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Research article

Costs and benefits of combined sewer overflow management strategies at the European scale

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ABSTRACT

Combined sewer overflows (CSOs) may represent a significant source of pollution, but they are difficult to quantify at a large scale (e.g. regional or national), due to a lack of accessible data. In the present study, we use a large scale, 6-parameter, lumped hydrological model to perform a screening level assessment of different CSO management scenarios for the European Union and United Kingdom, considering prevention and treatment strategies. For each scenario we quantify the potential reduction of CSO volumes and duration, and estimate costs and benefits. A comparison of scenarios shows that treating CSOs before discharge in the receiving water body (e.g. by constructed wetlands) is more cost-effective than preventing CSOs. Among prevention strategies, urban greening has a benefit/cost ratio one order of magnitude higher than grey solutions, due to the several additional benefits it entails. We also estimate that real time control may bring on average a CSO volume reduction of just above 20%. In general, the design of appropriate CSO management strategies requires consideration of context-specific conditions, and is best made in the context of an integrated urban water management plan taking into account factors such as other ongoing initiatives in urban greening, the possibility to disconnect impervious surfaces from combined drainage systems, and the availability of space for grey or nature-based solutions.

1. Introduction

Combined sewers are a widespread reality in Europe as well as other parts of the world (Zabel et al., 2001; Pistocchi et al., 2019; Quaranta et al., 2022). Combined sewers are usually designed to collect the dry weather flow (DWF), consisting of sewage from households, industrial discharges and seepage of groundwater, into the sewers, together with urban runoff, and convey a certain amount of the combined flow to a Wastewater Treatment Plant (WWTP). The WWTP generally receives a discharge of 4–6 times the average DWF in order to ensure the design pollution removal efficiency of the treatment process, although in some cases it can be > 6 (Quaranta et al., 2022). When the sewer network discharge exceeds the conveyance capacity of the network, the overflow is released into the environment. With wastewater treatment approaching compliance with the existing regulations in Europe (10th implementation report, European Commission, 2020), pollution from combined sewer overflows (CSOs) remains a significant pressure on the receiving water bodies and raises concern as a water management challenge (Gromaire et al., 2001; Pistocchi et al., 2019; Müller et al., 2020; Joshi et al., 2021; Montserrat et al., 2015, Ajuntament de Barcelona, 2021; Rombouts et al., 2013; Bar-Zeev et al., 2021; Owolabi et al., 2022). Increasing trends in the frequency of intense precipitation (Meehl and Tebaldi, 2004; Barceló and Sabater, 2010; Keupers and Willems, 2013) and urbanization (Fu et al., 2019) suggest that CSOs may worsen in the future as a European scale problem, impacting on the ecological status of rivers. At the same time, citizens are increasingly appreciating the recreational value of inland and coastal waters in urban areas, and less and less willing to accept sewage spills through CSOs (Water UK, 2021). The impacts of CSOs are usually related to the discharged volume, the duration of discharge and the type of pollution they convey. A fraction of the CSO volume consists of untreated sewage (the CSO's DWF

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Nomenclature

CS = combined sewer
CSO = combined sewer overflow
d = CSO duration (hours/y)
DWF = dry weather flow (Mm^3/y)
EU = EU27+ UK
FUA = Functional Urban Area
HRU = hydrological response unit (here 1 ha of impervious urban area connected to a CS network)
NBS = nature based solution
RTC = real time control
V_{CSO} = spilled CSOs (Mm^3/y)
V_{DWF} = spilled dry-weather flow through CSOs (Mm^3/y)
W_0 = catchment storage capacity (mm)
W_1 = network storage capacity (mm)
W_2 = tank storage capacity (mm)
WWTP = wastewater treatment plant
y = year

content), while the rest is runoff. Pollutants in CSOs derive from the DWF content, the pollutants removed from urban surfaces by runoff, and the pollutants remobilized from the in-sewer sediments and biofilms. In this paper, by CSO we mean the process of discharging overflow via a CSO structure.

CSO volumes, duration and DWF content can be reduced by limiting runoff contributions to the combined sewers (e.g. through urban greening or infiltration reduction), and by mitigating high flows within the sewer infrastructure (e.g. through storage capacity of buffer tanks). CSO impacts can be also mitigated through appropriate treatment processes before CSO is discharged into the receiving water bodies (particularly, constructed wetlands, e.g., Rizzo et al., 2020), and through real time control (Garofalo et al., 2017). The choice of the most effective strategy for CSO management depends on local constraints and drivers of costs and benefits (Casal-Campos et al., 2015; Dolowitz et al., 2018; Matzinger et al., 2011; Stovin et al., 2013), and a specific solution should be identified case by case. At the same time, addressing CSOs in a systematic and coordinated way requires a quantification of the possible CSO loads (e.g., volumes, duration and DWF content) at the large scale, and the cost-effectiveness of different management strategies.

In this study, we use a large scale urban hydrological model (Pistocchi and Dorati, 2018; Quaranta et al., 2022) to perform a screening level assessment of different CSO management scenarios for the European Union (EU) and former EU member state United Kingdom (UK). For these scenarios we quantify the potential reduction of CSO loads, estimating the corresponding costs and benefits. We compare the scenarios in terms of cost-effectiveness and we draw suggestions for CSO management strategies at the European scale.

2. Materials and methods

2.1. Hydrological model and calculation of CSO indicators

The large scale urban hydrological model applied here (Pistocchi and Dorati, 2018; Quaranta et al., 2022) quantifies the CSO originating from an urban hydrological response unit (HRU) representing 1 ha of impervious urban area connected to a combined sewer network. The model was applied to 671 functional urban areas (FUA) across the European Union and United Kingdom (EU27+UK), reflecting the continental variability of precipitation as well as the population density of urban areas (Fig. 1). Population density is a first approximation indicator of DWF, which is calculated here as the product of population in the HRU and a unit discharge of 200 L per capita per day. The 671 European FUAs house 320,090,394 inhabitants and represent 4,166,177 ha of impervious surface (Fig. 1).

