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Towards stormwater reuse risk management plans: Methodology and catchment scale evaluation of QMRA

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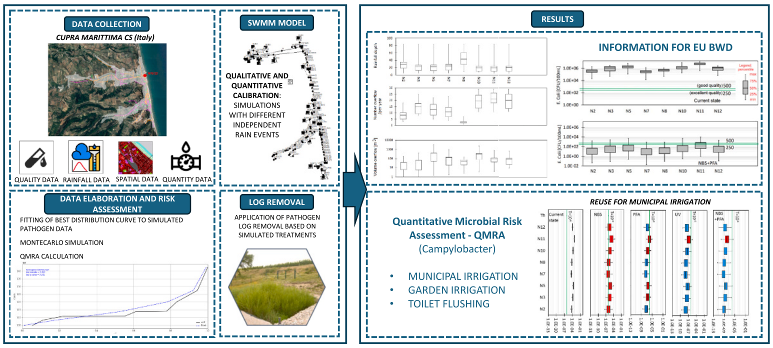
HIGHLIGHTS

- New methodology to calculate QMRA using SWMM simulation of stormwater
- Risk assessment was evaluated for municipal/garden irrigation and toilet flushing
- *E. coli*, frequency and volume of overflow can be used to describe bathing water profile
- Overflows treatment by NBS and disinfection reduces risk and *E. coli* concentration
- Outcomes of risk assessment used to support decision for stormwater management

GRAPHICAL ABSTRACT



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ABSTRACT

The reuse of stormwater represents a potential option for meeting water demands in water stressed regions as well as preventing and mitigating diffuse pollution of receiving water bodies. Particularly, the elaboration of a risk management plan for stormwater reuse may help to understand associated environmental and public health risks and design fit-for-purpose water treatment processes. In this work, it is presented an innovative methodology to perform quantitative microbial risk assessment (QMRA) for stormwater reuse by using data simulated by SWMM software. Particularly, 210 rain events were simulated by SWMM after qualitative and quantitative calibration of the sewer network model of the city of Cupra Maritima (Italy) to identify sewer overflows. Obtained concentrations of pathogens (i.e., *E. coli*, Campylobacter) in overflows from each critical spillway were fitted by theoretical distribution curves. Hence, QMRA for Campylobacter was performed by Monte Carlo simulation and by linking observed overflows to the exposure events of stormwater reuse for the scenario of 1) municipal irrigation, 2) garden irrigation and 3) toilet flushing as defined by the Australian Guideline for water recycling. Furthermore, QMRA analysis was repeated after simulation of sewer overflow treatment by nature-based solution (NBS) with and without disinfection (UV and performic acid - PFA). Stormwater treatments were simulated by applying uniform distributions of expected range of bacteria log removals. Results showed

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that stormwater treatment by nature-based solution and disinfections (PFA dose of 2.5–5 mg/L) were able to reduce the risk of Campylobacter infection to acceptable level for most of spillways in the three investigated reuse scenarios. In addition, produced data were elaborated to identify critical overflows discharging in bathing water according to the indications of the EU bathing directive.

1. Introduction

Stormwater harvesting involves collecting runoff from drains or creeks and represents a relatively new form of water reuse compared to rainwater tanks and the reuse of effluent from sewage treatment plants (Hatt et al., 2006; Xu et al., 2023). Moreover, reuse of stormwater is increasingly seen as a potential option for meeting water demands in water stressed regions. The rationale for harvesting stormwater for beneficial uses is to capture the excess stormwater before it contaminates the receiving water body and changes the stream hydrology, while providing a new source of water supply that may require less treatment than sewage for various non-potable uses (Fletcher et al., 2008; Grant et al., 2013; Hatt et al., 2006). However, reuse of stormwater is often impeded by social and institutional barriers resulting from a complicated mix of risk perceptions by multiple stakeholders (Dobbie and Brown, 2012). Particularly, one of the potential reasons for the limited exploitation of urban stormwater as a substitution water source is the lack of understanding of the pollutants' occurrences in the urban aquatic environment, and its associated environmental and public health risks (Jiang et al., 2015; Sidhu et al., 2012). Hence, a good understanding on the untreated quality of stormwater is essential as it allows for the development of risk management framework to ensure water quality excursions are avoided as well as to make informed choices on the design of "fit-for-purpose" water treatment processes. To pursue this goal, the Horizon Europe WATERUN project (https: //www.waterun.eu/) aims to set up an innovative methodology to contribute to the implementation of urban water runoff (UWR) management plans in cities according to a holistic perspective (from source identification to decision making). Particularly, one of the aims of the project is to combine modelling approaches of stormwater events with calculation of quantitative risk assessment to assist stakeholders in the decision-making process. The developed methodology will be tested in different European Cities and in different stormwater reuse/discharge scenarios. In the present work are presented the results of risk assessment related to the discharge and reuse of combined sewer overflows (CSO) in the coastal city of Cupra Marittima (Italy), which is located in the province of Ascoli Piceno in the Marche Region.

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., 2021; Crocetti et al., 2021). 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). Particularly, 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 >2 log factor in the concentrations of *Escherichia coli* and enterococci in the receiving water bodies (al Aukidy and Verlicchi, 2017). For this reason, the European Bathing Water Directive (BWD) (EU Directive 2006/7/EC) demands to elaborate so-called bathing water profiles for all bathing waters that receive short-term pollution such as CSO. Particularly, the bathing water profile needs to contain information on conditions likely to lead to short-term pollution, — the likelihood of such pollution and its likely duration, — the causes of the pollution and measures taken with a view to preventing bathers' exposure to pollution and to tackle its causes.

On the other side, regarding the possibilities of stormwater reuse, the Australian Guideline for water recycling – stormwater harvesting, and reuse (NRMMC–EPHC–AHMC, 2009) provides a guidance on managing potential public health and environmental risks associated with the reuse of waters generated from stormwater, including the case of harvested stormwater contaminated by CSO. Particularly, detailed indication is provided for the calculation of a quantitative microbial risk assessment (QMRA) (NRMMC–EPHC–AHMC, 2009), and recently, QMRA has been applied in some literature studies to evaluate health risk associated with different stormwater reuse scenarios (e.g.; toilet flushing, municipal irrigation, agricultural irrigation, etc.) using laboratory data of stormwater samples (Hatt et al., 2006; Jiang et al., 2015; Lim et al., 2015; Sidhu et al., 2012). Furthermore, some studies have also investigated the possibility of using the outcomes of hydrodynamic simulations of stormwater events to calculate QMRA. In those studies, the health risk assessment was conducted only in the case of direct ingestion of water during bathing activity or in the case of extraordinary flood events (Addison-Atkinson et al., 2022; Jørgensen et al., 2023; Mark et al., 2018; Sterk et al., 2016; Thorndahl et al., 2024), whereas there are not studies that used simulated data to calculate risk during planned reuse of harvested stormwater in urban areas or to evaluate the expected risk reduction after stormwater treatment. In the available literature, different models were tested to produce data for QMRA analysis in bathing water or during flood events, including the commercial software MIKE and the open-source Storm Water Management Model (SWMM) developed by US EPA (Addison-Atkinson et al., 2022). This kind of software is largely utilized by water utilities or other stakeholders managing the urban water cycle for the optimal design of green and grey infrastructures for stormwater management and treatment (Ghodsi et al., 2023; Hur et al., 2018; Szeląg et al., 2022; Yang et al., 2023). In the present work, it is presented an innovative methodology to integrate SWMM modelling with QMRA calculation with the aim to design and plan actions for stormwater reuse in urban areas and to produce information for the characterization of bathing water profile in the case of short-term pollution as required by the BWD. Particularly, estimation of pathogens concentration in CSO by SWMM modelling were utilized to (i) evaluate the microbial risk (QMRA) associated with three reuse scenarios (municipal irrigation, garden irrigation and toilet flushing) of harvested stormwater produced by CSO; (ii) to obtain information related to presence of critical conditions for bathing waters according to the requirements of the EU BWD; (iii) to evaluate optimal treatments of CSO to reduce pathogen contamination in bathing waters and to minimize the microbial risk associated with different reuse possibilities.

