectively. The degree of incidence due to overflows for each selected pollutant was further evaluated and is shown in **Fig. 4** for TKN, COD, TSS, BOD_5 and *E. coli*. The load associated to the users that were not connected to the sewer system turned out to be much smaller than the overflow, less than 4% for all simulations especially regarding the *E. coli* that has the impact less than 1%. The contribution of BOD_5 on the environment was associated with the WWTP effluent (55%) as well as the overflows (42%), and the same for COD with 62% for effluent and 36% for spillways activation. *E. coli* and TKN, on the other hand, had different origins, in fact, *E. coli* was derived almost entirely from the CSOs (99.2%), while TKN was associated mainly with the discharge of the effluent (95). Finally, the TSS was mainly associated with the CSOs (69%), but also had a contribution from to the WWTP effluent (29%).

3.2. CSO treatment

The disinfection tests were conducted to assess the performance of various chemical and/or physical agents and to identify the most efficient treatment system to be applied in possible mitigation scenarios of CSO impacts in the Vallescura basin. **Fig. 5a, b, c** and **d** show the log removals of *E. coli* and intestinal enterococci at different concentrations of disinfection agents, ranging from 2 and 6 mg/l for PAA and PFA; 10 and 20 mg/l for ozone and 85 and 256.5 mJ/cm^2 for UV.

The PAA disinfection tests were effective only on the *E. coli* removal with the log reduction of 2.5 for 2 mg/l and 2.7 for 4 mg/l, respectively. The application of PAA for intestinal enterococci showed poor effects with low log removal of 0.1-0.4. The application of PFA was found to be the most effective chemical disinfection agent in the lab tests, both for the removal of *E. coli* and intestinal enterococci. At the concentration of 2 mg/l, PFA allowed to reach a log removal of 4.6, while a maximum value of 3.7 was obtained for intestinal enterococci. Finally, ozone disinfection showed high removal efficiency only for *E. coli* with the log reduction of 3.9; meanwhile that of was 1.6 for intestinal enterococci. The on-site UV disinfection; on the other hand, showed the highest removal when applied in combination with the sand filter, reaching up to 8.2 and 6.7 units for *E. coli* and

intestinal enterococci at a high dose of 256.5 mJ/cm^2. The application of the belt filter before the UV showed comparatively less efficiency, with 4.6 and 3.8 log removal for *E. coli* and intestinal enterococci, respectively. The concentration of the final effluent was 40 CFU/100 ml for *E. coli* and 100 CFU/100 ml for intestinal enterococci after belt filtration + UV disinfection; whereas no indication of *E. coli* and intestinal enterococci was detected after the sand filtration + UV disinfection configuration.

The effect of contact time on the disinfection efficiency of PAA, PFA and ozone, was evaluated both for *E. coli* and intestinal enterococci considering the log reduction obtained in the function of specific dose (Dose = contact time x concentration). The removal results for PAA and PFA are given in **Fig. 5e** and **f,** respectively. Although the effect of contact time on the PAA and PFA treatments was not significant at all for all the concentrations ($p > 0.05$), PFA disinfection yielded high removal efficiency even at low doses, mainly for *E. coli* tests that obtained 3.8 log reduction at a dose of 10 mg/l*min. The PFA disinfection was also efficient on the removal of intestinal enterococci, whereas higher removal was obtained at high doses, as the log removal increased from 1.7 at the dose of 10 mg/l*min to 2.9 at the dose of 80 mg/l*min. The PAA disinfection was not efficient compared to PFA, with low log reduction units for intestinal enterococci (never higher than 1 log unit) and moderate values for *E. coli*, only at higher doses (log reduction of 1.3 at 10 mg/l*min dose and 2.5 at 120 mg/l*min). Finally, the disinfection efficiency of ozone at different doses are given in **Fig. 5g**. High log removal was achieved especially for *E. coli* up to 3.9 at the lowest dose of 70 mg/l*min. Moreover, there was a significant change in the removal of intestinal enterococci with the contact time ($p < 0.05$), while comparatively lower disinfection efficiency was obtained and only at higher doses, with log removals of 1.5 and 2.3 at a dose of 70 mg/l*min and 300 mg/l*min, respectively.