The model, described and discussed in detail in Quaranta et al. (2022), consists of a cascade of three linear reservoirs representing the catchment surface, the sewer network and the buffer tank at the head of the WWTP. In-sewer processes are neglected and we assume a complete mixing of DWF and runoff. The model uses as input a time series of rainfall with a 3-h resolution from 2001 to 2016. The rainfall that

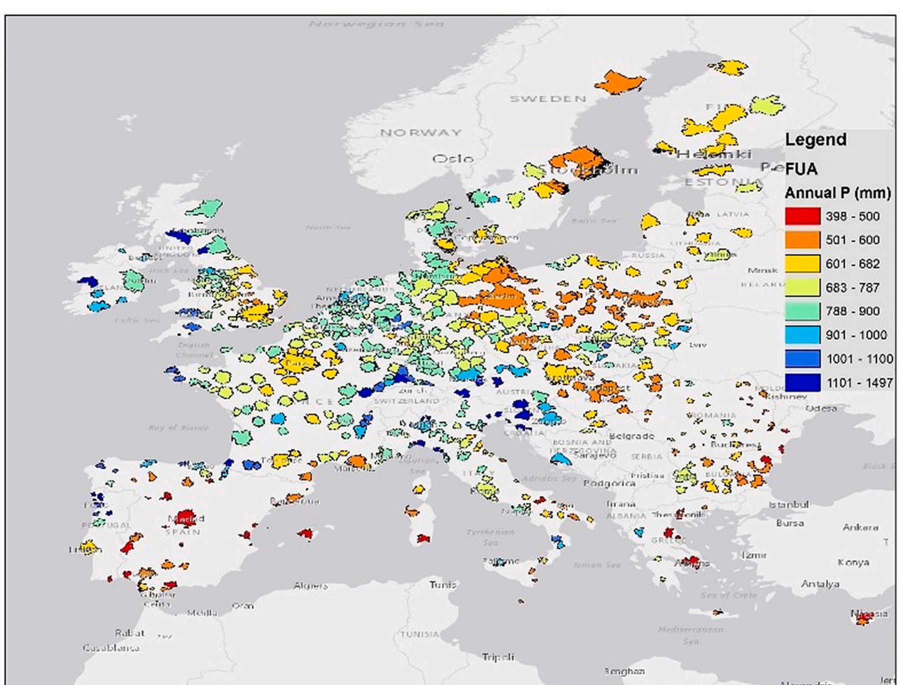

Fig. 1. EU27+UK FUAs, with the annual precipitation.

reaches the network depends on the catchment storage capacity and the rate constant for the depletion of the surface reservoir during dry weather. The model has six parameters representing the volume of each reservoir, the rate constant for the depletion of the surface reservoir during dry weather, the overflow threshold of the network and of the buffer tank. The overflow threshold of the network and the tank is defined as a multiple of DWF, also called “dilution ratio”.

Quaranta et al. (2022) present an extensive benchmarking of the model against independent CSO observations or estimates, along with a sensitivity analysis. They show that the model, applied with EU-wide constant default values of the parameters, yields simulations with absolute values of CSO volume and duration within a factor 2, and can be calibrated accurately in the presence of sufficient data. The model struggles to accurately describe the volume of small events (<1000 m^3 of overflow) which are most strongly influenced by local catchment and network features. Nevertheless, the contribution of small events to the annual CSO volume is quite modest, and even large percent errors on small events do not reflect into high errors on the annual volumes of overflow. Therefore, the model is reasonably realistic and appropriate to perform screening level assessments and scenario explorations at EU scale. Table 1 summarizes the model parameters used as default for our EU scale simulations, while we refer to Quaranta et al. (2022) for any additional detail.

We consider the following CSO pollution indicators:

1) Annual average CSO volume (V_{CSO}).
2) Volume of DWF contained in the CSO (V_{DWF}). This reflects the efficiency of the combined sewer system in limiting discharges of untreated wastewater to the environment.
3) Cumulative yearly duration of CSO (d).

The model was applied to a hydrological response unit (HRU) consisting of 1ha impervious urban area connected to a combined sewer network. The volume of CSO and DWF in CSO are expressed in units such as mm y^{-1} or $m^3 ha^{-1} y^{-1}$. These can be finally multiplied by the total impervious area (ha) served by combined sewers within each FUA to yield the cumulative volumes of CSO and its DWF content, assuming no scale dependence of the parameters (see Quaranta et al., 2022).

2.2. Scenarios

We considered the following CSO management approaches:

1) Limitation of runoff through urban greening.
2) Limitation of overflows by increasing the sewer infrastructure’s buffering capacity.
3) Treatment of CSO before discharging it to a receiving water body, thus reducing their pollutant load instead of their flow volume.
4) Real time control of the existing sewer network.

The first two and the fourth approaches aim at *preventing* CSO from happening, while the third aims at *repairing* its impacts. In order to simulate a given CSO management measure, we changed the model parameters reflecting the expected effect of the measure, as discussed below. This resulted in a number of scenarios that we simulated, of which details are summarized in Table 2.

Table 1
Model parameters and their baseline values.

Parameter	Symbol	Baseline Value
Storage capacity of the catchment surface	W_0	1.5 mm
Reservoir constant of the catchment surface	k_0	0.1 h^{-1}
Dilution rate of network pipes, that multiplied by the total DWF gives the maximum conveyance of the network to the tank (30 for Germany and Austria, unrestricted flow for the Netherlands)	d_n	7
Storage capacity of the network	W_1	5 mm
Dilution rate of the tank, expressing the maximum conveyance to the WWTP	d_t	4
Storage capacity of the tank	W_2	2 mm

1) Limitation of runoff through urban greening

Urban greening is a multipurpose strategy delivering several potential benefits in terms of climate change adaptation and sustainable cities, including the reduction of storm water runoff. In this study, as maximum ideal target, we simulated a scenario of extensive urban greening by increasing the storage volume of the urban surface reservoir (W_0) from the baseline value of 1.5 mm (Table 1) to 10 mm. The 10 mm (additional 8.5 mm of surface storage to the baseline 1.5 mm) are compatible with covering approximately 35% of the impervious surface with a soil 30 cm thick and with a storage capacity (difference between the water content at the saturation point and the field capacity) of 10% of its thickness, in line with Quaranta et al. (2021) and with Casal-Campos et al. (2015). This scenario could be theoretically implemented e.g. by greening of all the EU rooftop surfaces, or part of the roofs and part of other impervious areas (e.g., parking lots). Since in practice this would be almost impossible to implement, it is apparently an “upper limit”. We simulated also a more realistic, but still extensive, greening implementation scenario corresponding to $W_0 = 5$ mm, assumed to be in line with more realistic, while still ambitious, urban greening objectives, e.g. as proposed in the EU Biodiversity Strategy (European Commission, 2020a).

Table 2
Target scenarios (maximum achievable at the EU scale). CW = constructed wetland.