2. Material and methods

2.1. Description of the case study of Cupra Marittima

Municipality of Cupra Marittima located in the South of Marche Region (central Italy) has resident population of 5400 habitants but hosts during the summer months up to 285,000 tourists. This scenario is typical of several municipalities of coastal area of Mediterranean Sea with specific vocation of bathing tourism.

The drainage basin of Cupramarittima covers an area of 2.15 km^2 with a sewerage network length of approximately 50 km. The 37 % of this network is a combined system, whereas the rest of the system collects separately white and black waters (Table S1). In Fig. S1 is reported the catchment basin of Cupra Marittima with indication of the sewer network, where the WWTP is located near the coast and collects flows from the west and south part of the basin.

Along the sewage network there are 13 CSOs (4 line spillways and 9 spillways associated with pumping stations) that discharge excess flow during wet period into several surface streams that convey the collected water into the Adriatic Sea.

The location of CSOs along with other tanks with pumping stations that are not associated to CSO is shown in Fig. 1. The identification code (ID) utilized for network nodes, CSOs and pumping stations in this work are reported in Table 1. The distribution of population equivalent (PE) in the sub-catchment related to each identified CSO (Fig. S2) was derived from the number of users, both domestic and industrial in the sub-catchments.

The sewer network of Cupra Marittima was divided into macro-areas in order to identify measuring points that would allow the quantification and characterization of all flows entering the WWTP. Therefore, four main sections of the network were identified and named with letter A, B, C and D according to the placement of the flow meter devices Kaptor mini and presence of remote-control systems (pump on/off and water level measurements) (Fig. 1). Particularly, the KAPTOR$_{MINI}$ flow meters were installed at the closing point of section A and at the closing point of section C. Continuous measurements of flow rates in the network were registered from 26/08/2020 to 04/01/2021. From November 2020, the KAPTOR$_{MINI}$ flow meter of section A was moved to the closing point of section D. In the closing points of sections A and B, flow rate measurements were also obtained using the water level monitoring systems placed in the pumping station tanks. Further flow rate measurements

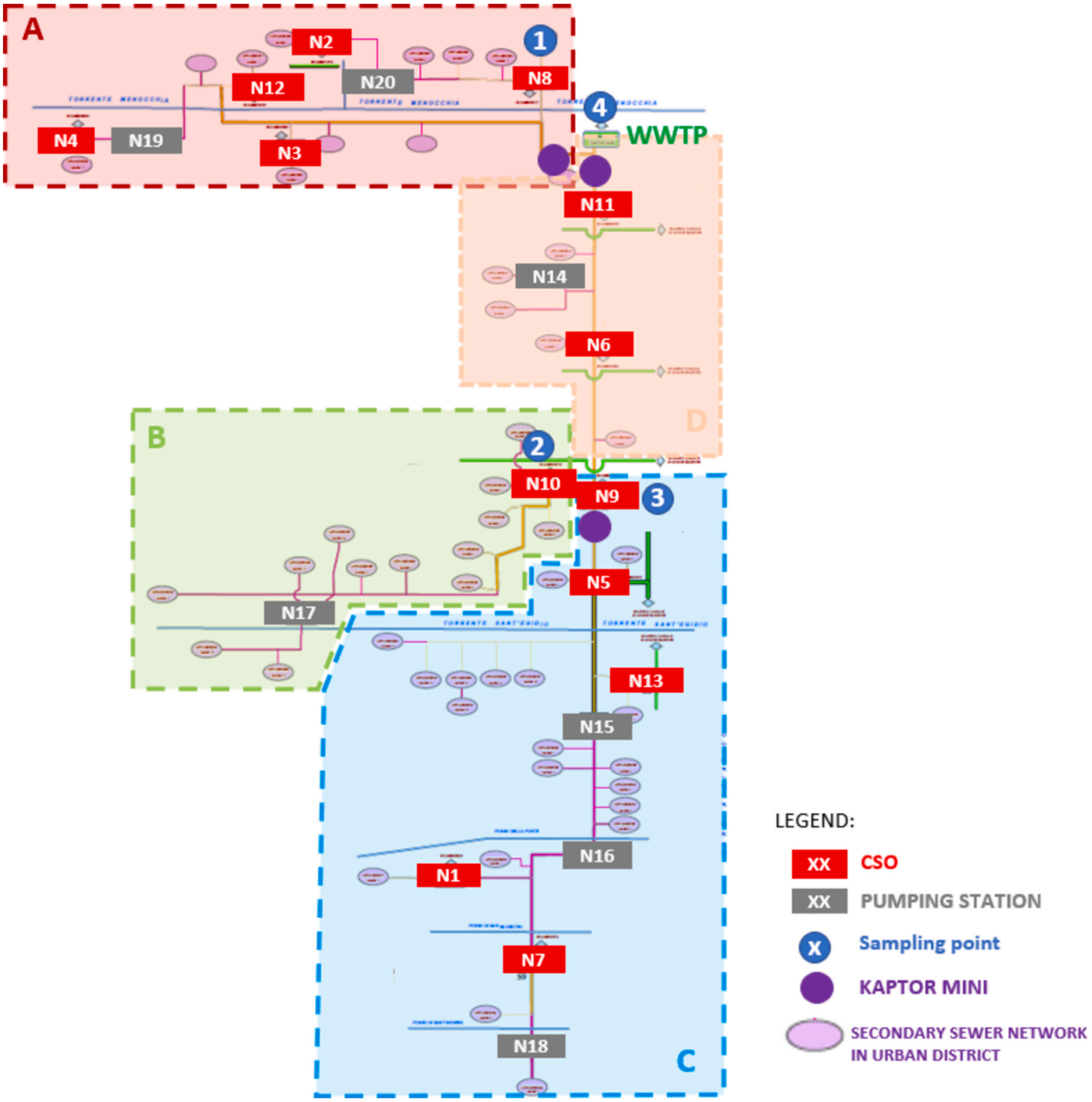

Fig. 1. Schematization of the sewer network system of Cupra Marittima with localization of flow meters Kaptor mini, sampling points, CSO and pumping stations.