3.3. Mitigation scenarios

Following the integrated simulations, four spillways (S277, S279, S280, S283) were identified with the highest impact on the environment corresponding to total 86.5% of the *E. coli* discharged by the CSOs. Possible minimization scenarios were developed and illustrated in **Fig. 6** to cease the impact

of these spillways through disinfection in the WWTP and in proximity of the overflows. In the first scenario, wastewater from S283 (the last spillway before the WWTP) is treated at the WWTP up to the maximum capacity available; while the Scenario 2 includes both Scenario 1 and *in situ* treatment at the two most critical spillways (S280 and S277). The maximum volume available at the WWTP was found as 2038 m³ and allowed to collect around 57% of the total annual overflow of S283. The WWTP equalization allowed treating 529 m^3 of the accumulated volume every day, so approximately 3.8 days were needed to discharge all the volume. Finally, using the capacity available at the WWTP, it is possible reduce the *E. coli* load by 28% in the Scenario 1 compared to the baseline case. Furthermore, the removal can be increased to 35% by easily adding new storage tanks in the WWTP. In the Scenario 2, in addition to the outline of Scenario 1, *in situ* UV treatment was considered with sand filter that ensures *E. coli* load reduction of 100% for both CSOs, which simulated a final *E. coli* removal up to 73%.

3.4. Cost assessment of possible disinfection solutions

An economic assessment was done considering *in situ* treatment of the overflow from spillway S277 during the typical year (average flow of 106,276 m^3/y). The application of all different disinfection methods used in this study was considered, and the final operating expenses (OPEX) and capital expenditures (CAPEX) were estimated from literature case studies with similar operating conditions as given in **Table 3**.

Table 3. Overview of operating (OPEX) and investment (CAPEX) costs for different disinfection methods.

Disinfection agent	Concentration or dose		Contact time (min)	Trasmittance (%)	OPEX (€/m^3)	CAPEX (€/m^3) *	Note	Reference
Ozone	1-4.3	mg/l	20	-	0.0045 ± 0.0038	0.0032 ± 0.004		(Collivignarelli et al., 2000; Mundy et al., 2018)
UV	19-70	mWs/ cm^2	n.a.**	n.a.	0.0032 ± 0.0044	0.0054 ± 0.0052	Pretreat ment unit is	(DEMOWARE, 2016; Heinonen-Tanski et al.,

						not included	2003; Wojtenko et al., 2003)
PFA	1.5-2	mg/l	n.a.	-	0.0143 ± 0.0058	0.00223 ± 0.00217	(Collivignarelli et al., 2000; DEMOWARE, 2016; Luukkonen et al., 2015; Luukkonen and Pehkonen, 2017)
PAA	1-5	mg/l	n.a.	-	0.023 ± 0.019		(Brady, 2009; Collivignarelli et al., 2000; Luukkonen et al., 2015; Luukkonen and Pehkonen, 2017)

* CAPEX was annualized considering a period of 20 years at an interest rate of 8% (EPA, 2003).

** n.a.: not analyzed.

Applying the obtained economic data, the final OPEX and CAPEX for different disinfection solutions are presented in **Table 4**. Maximum operating costs were found for PAA and PFA as 2,444 ± 2,019 €/y and 1,520 ± 616 €/y, respectively, which are mostly related to the chemical agent costs. The price of PFA and PAA are approximately 830 €/t for PFA solution (9%) and 1100-1200 €/t for PAA solution (12%) (Luukkonen and Pehkonen, 2017). UV disinfection had the lowest operation cost; however, higher investment costs were obtained both for UV and ozone (up to 11,061 € and 7513 €, respectively) and can be attributed to more complex installation necessities.

Table 4. OPEX and CAPEX estimated from literature cost for the present case study.

Disinfection agent	Concentration		Contact time (min)	Transmittance (%)	Flux (m^3/y)	OPEX (€/y)	CAPEX (€)
Ozone	10-20	mg/l	7-15	-		478 ± 404	3339 ± 4174
UV	85-256	mWs/cm^2	0.6-1.7	40	106276	340 ± 468	5635 ± 5426
PFA	2-4	mg/l	5-20	-		1520 ± 616	2327 ± 2264
PAA	2-6	mg/l	5-20	-		2444 ± 2019	

4. Discussion

Hydrodynamic and water quality models in streams have been extensively applied in different domains and scales to analyse the impact of CSOs in urban streams (Quijano et al., 2017; Riechel et al., 2016; Taghipour et al., 2019). Most of the studies regarding the modelling and/or controlling of CSOs focus on the indicator bacteria such as *E. coli* and intestinal enterococci since they are crucial indicator parameters for fecal matter and stated in the EC Bathing Water Directive (2006/7/EC). This directive clearly defines the conditions for a surface water body to be legally used as bathing water and how the water quality must be monitored. Surface waters classified as bathing water have to at least fulfil a "sufficient" quality in order to keep the status as bathing water (limit values for a sufficient water quality are 330 CFU (in 100 ml) for intestinal enterococci and 900 CFU (in 100 ml) for *E. coli* based on 90 percentile evaluation (Tondera et al., 2016). In this regard, disinfection is required to ensure the compliance with microbiological limits for the effluent discharges into the environment (in this case the effluent is represented by the CSOs) and to avoid mass loads of pathogens in receiving water bodies to comply with the bathing water quality.