Scenario n.	Short name	Description	Model parameter values
0	Baseline	Representative of the current situation	Baseline values (Table 1)
1	Grey	Moderate increase of buffer tank storage	$W_2 = 5$ mm
2	More grey	Large increase of buffer tank storage	$W_2 = 10$ mm
3	Green	Urban greening, soil of 30 cm thick on 17.5% of the surface, 10% of soil thickness is assumed to be storage capacity	$W_0 = 5$ mm
4	Green and grey	Implementation of both strategies, light	$W_0 = 5$ mm, $W_2 = 5$ mm
5	Green and more grey	Implementation of both strategies	$W_0 = 5$ mm, $W_2 = 10$ mm
6	More green	Urban greening, soil of 30 cm thick on 35% of the surface, 10% storage capacity	$W_0 = 10$ mm
7	More green and grey	Implementation of both strategies	$W_0 = 10$ mm, $W_2 = 5$ mm
8	More green and more grey	Implementation of both strategies, large	$W_0 = 10$ mm, $W_2 = 10$ mm
9	smaller, medium and larger wetlands	Improvement of CS treatment. Three CW scenario were assumed, each one with a proper CW design volume (50°, 75°, 95° percentile) respectively.	Baseline values. We assume the 50% removal efficiency of the CW reflects in an equal reduction of DWF content of the CSO that is treated
10	Green + CW	Scenario 3 + CW with design volume averaged between the 50° and 75° percentile	
11	Real Time Control	Applied to scenarios 0, 1, 2	Additional CSO reduction of the estimated CSO

As an alternative to urban greening, we could imagine to disconnect part of the impervious surfaces from the CS network. In this way, we could reduce the amount of runoff that reaches the CS, making overflows less frequent, and their volumes smaller. Disconnection may occur by allowing infiltration of rainwater in the soil, or by connecting part of the surfaces to a separate drainage system (Jefferies et al., 2008). When possible, these measures may prove very cost-effective. In particular, turning an urban surface back into unsealed soil supporting infiltration may contribute significantly to the mitigation of the hydrological impacts of urbanization. In addition, discharging rainwater from gutters or storm drains directly to nearby surface waters or unsealed soils allows preventing runoff and pollutants to reach the drainage system. However, very often these solutions are not feasible in dense urban areas, unless by implementing costly separate drainage systems. For this reason, we limit our assessment to greening options entailing a relatively thin soil cover of impervious areas yielding a limited buffer volume.

2) Limitation of overflows by increasing the sewer infrastructure's buffering capacity

The buffering capacity of the network can be increased through larger detention volumes. Compared to urban greening, it is a "grey" or traditional engineering solution. In this study, we simulated a scenario where the tank storage capacity is increased from the default value $W_2 = 2$ mm to $W_2 = 5$ mm, so that $W_1+W_2 = 10$ mm. This value is in line with the highest storage capacity known to be implemented in the EU context (e.g. in the Netherlands, Quaranta et al., 2022) and in agreement with the scenario investigated in Casal-Campos et al. (2015). We also simulated a scenario with $W_2 = 10$ mm, so that $W_1+W_2 = 15$ mm, with the aim of exploring the implications of a massive retrofitting of the network. The two preventing strategies (urban greening and sewer network retrofitting) can be also combined together (i.e. simultaneous increase of parameters W_0 and W_2).

3) Treatment of CSO before discharging it to a receiving water body

CSO treatment before discharging it to a receiving water body allows a removal of pollutants and a consequent reduction of the impacts of CSOs. "Green" solutions such as constructed wetlands (CW) are usually regarded as a cost-effective option in this respect. CW may bring several additional benefits including support to landscape quality and biodiversity (Rizzo et al., 2020; Hammer et al., 2020). In this study, we considered a scenario where CSOs are not reduced, but routed through a CW with a retention time of 1 day before discharge. This retention time is suggested as acceptable in order to achieve a significant removal of pollutants (Rizzo et al., 2020). The CW design volume required for a retention time of 1 day was calculated in the following way, for each FUA:

1) the cumulative volume of CSOs during 24 h (1 day) was calculated over the time series, obtaining the series of CSO daily volumes V_{24}; assuming a linear behavior and a time step of 3 h, $V_3 = V_{24}/8$ is the design volume referred to a time step.
2) from the series of CSO daily volumes we calculated the 95th, 75th and 50th percentile, assumed to be three possible design volumes V_{des};
3) a CW with a volume equal to those percentiles would retain the overflow for no less than 1 day in 95%, 75% and 50% of the cases, while for the rest the CSO volume in excess of the CW volume would be by-passed;
4) a volume balance was carried out for each design volume and for each time step of the time series. The inflow volume was the CSO volume, and the outflow volume V_{out} was calculated assuming a linear reservoir behavior. The outflowvolume in each time step is linearly proportional to the ratio of the cumulated volume V_c to the design one. When the cumulated volume is zero, the outflow volume is zero, and when the cumulated volume is maximum ($V_c = V_{des}$), the outflow volume during the time step is V_3.

Under these treatment scenarios, the CSO volume discharged to the environment does not change, but its content of pollutants (determining the impacts) is reduced by a percentage corresponding to the removal efficiency of the CW. Therefore we considered that the annual volume of DWF discharged with CSOs are virtually reduced by the same percentage. Rizzo et al. (2020) indicate a removal efficiency of 42%–96% for COD, 50%–80% for TSS, 45%–90% for BOD, >90% for NH4, 47–90% for total phosphorus. In the appraisal of scenarios, we considered 50% as a precautionary value of removal efficiency. We also explored a combined scenario, considering urban greening implementation with $W_0 = 5$ mm and a CW with a design volume calculated as average between the design volumes corresponding to the 50° and 75° percentile.

4) Real time control

Real Time Control (RTC) is an emerging water management strategy (Garrido-Baserba et al., 2020; Voutchkov, 2019), that aims at using data collected in real time to adjust the operation of the system (in this case, the CS network) pursuant a goal, that in our case is the reduction of CSOs. Van Der Werf et al. (2022) review RTC applications for CSO management by referring to a set of case studies (see Appendix 3). By plotting the CSO volume reduction in the case studies as a function of the initial CSO volume, we found that the reduction of CSO annual volumes could be expressed as a function of the current CSO volumes, by means of a power law equation (further described in Appendix 3) with $R^2 = 0.87$ and mean absolute error of 36%. We used the abovementioned power law equation to calculate the CSO volume reduction that could be achieved through RTC under certain management measures.