Table 1

Identification codes for tanks, CSO and pumping stations in the sewage network of Cupra Marittima.

ID Node	ID CSO	ID PUMPING STATION
N1	V331	–
N2	V388	–
N3	V335	–
N4	V336	–
N5	V050	S022
N6	V048	S020
N7	V054	S026
N8	V057	S029
N9	V049	S021
N10	V058	S164
N11	V047	S019
N12	V417	S167
N13	V051	S023
N14	–	S028
N15	–	S218
N16	–	S025
N17	–	S027
N18	–	S030
N19	–	S209
N20	–	S166

were available at the inlet of the WWTP of Cupra Marittima (section D).

Several sampling campaigns were carried out along the sewerage network at four selected points for the determination of the *E. coli*. Fig. 1 shows the sampling points: 1 (corresponds with N8), 2 (corresponds with N10), 3 (corresponds with N9) and 4 (corresponds with inlet of WWTP). Samples were representative of dry and wet conditions and were collected in different days of the year 2020 (2 samples in spring, 2 samples in summer and 2 samples in winter). Measured water quality parameters (i.e., *E. coli*) and flow rate data were used to calibrate the SWMM model of the sewer network of Cupra-Marittima.

2.2. SWMM modelling of sewer network system

The EPA software SWMM was used to estimate quantity and quality of water flowing in the sewer network system of Cupra Marittima (Rossman, 2010). The catchment model included 16 sub-catchments of 0.30–2.54 ha with an impervious area ranging from 11 % to 59 %. The sewer network featured 16 pumping stations, 251 junctions, 255 pipes, 13 outlets. In the event of hydraulic overloading, excess wastewater is discharged through the 13 storm overflows described previously (Table 1). The diameters of pressure pipes vary from 0.08 to 0.20 m, and those of gravity sewers from 0.5 to 1.0 m. The Manning coefficient of roughness of the channels (0.01–0.013 $m^{-1/3}\cdot s$) was determined according to the age of the pipes and the material used. The depth of the manholes varied from 0.9 to 10.0 m. The rainfall-runoff simulation was used to quantitatively assess the surface – runoff and flow of the sewer network for a single rainfall event and during a long period simulation. To verify the accuracy of the model, calibration of the model was done for the dry and rainfall period. This evaluation was done by comparing the measured values of the depth in tanks (N7, N8, N10) to the results simulated by SWMM. Due to the lack of depth for the pumping station N11, the calibration was based on the switch-on frequency of the pumps in the tanks. A rainfall event on 10.07.2020 and two events from the dry period (04.08.2020, 27.08.2020) were assumed for the calibration of the catchment outflow. Model validation was performed for the rainfall event of 16.10.2020 and for the dry period (01.10.2020, 03.11.2020).

Qualitative calibration was performed by entering concentrations measured during the sampling campaigns in the three selected sampling points (N8, N10, N9) in SWMM and then checking that the model output in the inflow to the WWTP could be compared to the laboratory analysis values. A detailed description of the methodology is given in Crocetti et al. (2021). Model evaluation was performed using the percent bias (PBIAS) method, which compares simulated data with observed data. Calculations were made using the following equation:

$$PBIAS = \frac{(y_{mes} - y_{sim})}{y_{mes}} \cdot 100\% \tag{1}$$

where: y_{mes} - value measured in field; y_{sim} - output value simulated by SWMM.

2.2.1. Continuous simulation

In order to determine the variability of pathogen concentrations for individual overflows (N2−N13), heavy rainfall events were separated from the rainfall time series for the period 1998–2007. For this purpose, the (DWA-A 118E, 2006) guidelines were assumed, which suggest a minimum rainfall depth of 10 mm and a period between independent rainfalls equal to 4 h. According to the above criteria, 210 rainfall events for 9 years (1997–2006) were separated, which were characterized by rainfall durations in the range $t_r = 30–2880$ min and rainfall depth $P_t = 10–62.5$ mm. The following parameters formed the basis for assessing the performance of the storm overflows: the volume of the discharge (V_{ov}), pollutant load (L_{ov}), average concentration of pathogens (C_m) in the discharged water (the equations for their calculation are given in Supporting Information - Text S1). For those calculations, rainfall data were obtained from the database of the “Centro Funzionale Multirischi della Protezione Civile”, which manages the monitoring network of Marche Region. The data were downloaded from the “Portale del Sistema Informativo Regionale Meteo-Idro-Pluviometrico Sirmip on-line” (Regione Marche, 2023).

2.3. QMRA calculation and integration with SWMM

A Quantitative Microbial Risk Assessment (QMRA) was carried out to quantitatively evaluate microbial risks for stormwater reuse according to the indications provided by the World Health Organization (WHO) guidelines (WHO, 2016), which identify four steps: i) Hazard identification; ii) Hazard characterization; iii) Exposure assessment; iv) Risk characterization.

2.3.1. Hazard identification

The first step of a QMRA procedure is to identify the possible hazardous pathogens that may be reason of illness for humans due to wastewater reuse practices. Goal of this work was to develop a methodology for risk assessment during stormwater management. Hence, all the elaborations were performed using Campylobacter as model pathogen. Particularly, Campylobacter is one of the reference pathogens indicated by WHO (2016) and by Australian Guideline (2006) to perform QMRA.

2.3.2. Hazard characterization

E. coli concentrations in sewage were simulated in SWMM for different stormwater events. Then, to define the expected concentrations of Campylobacter in the discharged overflows, typical ratios between *E. coli* and Campylobacter in raw wastewater were used (i.e.; *E. coli*/Campylobacter $= 1.00 \cdot 10^{-6}–1.00 \cdot 10^{-5}$) (Mara, 2008). Particularly, uniform distributions were utilized to apply the ratios defined by Mara (2008) and obtain data series of Campylobacter in discharged overflows. Calculated average *E. coli* and Campylobacter concentrations (C_m) for the simulated precipitation events were fitted by theoretical distribution curves. Different theoretical distributions were tested, including normal, log-normal, Generalized Pareto, GEV, Rayleight, Pareto, Gaussian Mixture (kernel) distributions. The Kolmogorov - Smirnov, Chi-square, Anderson - Darling test (Anderson, 1962; Mohd Razali and Bee Wah, 2011) was used to assess the goodness of fit between the theoretical and empirical distributions, and to select the best model (details in Text S2).