The efficiency of the disinfection systems depends on several factors: contact time, pH, temperature, concentration and type of microorganisms, disinfectant concentration, presence of interfering substances with TSS. The results of this particular study highlighted that the on-site UV disinfection test at a high dose (256.5 mJ/cm^2) was by far the most effective treatment on the removal of both *E. coli* and intestinal enterococci from CSO. The advantages of UV disinfection compared to the chemical agents, include no by-products, no chemical residual, and relatively compact size. However, the level of disinfection that can be achieved is often limited by particle-associated organisms in CSO water and the UV transmittance of CSOs can be as low as 30% and the TSS can reach 200 mg/l (Gibson et al., 2017); hence, the use of a pretreatment unit is utmost important to increase disinfection efficiency. Two pilot-scale disinfection units comprised of ozone and UV were tested by (Tondera et al., 2015) on CSOs; where the ozone was found to be more effective than UV (ozone: 3.1-3.4 log, UV: 1.7-2.2 log) on the reduction of *E. coli*, coliform bacteria and intestinal enterococci. On the other

hand, ozone yielded lower outflow values for the majority of the all investigated bacteria, viruses and parasites at the tested doses and no further increase in efficiency was found with enhanced dose for UV or ozone. This differentiation could be due to the presence of solid particles and thus particle-associated organisms, since filtration was used in our study to remove TSS. UV irradiation cannot properly penetrate in water due to turbidity.

In case of using a chemical agent, PFA is recommended as the PAA treatment only removed *E. coli* at a considerable level. Although comparatively higher removal efficiencies of *E. coli* and intestinal enterococci were achieved by PFA at increased contact time, the increase was not significant at all, hence shorter retention time can be selected. Accordingly, a CSO treatment condition at 2 mg/l PFA is recommended with short contact time for *E. coli* and with long contact time for intestinal enterococci. On the other hand, if the target pathogen is only *E. coli* and PAA treatment is preferred, treating CSO at low concentration (i.e. 2 mg/l) but at long retention time (i.e. 20 min) is highly recommended. Similar results were reported for the disinfection of CSO. PFA was found to be a more efficient disinfectant at low doses with short contact time, and treatment conditions for CSO as 2 mg/l PFA with 20 min contact time or 2 mg/l PAA with 360 min contact time was recommended (Chhetri et al., 2014). Although PAA is a strong disinfectant and allows to reach optimal disinfection efficiency, the necessity for longer contact time makes its application more challenging in local CSO treatment. Moreover, the degradation of PAA releases hydrogen peroxide in the treated water and its toxicity to organisms needs to be further considered. However, effective concentrations for aquatic organisms are reported as low as 2.4 mg/l (Chhetri et al., 2014). Whereas the degradation of PFA also releases specific by-products in the treated water, only formic acid and water are produced and neither of them is toxic to aquatic fauna. What must be considered is that PFA is an unstable product and needs to be generated on-the-spot (Chhetri et al., 2014). In another study (Tondera et al., 2016), pilot-scale PFA treatment was conducted to the overflow stream after a CSO storage tank, and the concentrations of *E. coli*, coliform bacteria and intestinal enterococci were below the detection limit with a contact time of 10 min. Similarly, in this study, PFA was more effective on the intestinal

enterococci removal at longer contact time. From this point of view, PFA disinfection can be considered at long contact time to efficiently react with all targeted organisms (McFadden et al., 2017) compared the disinfection efficiency of PAA and hypochlorite on CSO-like wastewater and for a water matrix containing a pure *E. coli* culture without any pretreatment. The disinfection by PAA was found to be more efficient than disinfection by hypochlorite for all solids size fractions; while the disinfection efficiency was reported to decrease above pH 7.5. The matrix of the CSO waster (i.e. TSS) is critical here for the selection of an organism-targeted disinfection that put the use of a pretreatment section forward; since the disinfection agent as well as operating conditions differ and affect the treatment efficiency drastically.

The pollutant loads discharged by intermittent CSO outfalls were analyzed and compared to those released by the local WWTP in another coastal area in North-east Italy (Al Aukidy and Verlicchi, 2017). The authors highlighted that the CSO microbiological load (i.e. *E. coli* and enterococci) was much higher (>90%) than that of the WWTP, particularly during periods of heavy rain in the summer. UV disinfection was further recommended for the effluent of the most critical CSO outfall in terms of discharged microbial load. A pilot-scale compact advanced treatment system for CSOs was recently developed and validated by (Botturi et al., 2020) that consisted of a dynamic rotating belt filter, adsorption on granular activated carbon and UV disinfection steps. The system achieved high removal of 91.7%, 69.9% and 100% for TSS, COD and *E. coli*, respectively, while moderate nutrient removal efficiencies (41.6% N and 18.9% P) were obtained. Such combined systems propose a great potential for the treatment of critical CSOs to meet water quality in recreational and touristic areas.