2.3. Cost and benefit assessment

In order to appraise the cost-effectiveness of measures under the above scenarios, we computed the corresponding annual costs by including the repayment of investments, and operation and maintenance (O&M). O&M is assumed equal to 1% of the investment every year (in line with e.g. Menin et al., 2020 for Italy). The repayment of investments is calculated assuming a discount rate of 2.5% and a lifetime of the investments of 40 years for urban greening (in line with e.g. Ajuntament de Barcelona, 2021), 30 years for a CW, and 100 years for the grey infrastructure (in line e.g. with Ajuntament de Barcelona, 2021).

1) Costs of the Limitation of runoff through urban greening

For the "green" prevention strategy, the required urban greening area in each FUA is calculated from the chosen value of surface storage W_0, as $A = \frac{W_0 - W_{0,baseline}}{t \cdot p} S$, where S is the FUA impervious surface (FUAs total surface of 4,166,177 ha), t is the implemented soil thickness and p the effective porosity (10%), and $W_{0,baseline} = 1.5$ mm. The cost of greening is highly case-specific: it is usually 50 €/m^2 (Quaranta et al., 2021; Joshi et al., 2021, and several case studies reported by Gruppo CAP, 2021, pers.comm.), but can reach approximately 150 €/m^2 (Sien Kok, 2022, pers. comm.; Menin et al., 2020; Ajuntament de Barcelona, 2021; Montalto et al., 2007) and even up to 350 €/m^2 for permeable paving (Digman, 2018; pers.comm as cited in Sriwastava et al., 2021). The cost of urban greening was set to 50 €/m^2 as the most recurrent value. The implications of the assumed costs are analyzed in the Discussion section.

2) Costs of the limitation of overflows by increasing the sewer infrastructure's buffering capacity

The cost per unit volume of a grey solution (which we assume to be a buffer tank) includes both the concrete structure itself, excavation and spoil disposal, and the costs related to the equipment and hydraulic monitoring. For very large volumes, the cost of equipment is negligible, so that a typical cost is around 500 euro/m^3 (Gruppo CAP, pers. comm., 2021; Conte et al., 2020; Menin et al., 2020; Ajuntament de Barcelona, 2021). However, for tank volumes between 100 m^3 and 1000 m^3, the cost related to the equipment becomes more relevant, and the cost per unit volume increases. Therefore, we assume a cost of buffer tanks equal to 1000 €/m^3, that is an average cost of literature data (see Appendix 1).

3) Costs of treatment of CSO before discharging it to a receiving water body (CW)

The cost of a CW for the treatment of CSOs before discharge was estimated by multiplying the required area (required volume divided by average effective depth) by the cost per unit area. The effective depth was assumed equal to 1 m and the unit cost equal to 500 €/m^2, in the mid-upper range of costs from the literature reported in Appendix 1.

4) Costs of real time control (RTC)

RTC cost depends on the number of sensors and actuators and their location, and some examples can be found in Appendix 3. However, costs are difficult to parameterize, so that they are not quantified here. Anyway, for a given reduction of CSO volume, their cost is generally much lower than that of a grey solution.

5) Benefits

The benefits of CSO management include the removal of pollution as well as possible co-benefits, especially when urban greening is implemented, such as carbon sequestration, support to biodiversity, mitigation of heat wave effects and social and economic use of spaces.

Here we quantified the benefits of pollution removal by attributing a shadow price to the conventional pollutants conveyed by the CSO, based on Hernández-Sancho et al. (2015). A shadow price is the equivalent of the environmental damage avoided if these pollutants are removed or recovered. Therefore, they can be interpreted as an estimate of the environmental benefits gained from the treatment. The assumed shadow prices are shown in Table 3, together with the concentrations of pollutants in DWF and runoff. With these values, the shadow price of avoiding 1 m^3 of DWF spill through CSO is $Pr_{\mathrm{DWF}} = \sum_i Pr^i_{sh} \cdot C^i_{DWF} = 1.37$ Euro, and the shadow price for 1 m^3 of avoided runoff (avoided volume of CSO minus avoided volume of DWF) is $Pr_{\mathrm{runoff}} = \sum_i Pr^i_{sh} \cdot C^i_{runoff} = 0.005$ Euro, where Pr^i_{sh} is the shadow price of the pollutant i per unit mass, while C^i_{DWF} and are its concentration in DWF and in runoff, respectively (Table 3). The benefit associated to the avoided CSO is therefore:

$$B_1 = \left[V_{\mathrm{CSO}} - V^*_{\mathrm{CSO}} - \left(V_{\mathrm{DWF}} - V^*_{\mathrm{DWF}}\right)\right] C_{\mathrm{runoff}} + \left(V_{\mathrm{DWF}} - V^*_{\mathrm{DWF}}\right) C_{\mathrm{DWF}}$$

where V_{CSO} is the annual CSO volume (m^3), and V_{DWF} is the annual spilled volume of DWF (m^3) under a given scenario, and V_{DWF}*, V_{CSO}* are the corresponding values in the baseline scenario. It should be stressed that the shadow prices used in this study were suggested for "chronic" pollution problems, and may therefore underestimate the value of mitigating "acute" pollution arising from CSOs, where pollutants are released in relatively small amounts, but concentrated in time, so to disproportionally harm the ecosystems and/or hinder the recreational use or attractiveness of the receiving water bodies. Moreover, the shadow price of Hernández-Sancho et al. (2015) for micropollutants is very low and unlikely to be representative of the real value of avoiding the release of chemicals of emerging concern present in CSOs.

For urban greening and constructed wetlands, we considered also a carbon sequestration CO2seq = 500 kg CO2-equivalent ha^{-1} y^{-1}. This value is conservatively assumed much lower than indications from the literature (Were et al., 2019) to account for the high variability of operating conditions in an urban context, leading to suboptimal carbon sequestration. At a price of $C_{\mathrm{GHG}} = 0.09$ Euro/kg (Table 3) (GHG = greenhouse gas) the corresponding benefit for a surface area A is:

$$B_2 = C_{\mathrm{GHG}}\, CO_2seq\, A.$$

The benefits of urban greening in the energy context (heat island mitigation and reduced cooling request in summer) can be extrapolated from Quaranta et al. (2021), who calculated benefits of 29.6 10^9 € per year for A_r = 2,645,000 ha of greened impervious surface. In this study we scale these benefits with A/A_r. For the CW scenario, only the heat island mitigation benefit is considered (11.2 10^9 € per year for A_r of greened impervious surface). The benefit of cooling reduction in summer is only realistic if greening is implemented on cooled surfaces, e.g. on roofs, and it is thus overestimated in our assessment, since we did not strictly limit the greening scenario to green roofs. Additional benefits could not be quantified within the scope of this exercise (see the Discussion section). It is therefore anticipated that the benefit-to-cost ratio of the various policy scenarios considered here is underestimated and should not be read at face value.