2.3.3. Exposure assessment

In the exposure assessment, it is needed to define all the activities through which people enter in contact with pathogens during stormwater reuse. In this study, as reuse scenarios were considered garden irrigation, municipal irrigation, and toilet flushing, which are possible reuse options of harvested stormwater in urban and peri-urban contexts. In those reuse scenarios, target people that may be exposed to hazard pathogens are: i) users of and those passing by municipal areas irrigated with harvested overflow water (for municipal irrigation); ii) occupiers of homes supplied with harvested overflow water through dual-reticulation systems (for garden irrigation and toilet flushing). According to the Australian Guideline for water recycling (2006), in the mentioned cases, the exposures is from indirect ingestion via contact with plants and lawn or ingestion of spray. Hence, the exposure volumes and frequencies of exposures per person provided by the Australian Guideline for water recycling were used in this study (Table 2), which are suggested for both wastewater reuse and stormwater reuse (NRMMC–EPHC–AHMC, 2009).

The dose of pathogens with which the exposed persons enter in contact was calculated with the following equation:

$$d = \frac{c^{*}exposure}{event} \tag{2}$$

Where:

- c = concentration of pathogens in water
- exposure/event = volume (mL) with which people enter in contact in a single event of exposure during a certain activity (obtainable by Ingestion Volume in Table 2).

Then, a mathematical functional relationship between the number of pathogens someone is exposed to and the probability of occurrence of the related adverse effect was identified. Indeed, a fraction of infected people may develop different health outcomes. In this study, according to what suggested by Haas et al. (2014), a Beta-Poisson model has been used to calculate the probability of infection (P_{inf}) for Campylobacter:

$$P_{inf} = 1 - \left(1 - \frac{d}{\beta}\right)^{-\alpha} \tag{3}$$

Where $\alpha = 1.44 \cdot 10^{-1}$ and $\beta = 7.58$ are dose response constants (NRMMC–EPHC–AHMC, 2009).

2.3.4. Risk characterization

This last step in risk assessment aims at integrating information from hazard identification, dose response and exposure assessment, to determine the magnitude of risk. Hence, dose response relationships were used to calculate the probability of infection in one year, and the parameter “Disability-adjusted life years (DALYs)”, which is the metric for expressing the burden of disease within a population as suggested by WHO (2016).

Once calculated P_{inf}, the total probability of infection in one year is obtained by the following equation:

$$P_{inf/\mathrm{year}} = 1 - \prod_{1}^{N}\left(1 - P_{inf\,i}\right) \tag{4}$$

Where:

- N = number of events of exposure for the selected activity occurring in one year (frequency/person/year) (i.e., Frequency in Table 2)
- $P_{inf\ i}$ = probability of infection calculated for the event i by eq. 3
- $P_{inf/year}$ = annual risk of infection per person per year (pppy)

Table 2
Exposure assessments used in this study according to the Australian Guideline (NRMMC–EPHC–AHMC, 2009).

Activity	Route of exposure	Ingestion Volume (mL)	Frequency (events/year)
Municipal irrigation	Ingestion via contacts with plants and lawns	1	50
Garden irrigation	Ingestion via contacts with plants and lawns	1	90
Toilet Flushing	Ingestion of spray	0.01	1100

Risk characterization was conducted by the use of Monte Carlo (MC) simulation as suggested by Drechsel et al. (2010) for wastewater reuse, but with some modifications. Particularly, $P_{inf\ i}$ (eq. 3) was calculated *N* times in one year (i.e., the Frequency specified in Table 2) by sampling *N* pathogen concentration values from the obtained distribution curve for Campylobacter fitted by simulated SWMM data (the step for the definition of the distribution curve is described in Hazard characterization). However, for this calculation was also considered the average number of precipitation events that can occur in one year, or better the average number of sewer overflows occurring in a selected spillway in one year (N_p), which are determined by SWMM modelling. It was assumed that the same number of exposure events for a selected reuse activity (e.g., municipal irrigation) are linked to all the sewer overflow events occurring in one year (N_p). Hence, when $N > N_p$ (i.e., the Frequency suggested by the Australian Guideline in Table 2 is higher than the observed overflow events), $P_{inf\ i}$ for N/N_P exposure events was calculated using the same Campylobacter concentration in eq. 3. The assumption is plausible, since a generic reuse activity can be accomplished multiple times and in different days by using the same harvested stormwater. Then, the probability of infection in one year was calculated by eq. 4 considering all the N exposure events occurring in one year (i.e., the Frequency specified in Table 2). Finally, the calculation of the annual risk of infection per person per year (pppy) was repeated in 1000 trial simulations (MC size). Once the value “$P_{inf/year}$” has been calculated (1000 different calculations were available), the probability of illness (P_{ill}) in one year was obtained multiplying ″$P_{inf/year}$″ with the *ratio illness/infection*, which is provided by literature and it is 0.3 for Campylobacter (NRMMC-EPHC-AHMC, 2006):

$$\mathrm{Pill} = P_{inf/\mathrm{year}} {*} \mathrm{ratio\ illness/infection} \tag{5}$$

WHO guidelines consider Disability-adjusted life years (DALYs), as a metric for expressing the burden of disease within a population. The DALY is a health gap indicator for the status of health of a population expressed as burden of disease due to a specific disease or risk factor, and it takes into account both the morbidity and the mortality caused by a specific disease. A health-target of 10^{-6} DALYs was set by WHO as tolerable health risk (WHO, 2016).

The DALY value can be calculated by the following equation:

$$\mathrm{DALY\ per\ year} = \mathrm{Pill}{*}\mathrm{DALYd}{*}\mathrm{susceptibily\ fraction} \tag{6}$$

Where:

- Pill = probability of illness per year
- DALYd = DALY per case

DALYd = 0.0046 for Campylobacter WHO (2016). Once values of DALYs per year for each pathogen have been calculated, the obtained values can be compared with the tolerable level of risk (10^{-6} DALY/person per year) set by WHO in order to understand if the risk is acceptable or not. On the other side, US EPA considers one infection per 10,000 individuals in one year ($P_{inf/year} = 10^{-4}$ pppy) as reasonable threshold for microbial diseases (US EPA, 2010). In this work, where a MC size of 1000 trials has been used to repeat risk calculation, 1000 values of DALYs and $P_{inf/year}$ were available to be compared with related thresholds.

2.4. Legislative boundaries for bathing activities

In the case of bathing water activities, adverse health effects are related to the exposure of bathers to pathogens during bathing activities.

Hence, to reduce the risk of widespread illness connected with aquatic recreational activities, the European Commission has set standard limits for the presence of pathogens in water. Particularly, the EU directive, 2006/7/EC on bathing water provides a classification of water quality based on results of campaign measurements of the concentration of the indicator organisms *E. coli* (Table 3). Furthermore, the same directive requires the realization of a bathing water profile containing information on conditions likely to lead to short-term pollution, including the likelihood of such pollution and its likely duration.

In this context, simulation of CSO volume outflows after stormwater events and the estimation of *E. coli* concentrations in the discharged water can be considered useful parameters to identify bathing sites subjected to short-term pollution events.

In this work, the limits of *E. coli* concentration provided by the EU directive, 2006/7/EC were assumed as threshold values to characterize the possible occurrences of shot-pollution events connected with CSO (Table 3).