Economic assessment of disinfection systems is not straightforward and related costs cannot be easily compared due to the varying application techniques and type of disinfectants. Each alternative should be evaluated based on the characteristics of a particular site and the physical-chemical properties of the flux to be treated (EPA, 1999; Luukkonen and Pehkonen, 2017). In previous years, chlorine has traditionally been used to provide disinfection due to its low cost. Since 1970s, growing awareness of the adverse environmental impacts has fostered a strong interest in alternative disinfection

technologies for CSOs (EPA, 2003). Other chemical and physical agents as UV, ozone, PAA and PFA has been tested in different studies both for CSO and wastewater disinfection.

The on-site application of the disinfection systems needs a specific survey on the area to understand the possibility of implementation in terms of available environment close to the spillway, equipment and facilities. This can be more challenging for UV and ozone, whose configuration require a more careful evaluation of the boundary conditions, related to the specific equipment necessities. Considering the chemical disinfection with PAA and PFA, the operating conditions of the case studies in **Table 3** (concentrations of 1.5-2 mg/l and 1-5 mg/l, for PFA and PAA, respectively) are similar to the ones tested in this study (concentrations of 2-4 mg/l and 2-6 mg/l, for PFA and PAA, respectively). Furthermore, regarding the ozone treatment, the doses obtained from the literature overview were comparable with this paper. On the other hand, the cases on the UV disinfection shows lower operating values when compared to the present study (maximum 70 mWs/cm^2 in the literature and a range of 85-256 mWs/cm^2 in the present study), but the specific transmittance of the literature cases are not defined, which affects the final efficiency of the system.

5. Conclusion

An integrated catchment-wide hydraulic-water quality modelling and impact assessment approach for CSO control measures were developed at an urban catchment in the Central Italy by the calibration and validation with overflow-based monitoring data. The simulations showed that among the three sources of environmental pollution considered, *E. coli* generated by CSO accounted for most of the pollutant loads and could have a contribution to the deterioration of the coastal bathing water quality. In this regard, various disinfection tests were designed and implemented targeting the mitigation of microbial loads from CSOs. An on-site treatment with the UV disinfection coupled with sand filtration unit provided no microbial indicators as *E. coli* and intestinal enterococci in the effluent; meanwhile PFA treatment also yielded high removal efficiencies and is recommended in the case of using a chemical disinfectant agent even at low doses with short contact time. Possible mitigation scenarios were further outlined for estimating the impact of treatment on the CSO events in the

catchment as follows: (1) a baseline scenario, (2) Scenario 1 including a potential treatment of a spillway in the WWTP and (3) Scenario 2 including Scenario 1 and additionally *in situ* treatment of the two most critical spillways by sand filter + UV disinfection configuration. The results of Scenario 2 highlighted a final *E. coli* removal up to 73%. The cost assessment of the disinfection agents on the most critical spillway in Scenario 2 also favored UV and PFA based on the OPEX and CAPEX (+OPEX), respectively. Similar approaches can address the needs of municipalities/water utilities to develop mitigation policies for these overflow events and help to maintain bathing water quality.

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Conflict of interest

The authors declared no conflict of interest.

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Figure Captions

Fig. 1. Modelled study area in Rio Vallescura (Marche Region, Central Italy). Discharge points of spillways (red points) and Lido di Fermo WWTP (green point), sampling points (yellow points) and the sewer system (black line).

Fig. 2. On-site treatment using UV disinfection system coupled with two parallel filtration units (belt filtration and sand filtration).

Fig. 3. Total flow and pollutant concentration in the overflow based on the SWMM model (typical year simulation).

Fig. 4. % of incidence of the different source of pollution for TKN, COD, TSS, BOD_5 and *E. coli.*

Fig. 5. Effect of treatment concentration on the removal of *E. coli* and intestinal enterococci by **a)** peracetic acid (PAA) **b)** performic acid (PFA) **c)** ozone (O_3), **d)** ultraviolet (UV) with sand filter. Effect of treatment dose on the removal of *E. coli* and intestinal enterococci by **e)** peracetic acid (PAA) **f)** performic acid (PFA) **g)** ozone (O_3).

Fig. 6. *E. coli* load discharged by CSO outfalls for three case scenarios. Base case: actual scenario (no accumulation at the WWTP and no local treatment system); Scenario 1) The wastewater out from S283 is treated at the WWTP up to the maximum capacity available; Scenario 2) SCENARIO 1 + *in situ* treatment at the two other more critical spillways identified (S280 and S277).