Table 3
Shadow price of pollutants assumed for the calculations (assumed constant throughout the EU), and concentrations used to compute benefits.

Parameter	Shadow price	Unit
Atmospheric CO2	90	€/ton CO2e
TSS	0.005	€/kg
MP	40	€/kg
N	20	€/kg
P	30	€/kg
BOD	0.05	€/kg
Parameter	Concentration	Unit
TSS in runoff	70	mg/L
BOD in runoff	11	mg/L
MP in runoff	100	ug/L
TSS in DWF	200	mg/L
MP in DWF	100	ug/L
N in DWF	55	mg/L
P in DWF	8.4	mg/L
BOD in DWF	300	mg/L

3. Results

The hydrological model was applied to the 671 FUAs with the setup described in Quaranta et al. (2022), to calculate V_{CSO}, V_{DWF} and d, with reference to a 1-ha urban HRU as described above. The CSO volume and DWF spill volume computed for a HRU were scaled with the impervious area within each FUA and multiplied by an assumed percentage of the area served by combined sewer networks, extrapolated from the best available country-level estimates (Pistocchi et al., 2019), in order to obtain total volumes.

Under baseline conditions, the resulting annual CSO volume across all of the 671 FUAs is V_{CSO} = 5782 million m^3 per year (Mm^3/y). The DWF content in CSO is V_{DWF} = 463 Mm^3/y. This represents 1.98% of the DWF generated from the ca. 320 million population living in the 671 FUAs. The average spill duration per year is d = 98 h per FUA, with the following percentiles: $d_{99.7\%}$ = 220 h, $d_{95\%}$ = 165 h, $d_{75\%}$ = 111 h and $d_{50\%}$ = 89 h. Under the various scenarios simulated with the model, V_{CSO} and V_{DWF} decrease and the cumulative duration of overflows is reduced depending on the model parameters, reflecting the extent to which CSO is addressed. With prevention measures ("green" and "grey" scenarios) the DWF spills through CSO may decrease from about 1.98% down to about 0.83% of the generated DWF, the CSO volume may be approximately halved, and the duration decreases from 98 h/year to about 30 h/year (Table 4 and Fig. 2). Duration, volume and the percentage of DWF spilled with CSO are apparently correlated with each other.

Table 4
Results of the investigated scenarios, with Costs (C) and Benefits (B) estimation for each strategy in billion €. The scenarios are ordered with respect to the reduction of DWF content in CSO.

Scenario	Short name	*A* for greening (ha)	Tank volume for grey scenario (Mm^3)	V_{CSO} (Mm^3/y)	V_{DWF} (Mm^3/y)	*d* (h)	C Green	C Grey	C Total	B_1 pollution control	B_2 GHG	Energy and microclimate benefits	B/C (%)
0	Baseline	–	–	5782	463	98	0.0	0.00	0.00	0.66	0.00	–	–
1	Grey	–	125	5397	405	87	0.0	4.66	4.66	0.08	0.00	–	1.7
2	More grey	–	333	4944	361	69	0.0	12.44	12.44	0.14	0.00	–	1.2
3	Green	486,054	–	4651	358	66	12	0.00	12.11	0.15	0.02	5.44	46.3
4	Green and grey	486,054	125	4336	314	61	12	4.66	16.77	0.21	0.02	5.44	33.8
5	Green and more grey	486,054	333	3972	281	47	12	12.44	24.55	0.26	0.02	5.44	23.3
6	More green	1,180,417	–	3327	244	40	29	0.00	29.41	0.31	0.05	13.21	46.2
7	More green and grey	1,180,417	125	3118	216	38	29	4.66	34.08	0.35	0.05	13.21	40.0
8	More green and more grey	1,180,417	333	2866	195	30	29	12.44	41.85	0.38	0.05	13.21	32.6
9	Smaller wetland (50° percentile)	3586	40.5	4826	355	98	1.0	–	1.03	0.40	0.0003	0.02	39.8
10	Medium wetland (75° percentile)	9437	107	3978	286	98	2.7	–	2.7	0.45	0.00085	0.04	17.9
11	Larger wetland (95° percentile)	27,226	309	3101	238	98	7.9	–	7.9	0.48	0.0025	0.12	7.7
12	Green + CW	6512	74	3713	271	98	14		13.99	0.46	0.022	5.47	42.5

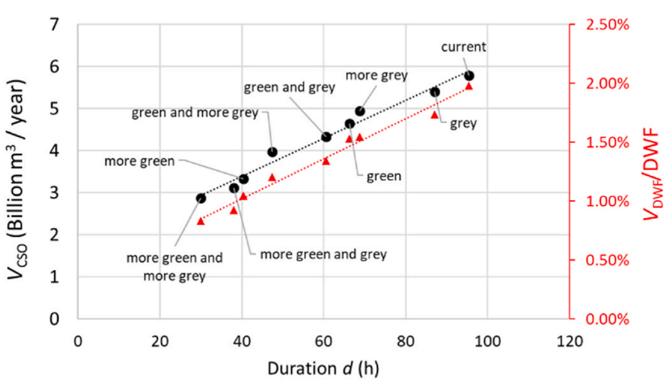

Fig. 2. CSO volumes and spilled DWF (as percentage on the total produced DWF) versus average duration, i.e. depending on the strategy considered.

For each scenario, we also computed the costs and quantified benefits as explained above (Table 4). Prevention measures entailing infrastructure retrofitting, extensive greening of urban spaces or both are usually quite expensive, and improvements imply increasing costs. While local conditions may reveal opportunities to reduce costs in some cases, our quantification of costs provides an order of magnitude of several billions Euro per year across the EU (minimum 4.7 billion € for a "grey" solution, increasing almost 10-fold for an ambitious, combined "green" and "grey" solution, 41.9 billions – see Table 4). In general, "green" solutions are less expensive than "grey" solutions to achieve the same CSO load reduction, and bring additional benefits. The quantified benefits alone increase the benefit-cost ratio (B/C) by more than 1 order of magnitude compared to grey solutions with similar capacity to reduce pollution.

Compared to prevention measures, treatment measures appear to be much more cost-effective. Under the *smaller wetland* scenario, the volume of CSO discharged without treatment is reduced of around 1000 Mm^3/y as under the *green* or the *more grey* scenario, but at remarkably lower costs and with an about 100-fold smaller space requirement than for the *green* scenario. The *larger wetland* scenario reduces CSO by around 3000 Mm^3/y as the "*more green*" and "*more green and grey*" scenarios, but at a lower cost and requiring an area that is about 40 times smaller.