2.5. Simulated CSO treatments

To reduce *E. coli* and Campylobacter concentration in overflow water, treatments for CSO were simulated by applying typical bacteria log-removal reported in literature (Crocetti et al., 2021; NRMMC–EPHC–AHMC, 2009; Ragazzo et al., 2013; Rocher and Azimi, 2021). Simulated treatments and expected range of bacteria log-removals are reported in Table 4 for different stormwater treatments. Final *E. coli* and Campylobacter distributions after simulated treatments were obtained applying uniform distribution of expected log-removal. Simulated treatments included green infrastructure (i.e., bioretention filters and ponds) alone or in combination with a disinfection process (i.e., performic acid disinfection).

Particularly, simulated treatments for CSO discharges included the combination: i) Green Infrastructure (NBS) alone; ii) PFA; iii) UV; iv) NBS + PFA. Once obtained new distribution curves for campylobacter concentrations in CSO outflows, QMRA calculations were repeated to assess the new suitability of the treated water for reuse applications.

3. Results and discussion

3.1. Calibration and validation of SWMM model and fitting of distribution curves to simulated pathogen concentrations

Results of quantitative SWMM model calibration and validation are reported in Table S2 in terms of observed PBIAS. PBIAS calculations were referred to simulated and measured depths of water in tanks N7, N8, N10 and frequency of switch-on of the pump in N11. Particularly, observed bias ranged between 0.021 and 0.35 for the calibration step and between 0.018 and 0.041 for the validation. These results are indicative of a very high performance of the SWMM model to reproduce flows in the sewer network in both dry and wet conditions as observed in previous studies (Crocetti et al., 2021; DWA-A 118E, 2006; Hong et al., 2021). Comparison of in-situ measurements and SWMM model predictions are also reported in graphical form in Fig. S3 and Fig. S4 for the rainfall events 10.07.2020 and 16.10.2020, respectively.

Simulation of *E. coli* along the sewer networks and at the inlet of the WWTP was also very performant with observed bias ranging from 0.052 to 0.150. Furthermore, measured and predicted data resulted high correlated with a coefficient of determination $R^2 = 0.86$ (Fig. S5). Prediction of *E. coli* concentrations in the discharged overflows was used to collect information useful for the bathing water profile of receiving seawater, and to estimate Campylobacter concentration for the risk assessment in the selected stormwater reuse scenarios.

Table 3
Standard limits for *E. coli* concentration established by the EU Directive, 2006/7/EC for bathing sites in coastal waters and transitional waters.

Parameter	Excellent quality	Good quality	Sufficient
Escherichia coli (cfu/100 mL)	250[a]	500[a]	500[b]

[a] = *Based upon a 95-percentile evaluation*
[b] = *Based upon a 90-percentile evaluation*

Obtained data series for *E. coli* for overflows N1 – N13 in the period (1997–2008) were fitted by theoretical distributions. For the selected distribution curves, empirical parameters, and results of the test statistics used to assess the fit are presented in Tables S3.

3.2. Simulated E. coli concentrations and info for bathing water profile

Results of SWMM simulation can provide useful information that can be used to describe the profile of bathing sites affected by sewer overflows as required by the BWD (EU Directive, 2006/7/EC). Particularly, by the performed simulations, it is possible to obtain for each critical spillway the following information: i) the precipitation depth in mm that caused sewer overflows, ii) the annual frequency (number of overflow/year) of sewer overflows; iii) the volume of discharged water during each overflow event; iv) expected *E. coli* concentration in the discharged water for each overflow event. All those data are reported in form of box plot in Fig. 2, where *E. coli* concentrations are also compared with thresholds set by BWD (Table 3). Particularly, these data can be utilized by interested stakeholders to identify critical spillways and plan suitable management measures that avoid compromising bathing water quality.

In addition, application of bacteria log removals (Table 4) by using uniform distribution to the obtained *E. coli* dataset can be useful to evaluate the effectiveness of different CSO treatments to minimize the load of pathogens discharged in the receiving bathing water. In Fig. 3, are reported expected *E. coli* concentration after sewer overflows treatment with i) Nature Based Solution (NBS); ii) disinfection by PFA, iii) NBS and PFA disinfection. Reported overflow events are related to 9 years (1997–2006) period.

By the analysis of Fig. 2 and Fig. 3, it is clear that the most critical spillways for sewer overflows in Cupra Marittima are the nodes N5, N10, N11 and N12. Indeed, in those nodes were obtained the highest frequency for sewer overflow occurrence, the highest volume of discharged water and the highest concentration of *E. coli* in water. Overall, all spillways discharging overflows in Cupramarittima shows some critical issues, since it is not be possible to assure the respect of limits set by the EU BWD during all simulated precipitation events and even after application of different treatment processes, including NBS and disinfection (Fig. 3). Hence, additional actions should be planned by the water utility and the municipality to control this short-term pollution phenomenon, such as limiting bathing activity after intense precipitation events.

3.3. Risk assessment for stormwater reuse

The risk calculated in this work is based on SWMM simulation of sewer overflows, and it can be used by water managers to potentially inform the public about a safe utilization of this available source of water or to plan further management/treatment measures to improve the quality of the overflow water. Here, the risk assessment was accomplished for three potential utilizations of stormwater. Particularly, the human health risk related to an infection by the bacterium Campylobacter was calculated when CSO water is used for garden irrigation, municipal irrigation, and toilet flushing. To assess the potential benefits of CSO treatment technologies to improve water quality and extend reuse possibilities, the QMRA calculation was repeated after simulated treatment of sewer overflows by NBS, disinfection with PFA, UV disinfection, and NBS followed by PFA disinfection.

Results of QMRA for all critical spillways in Cupra Marittima are reported in terms of DALY/year in Fig. 4 in the case of municipal irrigation, in Fig. 5 for garden irrigation and Fig. 6 for toilet flushing. Similar graphs, but in terms of $P_{inf/year}$ are reported in supporting

Table 4
Expected bacteria log-removals for simulated CSO treatments.

Treatment	Typical dosages	Log-removals	Reference
Nature Based Solution/Green Infrastructure	–	0.5–3.0	(NRMMC–EPHC–AHMC, 2009)
UV disinfection	100–200 mJ/cm^2	2–4	(Crocetti et al., 2021; NRMMC–EPHC–AHMC, 2009; Ragazzo et al., 2013; Rocher and Azimi, 2021)
PFA disinfection	2.5–5 mg/L	2.5–3	Australian (Crocetti et al., 2021; NRMMC–EPHC–AHMC, 2009; Ragazzo et al., 2013; Rocher and Azimi, 2021)

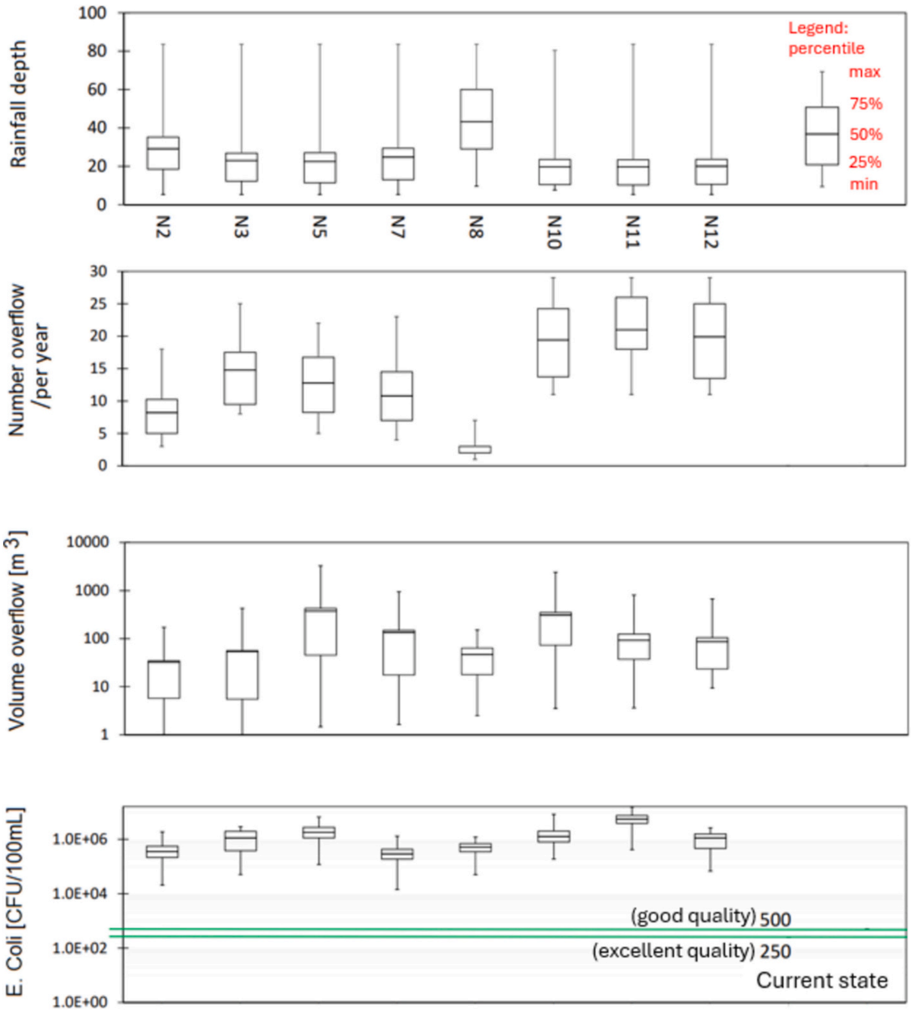

Fig. 2. Precipitation depth causing sewer overflow, frequency (annual number of overflows), volume of discharge and mean concentrations (per single event) of *E. coli* observed during simulated overflows in Cupra Marittima. SWMM modelling included 210 rainfall events occurring in 9 years (1997–2008). The box plot shows the minimum, first quartile, median, third quartile, and maximum of simulated values. Green lines indicate thresholds set by EU Directive, 2006/7/EC to define excellent and good quality of bathing water. The evaluation is related to the current state without treatment.

information (Fig. S6 – S8). Calculated risks are acceptable for both US EPA (2010) and WHO (2016), when the 95 percentiles of calculated metrics of the Monte Carlo generated dataset are below the established thresholds.

By the analysis of Fig. 4–6, it is possible to observe that, although differences are very small between the selected reuse options, the highest risk is related to the reuse of stormwater for municipal irrigation. The second highest risk was calculated for garden irrigation, whereas toilet flushing had the lowest microbiological risk. In fact, considering municipal irrigation, treatment by UV disinfection or NBS + PFA do not allow to obtain acceptable DALY/year values for all CSOs as observed for other reuse scenarios. Moreover, considering PFA disinfection, the number of CSOs with insufficient quality for municipal irrigation reuse is much higher than in the other two reuse scenarios. Differences in the obtained results in terms of risk assessment for different reuse scenarios are dependent on the exposure volumes and frequencies of exposures per person provided by the Australian Guideline for water recycling, which were used in this study (Table 2). Particularly criteria for exposure assessment are more severe for the reuse scenario of municipal irrigation compared to the other reuse possibilities investigated in this study.

The overflow in node N11, which was the one with the highest estimated pathogen concentration (Fig. 2), has the highest microbiological risk for all reuse scenarios. Particularly, considering municipal irrigation reuse, no treatment allows to reduce the Campylobacter concentrations at node N11 to obtain the 95 percentile of DALY/year

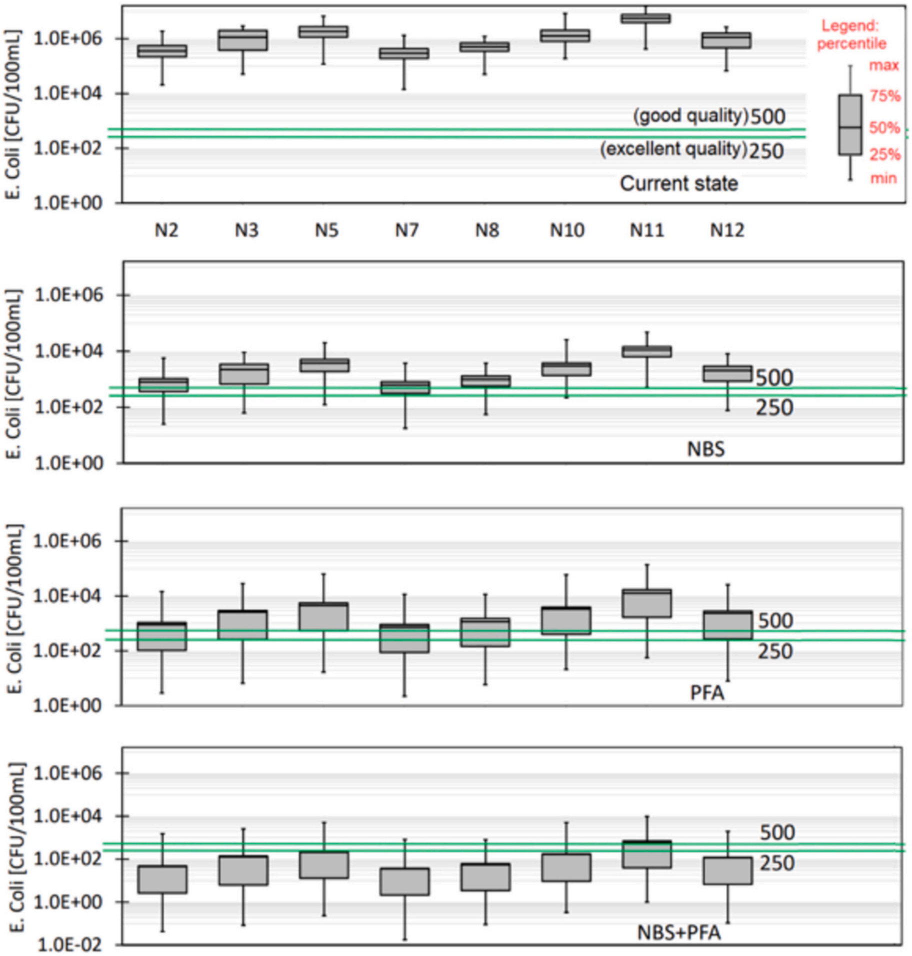

Fig. 3. *E. coli* concentrations in sewer overflows from critical spillways before (current state) and after treatment with i) NBS, ii) disinfection by PFA, iii) NBS and PFA disinfection during all simulated precipitation events. *E. coli* concentrations are compared with thresholds set by EU Directive, 2006/7/EC to define excellent and good quality of bathing water. The box plot shows the minimum, first quartile, median, third quartile, and maximum of simulated values.

values below the threshold set by the WHO. On the other hand, the lowest risk was estimated for spillways N7 and N8 in all investigated reuse scenarios.