Fig. 3 plots together the reduction of CSO under each scenario as a function of the corresponding cost, showing that the prevention and treatment strategies follow separate trends. The combined scenario "CW + green" is obviously midway of the two trends. This scenario entails the same CSO reduction as the *green and more grey scenario*, with a similar benefit to cost ratio of that of the *green* and *more green* scenarios, and with a cost slightly higher than the green scenario. Furthermore, the area required for CW is noticeably reduced with respect to the CW area of the larger wetlands, thus overcoming possible space limitations.

By applying our power law equation (Appendix 3) to estimate the reduction of CSO volumes through RTC in all the 671 FUAs under the baseline scenario (scenario 0), the overall saved CSO volume is 1236 Mm^3, with annual volumes reducing from 5782 Mm^3/y to 4546 Mm^3/y (−21.4%), at an investment cost arguably much lower than required by

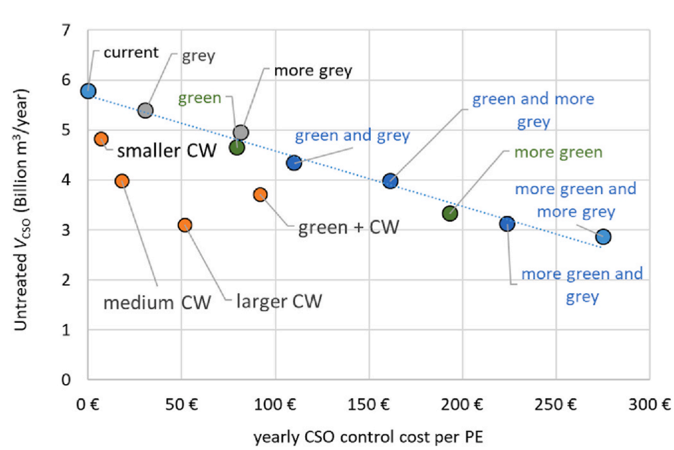

Fig. 3. Summary of results. The yearly cost per PE was obtained dividing the total cost by the population living in the considered FUAs and served by a CS (152,200,521 people). By implementing RTC, the untreated CSO volume further reduces by 21% with an arguably small increase of investment cost (not quantified here).

the implementation of grey solutions for the same benefit. RTC performances strictly depend on local factors (particularly the extent, slope and available volume of drainage networks), hence our results can be only regarded as indicative of an average achievable benefit of RTC at the EU scale. The same calculations performed in the other scenarios lead to a CSO annual volume reduction of 21.5% (grey scenario - 1) and 21.7% (green scenario −3).

The calculated benefits of all scenarios are shown in Table 4 along with the costs. Depending on the scenario, they cover at best less than a half of the estimated costs. Grey solutions have an apparently much lower benefit-to-cost ratio than green and combined solutions.

4. Discussion

Using a European-scale urban hydrological model, we simulated various scenarios of CSO management, and showed how CSOs can be substantially reduced through *prevention* or *repairing/treatment* measures, although they cannot be completely eliminated. The former strategies aim at avoiding overflows and are rather expensive. The latter strategies do not reduce overflow volumes, but remove pollution to an extent that may be comparable to the prevention measures, while presenting typically much lower costs. Compared to grey solutions of infrastructure retrofitting, green solutions may cost less for the same effectiveness, and show a much higher benefit/cost ratio. Extensive urban greening may deliver widespread benefits to urban dwellers that were only partly quantified in this assessment (Appendix 2). It may also make cities more resilient against floods and climate extremes, thus qualifying to attract additional potential investments related to climate change adaptation beyond wastewater management. Our results are supported by other studies in the literature (e.g. Joshi et al., 2021; Menin et al., 2020; Conte et al., 2020). Combinations of the strategies (e.g., *green and grey*, or *wetland and green*) can improve the benefit to cost ratio and allow to overcome space limitations and optimize costs.

Urban greening may entail a significant contribution of private investments, e.g. when it includes green roofs (Quaranta et al., 2021), and may have important implications in terms of architectural quality and urban attractiveness, hence real estate values. This can make urban greening a viable investment in some cases, although possibly more difficult to scale up. Infrastructure retrofitting is usually faster to implement than extensive urban greening, because decisions are mostly made at a technical level by the water managers. However, the corresponding costs reflect directly in the water bills.

Treatment measures show to be cheaper and more cost-effective. While they may be still regarded mainly as investments by water managers, they require relatively large spaces compared to grey solutions and have more apparent implications on the organization of the urban environment. They may bring benefits comparable to extensive greening under many respects, but they are typically less useable by citizens, hence they may not be attractive as investments outside water management. In any case, local conditions may reveal many opportunities and limitations, suggesting that an effective management of CSO should be planned carefully at urban level by harnessing the best combinations of grey and green, prevention and repairing measures in each case.

In the end, deciding on measures for CSO reduction entails consideration of the specific context and synergies with other possible investments. While the benefits quantified above cannot cover all the costs that we assume, the costs of CSO control may be acceptable when the benefits include other substantial aspects, including the avoidance of "acute", short term pollution events that damage ecosystems and hinder the recreational or aesthetic value of the receiving water bodies. Schasfoort et al. (2018) assess the willingness to pay (WTP) for the improvement of one class in ecological status of water bodies at about 25 €/person. Johnson and Geisendorf (2022) show that citizens are generally willing to pay for environmental improvements due to NBS implementation, e.g. avoiding short term pollution from CSO impairing recreational and other use of water bodies and fish kills, increases in urban biodiversity and summer temperature mitigation. They show for the case of Berlin a WTP between 25 and 180 €/person/year depending on the effects that CSO control can produce. Most of the scenarios considered here entail costs compatible with this range of WTP (see Fig. 3) and can result feasible under the appropriate circumstances.

The estimation of costs is also uncertain, due to the impossibility to generalize costs in an accurate way for interventions so inherently depending on the local conditions. If we assumed different costs of the various grey and green solutions within the range of values found in the literature (see also Appendix 1) the ranking of scenarios in terms of benefit-to-cost ratio could change slightly. However, this would not change substantially the pattern of cost-effectiveness shown in Fig. 3. The costs of storage may be smaller than assumed here, e.g. in the case of revamping obsolete infrastructure, when storage may be obtained in existing green spaces, or anyway does not entail costly structural works. We can suppose that in case of retrofitting of existing structures, or in case of tanks of large size, the grey infrastructure costs could approach the indicative lower limit of 500 €/m^3. In other contexts, costs may be higher, especially in case of small tanks (Appendix 1). The cost of greening may be higher, as discussed in the Method section, but this would not change the implications of our study at the EU scale. The CW cost was assumed 500 €/m^3 but, as highlighted in Appendix 1, it could be as low as 200 €/m^2, making these measures more cost-effective, but without changing the general findings of our study.