Treatment of stormwater significantly reduces the DALY/year calculated by QMRA procedure. Particularly, overflows at node N2, N7, N8 and N12 have already a microbiological quality that allows reuse of stormwater for all investigated reuse scenarios by applying a simple treatment with PFA disinfection. Otherwise, disinfection by UV processes or combination of NBS and PFA disinfection are needed to reduce the risk to acceptable level in all the other spillways. Exception is the overflow at node N11 for municipal irrigation as previously discussed. Overall, the combination NBS and disinfection seems to be an effective treatment measure to produce water exploitable for different reuse options.

When the QMRA is calculated in terms of $P_{inf/year}$, results are a little bit more stringent than when the risk is calculated as DALY/year (Fig. S6 – S8). This fact was also observed in previous work (Lim et al., 2015). For example, reuse is not possible according to US EPA (2010) guidelines for municipal irrigation at nodes N5 and N11 even when applying NBS + PFA treatment. On the contrary, this reuse scenario is not allowed only at node N11 if considering WHO (2016) threshold.

4. Conclusions and implication for management of UWR

In this work was elaborated an innovative methodology to allow calculation of a quantitative microbial risk assessment (QMRA) for stormwater reuse in urban areas by using data modelled by SWMM software. Particularly, 206 precipitation events registered in the period 1997–2008 were simulated by SWMM software after the sewer network model of the city of Cupra Marittima (Italy) was calibrated and validated using quantitative and qualitative data obtained by field campaigns and laboratory analysis.

The developed methodology allows to perform risk assessment for stormwater reuse according to the indications provided by the World Health Organization (WHO) guidelines (WHO, 2016) and by the Australian Guideline for water recycling (NRMMC–EPHC–AHMC, 2009). The proposed methodology utilizes a Mote Carlo approach to increase the number of annual risk calculations to make generated results more robust and it takes into account the number of overflow events occurring in one year. Criteria for exposure and risk assessments are those suggested by the available regulations and guidelines (i.e., WHO and Australian Guideline for water reuse).

In the present work, the proposed methodology was utilized to assess microbial risk related to the reuse of stormwater for municipal irrigation, garden irrigation and toilet flushing in the urban area of Cupra Marittima and considering the bacterium Cryptosporidium as infection agent. Then, the risk assessment was repeated after simulation of stormwater treatments, including NBS, disinfection with PFA, UV disinfection and combined NBS and PFA disinfection. Outcomes of the simulations were able to indicate the spillways that after treatment were able to produce overflow water suitable for the investigated reuse scenarios in this study.

Finally, impacts on receiving bathing water were estimated by calculation of *E. coli* concentration in sewer overflows, discharged

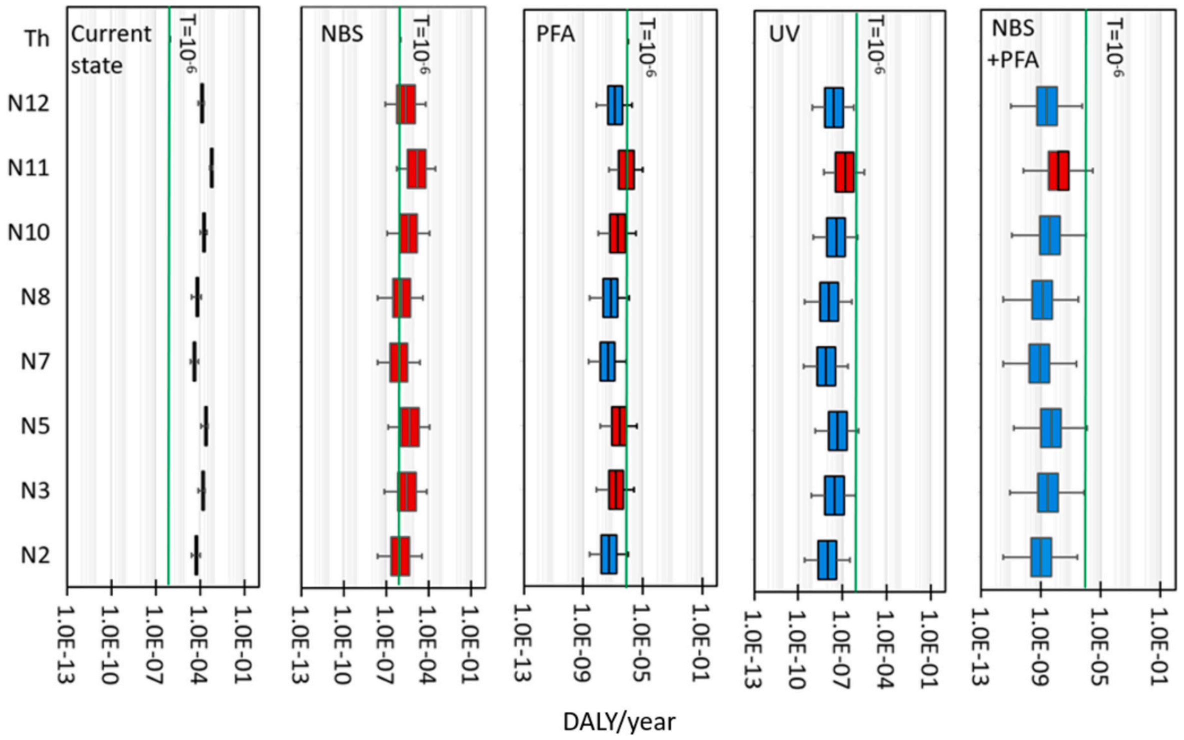

Fig. 4. DALY/year of Campylobacter related to stormwater reuse for municipal irrigation for different CSO treatment scenarios: a) current state (no treatment), b) NBS, c) PFA, d) UV, e) NBS + PFA. The box plot shows the minimum, first quartile, median, third quartile, and maximum values. Particularly, box plots in red indicate that calculated 95 percentile of DALY/year is higher than WHO threshold (10^{-6} DALY/year). The blue box plots indicate acceptable risk values.