The scenarios considered in this study have also some limitations. The assumptions made on the prevention measures reflect a very high level of ambition and ignore the lower-cost alternatives that could be feasible in many cases, thus pushing the costs very high. For instance, in some urban areas it could be possible to increase the surface storage of a few mm by modifying the storm drains of paved surfaces, or by dispersing runoff into adjacent pervious areas instead of draining it to the sewers, with very limited costs compared to those assumed for urban greening.

Certain technical solutions may cause unintended problems that we ignored in this assessment. For instance, a large increase of the network's buffering capacity may cause longer wastewater residence time during dry periods, and consequent increase of organic carbon degradation upstream the WWTP, negatively impacting denitrification. This aspect has received particular attention from planners in the German context (DWA, 2020). Space limitation and local constraints may also represent obstacle in the implementation of these measure. Among repairing/treatment measures, we refer to CW as a general solution. However, these require large spaces that cannot be available in practice (Nakamura et al., 2017). For instance, in Germany it is estimated that only 20% of the catchment area drained with a CS can be connected to a constructed wetland (Fuchs et al., 2017). At the same time, it should be noted that land acquisition costs in urban areas can be extremely high, and often represent a major constraint for CW, but also for the expansion of buffer tanks. For what regards urban greening (prevention strategy), it is often difficult to find available space to be replaced with a vegetation cover due to either competing land uses (e.g. traffic) or other limitations (e.g. limits of building structures supporting the additional weight of green roofs, and slow implementation). Versini et al. (2020) showed that the urban roof surface of some EU capitals covered by green roofs varies between 0.1% and 2.5% (see Appendix 4 for more details) making our theoretical upper limit of 35% extremely challenging to reach, if considering only roofs. Moreover, they stress the necessity to better take into account the spatial distribution of green roof implementation, rather than density alone, in order to optimize their performances.

The additional reduction of spilled volume enabled by RTC was shown to be about 20% on an annual basis and averaged over the FUAs considered. Costs of RTC are often much lower than those of prevention and repairing measures (e.g. Dirckx et al., 2011), in which case RTC should be regarded as a complement, and not an alternative to the other types of measures. An advantage of RTC is that no additional land is required, and is very cost-effective if certain conditions are met, low slope terrain and a large volume sewer system. Large cities are therefore predestined for implementation.

5. Conclusions

In this study we performed a screening level assessment of different mitigation strategies to reduce CSO loads, focusing on annual volume, DWF content and spill duration. Using a European-scale urban hydrological model, we showed how CSOs can be substantially reduced through prevention or treatment measures. Prevention strategies aim at avoiding overflows and are rather expensive. They can be green strategies, e.g. urban greening and green roofs, or grey strategies, e.g. increase of tank storage and conveyance capacity of the combined sewer network. Green strategies entail higher multipurpose benefits, e.g. wastewater and urban runoff reduction, urban heat islands mitigation, carbon removal and biodiversity improvement. Therefore, green strategies exhibit a benefits to costs ratio that is generally one order of magnitude higher than the corresponding grey ones, and can attract investments from different sectors and contribute to different policy strategies. Furthermore, citizens are often willing to pay for benefits entailed by green solutions. An optimization of the existing infrastructure including real time control may significantly reduce CSOs, and should be regarded as "low-hanging fruits". RTC implementation is easier and related investment costs are typically smaller than costs of the other investigated strategies, but the achievable CSO reduction is limited and may not be sufficient in the absence of other management measures**.** Treatment strategies do not reduce overflow volumes, but remove pollution to an extent that may be comparable to the prevention measures, while presenting typically much lower costs and supporting landscape quality and biodiversity. However, space availability may critically limit their implementation. An optimization of combinations of the different strategies can help overcome space limitations and reduce costs.

Therefore, cost-effective management of CSO requires solutions tailored to the specific conditions in each urban area. CSO management strategies may be better accommodated in appropriately designed urban water management plans, taking into consideration the needs to improve the ecological status of the receiving water bodies, together with multiple objectives including urban development, climate change adaptation, biodiversity support and pollution control, and potentially mobilizing investments from a variety of actors.

Credit author statement

E.Q. and A.P. performed the calculations and wrote the paper. The other authors reviewed the paper, provided input data on costs and supported the assumptions with their input and insights.

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 1

Table A1
Unit costs 2021 of real projects, South Germany, data collected by S.F. and from Office fédéral de l'environnement (2003).

grey infrastructure element	Cost	Unit
Sewer DN 500 mm	600	€/m
Sewer DN 1000 mm	1170	€/m
Constructed wetland small (100 m^2)	2000	€/m^2
Constructed wetland large (5000 m^2)	650	€/m^2
Stormwater retention ponds small	240	€/m^3
Stormwater retention ponds large	120	€/m^3
CSO tank >20 m^3/ha	2500	€/m^3
CSO tank <10 m^3/ha	4000	€/m^3

Table A2
Total average cost per facility

Constructed wetland in Germany 100 m^2/ha	65,000	€/CW
Stormwater retention small in Germany 150 m^3/ha	36,000	€/ha
Standard CSO in Germany 20 m^3/ha	50,000	€/ha

Table A3
Literature data.

Strategy	Cost	Unit	Country	Reference
Tank, 16,500 m^3	590	€/m^3	Italy	Gruppo CAP (2021), pers. comm.
Tank, 500,000–1,000,000 m^3	400–500	€/m^3	Spain	Ajuntament de Barcelona (2021)

(*continued on next page*)

Table A3 (*continued*)

Strategy	Cost	Unit	Country	Reference
Tank	500-1500	€/m^3	The Netherlands	Stichting RIONED (2022)
Tank	1400–2000	$/$m^3$	U.K.	Digman, 2018, pers. comm
Tank	140-1170	$/$m^3$	U.S.A.	Montalto et al. (2017)
Tank	1000	€/m^3	Belgium	Colas et al. (2004)
Tank	2000–4000	€/m^3	Germany	Table A1
Tank	500	€/m^3	Estonia	Kändler et al. (2020), excluding pump cost (2000 €/tank), indirect costs of missing parking revenue and maintenance costs (500 €/tank/year)
Tunnel	500–845	$/$m^3$	Turkey	Cohen et al. (2012)
Wetland, 1 m soil+ 1 m ponding	200-1000	€/m^3	Germany	€/m^3 = 79,578 $V^{-0.681}$, with V the m^3 volume, NRW (2015), from statistical analysis
Wetland	Order of 10^2	€/m^2	The Netherlands	H.J. Liefting, most is land purchase
Wetland	115	€/m^2	U.K.	Susdrain (2019)
Wetland	480	€/m^2	U.S.A	Montalto et al. (2007)
Wetland	170	$/$m^2$	U.S.A., U.K., Germany	Taillardat et al. (2020)
Wetland	185	€/m^2	Italy	Masseroni et al. (2018)

Appendix 2. additional benefits of NBS

In this Appendix, two case studies are described to show the additional economic benefits that urban greening and related NBS can generate.

In Italy, Gruppo SMAT implemented a NBS to store water from river Po, to be then treated for drinking use. The total cost was 20 Million €. Among the several benefits, the quantified ones were the reduction of cost by 31% of chemical reactors in the next treatment processes (225,000 €/y), better operation of the water treatment facilities with a cost saving of 70,000 €/y, and a reduction of chemical substances in the treated water (ammonia reduced by 50%, turbidity by 60%, iron by 30% and micro-organism by more than 90%).

Ajuntament de Barcelona (2021) quantified the damage of CSOs, calculating a damage related annual cost of 48 M€ to properties, 13 M€ to commercial activities and 39 M€ to the environment. The combination of drainage elements on the streets, green roofs and 10 headwater basins in natural areas with total capacity of 128,700 m^3 could manage 28% of the annual discharged volume and could reduce by 14%–34% the urban area at risk (damage on mobility and people). If these measures are implemented in combination with grey measures, the affected urban area can reduce by 59%–99%. Furthermore, by implementing the mentioned anti-CSO measures, the annualized value of benefits is almost 27 Million € in the face of an annualized cost of 16 Million €.

Appendix 3

Real time control can help in CSO mitigation (Colas et al., 2004; Van Der Werf et al., 2022), and it can be classified into local control systems, or system-wide control systems, where the former type is less expensive but with less relevant efficacy at the large scale (e.g. the whole city scale) (Eulogi et al., 2022).

For example, in Paris, CSO volume could be reduced by almost 25% by application of real-time control to the system, with a cost saving of 1.1 billion €. In Louisville, the municipality has reduced the cost of CSO long-term control program by $150 million by integrating a real-time control system, with a CSO volume reduction by 50% on an annual basis. In another application in Quebec, $90 million were saved in the capital cost to the Quebec City CSO Control Program, with a CSO volume reduction by almost 23% (Colas et al., 2004). In Berlin, €90 million were invested to reduce CSOs, in which the cheapest measures are real time control inside the CS. In Ancona and Falconara Marittima (Italy), € 22 million have been planned to be invested for CSO management (Botturi et al., 2021). Kändler et al. (2020) calculated that the investment cost of a smart inlet system would be 671, 404 €, while the budget of the construction of the detention tanks would be 992,510 €, for an area of 12 ha in Tallin (Estonia). The difference in the investments stems from the scale of construction works. Also, the construction period of these two alternatives varies significantly from two weeks in the case of the smart inlet to eight weeks for detention tanks. Therefore, the indirect costs of smart systems are 100,000 € while the detention tanks reach 400,000 €. Consequently, the investment of a smart system is 1.8 times lower than in the case of the detention tank system. Pleau et al. (2005) estimated the costs of real time control in CS systems in Quebec. In Van Der Werf et al. (2022), additional case studies across Europe are described.

Considering the case studies listed in Van Der Werf et al. (2022) on the benefits of CS digitalization and real time control (RTC), Table 1 can be compiled, extracting the original data from the case study-related papers.

Table A4
Case studies and related data.

Location	Number of CSO events	Catchment impervious surface (ha)	Overflow pre-RTC m^3	Overflow reduction m^3
Klagshamn, Sweden	1	80		
Flensburg, Germany	10		190285	173159
Dresden, Germany	24	7500	4800000	1800000
Rauch and Harremoes, 1999, idealized catchment	1	1020	37300	33500
Vienna, Austria	24	8720	320896	43000
Quebec, Canada	7	32500	49716	43252
Eindhoven, the Netherlands	28 (4 main)	4000	2500000	362500
South Bend, US	1 year		458	312
Cosenza, Italy	15	212	379668	151579
Perinot, France	31	45.9	112431	11243
Flanders, Belgium	5	113	218059	73962
Badalona, Spain	3	2000	1356925	1180569

(continued on next page)

Table A4 (*continued*)

Location	Number of CSO events	Catchment impervious surface (ha)	Overflow pre-RTC m^3	Overflow reduction m^3
Unknown	1	540	21297	14797
Southern Germany	3 years	109	355169	39069

The regression equation presented in Figure A1 was derived, with an average absolute error between predicted and real value of the CSO reduction equal to 36%.

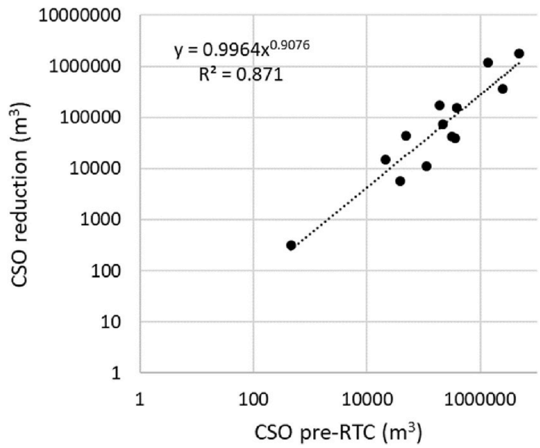

Fig. A1. Regression equation from literature data.

Appendix 4

Table A4.1 shows the green roof surface for some European cities, and the relative percentage with respect to the total impervious surface of the FUA associated to the city (and neglecting the green roofs that may have been installed on roofs of the FUA outside of the city) (Livingroof, 2022).

Table A4.1
Green roof surface in some EU27+UK cities.

City	Green roof area in the city (ha)	Imp. surface of the FUA (ha)	%
Stuttgart	200	36229.1	0.55
Linz	50	11925.1	0.42
Munich	314	36079.6	0.87
Vienna	256	37783.4	0.68
London	151	94990.8	0.16
Düsseldorf	69.8	20276.3	0.34
Berlin	400	75853	0.53
Rotterdam	23.5	21436.8	0.11
Amsterdam	30	32234.5	0.09

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