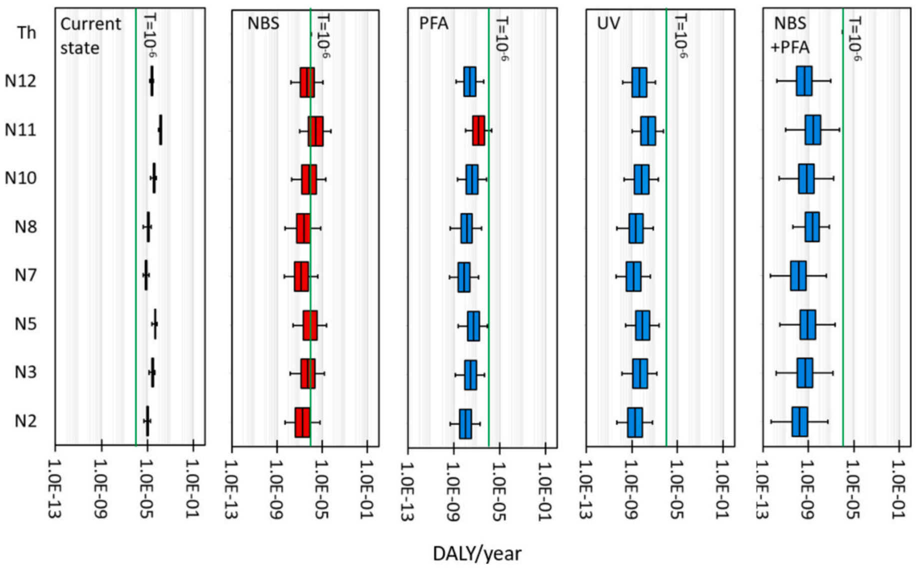

Fig. 5. DALY/year of Campylobacter related to stormwater reuse for garden irrigation for different CSO treatment scenarios: a) current state (no treatment), b) NBS, c) PFA, d) UV, e) NBS+ PFA. The box plot shows the minimum, first quartile, median, third quartile, and maximum values. Particularly, box plots in red indicate that calculated 95 percentile of DALY/year is higher than WHO threshold (10^{-6} DALY/year). The blue box plots indicate acceptable risk values.

volumes during overflow, annual frequency of overflows in each critical spillway as required by the EU BWD, 2006/7/EC for the definition of the bathing water profile of sites receiving short-term pollution. Hence, *E. coli* concentrations before and after simulated treatments were compared with thresholds established by this EU directive to define quality of the bathing water.

Reassuming, outcomes produced by this work can be used by interested stakeholders in the decision-making process for stormwater management and to plan fit-for-purpose treatment of overflow waters taking into account information related to human health risk assessment.

It is noteworthy to highlight that the outcomes and methodology produced in this study can be used to answer some of the new challenges required by the Proposal for a Directive of the European Parliament and of the Council concerning urban wastewater treatment (EU, 2023), which indicates that Member States should ensure the adoption of integrated urban wastewater management plans at local level for large agglomeration (> 100,000 pe) and where sewer overflows or urban

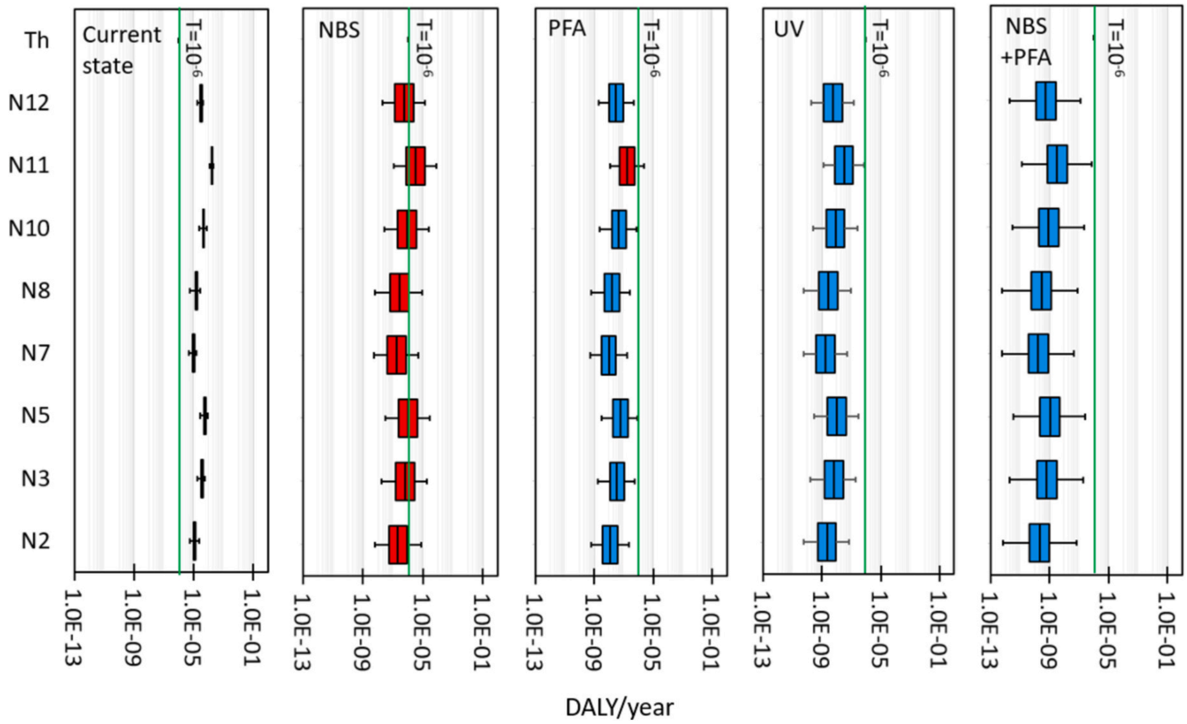

Fig. 6. DALY/year of Campylobacter related to stormwater reuse for toilet flushing for different CSO treatment scenarios: a) current state (no treatment), b) NBS, c) PFA, d) UV, e) NBS + PFA. The box plot shows the minimum, first quartile, median, third quartile, and maximum values. Particularly, box plots in red indicate that calculated 95 percentile of DALY/year is higher than WHO threshold (10^{-6} DALY/year). The blue box plots indicate acceptable risk values.

runoff poses a risk for the environment or public health. The main goal of this new plan is to combat pollution from rain waters (urban runoff and sewer overflow) through the reduction of quantity discharge and phasing out of untreated discharges through separate collection systems, also promoting new form of reuse (e.g., stormwater reuse).

CRediT authorship contribution statement

Bartosz Szelag: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Lucia De Simoni:** Writing – review & editing, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Adam Kiczko:** Writing – review & editing, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Massimiliano Sgroi:** Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Anna Laura Eusebi:** Writing – review & editing, Supervision, Resources, Project administration. **Francesco Fatone:** Writing – review & editing, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2025.178552.

Data availability

The data that has been used is confidential.

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