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Constructed wetlands for the treatment of combined sewer overflow upstream of centralized wastewater treatment plants

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ABSTRACT

Combined sewer overflows (CSOs) constitute nowadays a major environmental concern, representing one of the main untreated sources of pollution for receiving water bodies. Additional, in recent years, the frequency and intensity of CSOs have increased due to the growing urbanisation and climate change. Although there is no single effective strategy, one of the most promising approaches for the control and treatment of CSOs can be found in nature-based solutions (NBS), such as constructed wetlands (CWs). Despite the demonstrated potential of CWs to treat CSOs, the only data reported in the literature refer to CSO-CW systems located along the sewerage network. This research represents, to the best of our knowledge, the first monitoring of a full-scale CSO-CW designed to treat the combined sewer overflow upstream of the WWTP located in Carimate, in the province of Como (Italy). The system is a multistage CW, composed by a 1st vertical subsurface flow (VF) stage (total area of 8500 m^2) and a 2nd free water surface (FWS) stage (total area of 4500 m^2). The observed removal rates during the 3 years monitoring campaign (mean values equal to 83.2%, 64.6%, 63.8% for COD, TP, and N-NH_4^+ respectively) confirmed the treatment efficiency of CW system for all the investigated parameters, consistent with literature data for CSO-CWs in line with the sewerage network, despite its large scale and different hydraulic characteristics. Furthermore, the system also provides additional ecosystem services such as flood mitigation (average CSO interception of 82%), enhancement of biodiversity and a low operational and maintenance cost.

1. Introduction

Combined sewers (CSs) are designed to convey domestic and/or industrial wastewater into the sewers together with urban stormwater runoff (Botturi et al., 2021). In recent years, these systems have been replaced by separate sewers, in which domestic sewage and stormwater flows are conveyed through different pipes. Nevertheless, numerous examples of CSs can still be found in different European countries, such as Italy, Germany, France, Belgium, Greece, and Poland (Pistocchi et al., 2019). To achieve a satisfactory level of pollutant removal, Wastewater Treatment Plants (WWTPs) should have the capacity to receive a discharge of 4–6 times the average dry weather flow (DWF), consisting of domestic sewage, industrial discharges, and groundwater seepage (Giakoumis and Voulvoulis, 2023; Quaranta et al., 2022a; Quaranta et al., 2022b), even if this condition is often not fulfilled in order to guarantee an optimal functioning of the WWTPs, which are usually designed to receive a maximum of 2–3 times the DWF. During particularly intense storm events, however, the discharge of the sewage network may exceed the network's conveyance capacity. When combined sewer overflows (CSOs) occur, there is a direct release of the excess of wastewater into nearby streams, rivers, or other water bodies through a series of overflow structures, which control CS systems (Rizzo et al., 2020; Yu et al., 2022; Petrie, 2021; Botturi et al., 2021). Since the water released by CSOs is untreated, in addition to hydraulic shock, the greatest concern is related to the consequent environmental contamination. Although discharge events are short and occur only a few dozen times per year, the release of large volumes of untreated water during CSOs results in significant quantities of conventional pollutants, micropollutants, pathogens and heavy metals entering the receiving water bodies (Tondera et al., 2013; Tondera, 2019; Schreiber et al., 2016; Petrie, 2021; Botturi et al., 2021). On a European scale, the issue of CSO-related pollution is not directly regulated, despite the latest

Abbreviations: CSO, Combined sewer overflow; WWTP, Wastewater treatment plant; CW, Constructed wetland; NBS, Nature-based solution.

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evaluation of the EU Urban Waste Water Treatment Directive (UWWTD) (271/91/EC) highlighting the need to control CSO pollution, which is recognised as being responsible for the discharge of BOD, N, P and coliform loads higher than 5 million population equivalent (PE) (Botturi et al., 2021; Crocetti et al., 2021).Therefore, nowadays it is one of the main untreated sources of contamination, according to the Water Framework Directive (2006/7/EC) (Pistocchi et al., 2019). The most concerning consequences of CSOs include a significant contribution to the failure of European water bodies to achieve good status (European Commission, 2019), but also the loss of bathing water status established by the corresponding EU Directive (2006/7/EC) (Al Aukidy and Verlicchi, 2017; Botturi et al., 2021). Moreover, the criticality of CSOs may even worsen in the future due to increased soil sealing as a result of expanding urbanisation (Fu et al., 2019; Botturi et al., 2021) and the expected growth in the frequency of intense storm events (Meehl and Tebaldi, 2004; Barceló and Sabater, 2010; Keupers and Willems, 2013; Botturi et al., 2021). In addition to the environmental issues of CSOs, there are also economic/social implications. In fact, sewage spills during overflows also result in a severe limitation of the recreational use of urban inland and coastal waters, unacceptable to citizens.

As combined sewer overflows have become a priority challenge for city and watershed management, several strategies have been proposed for their mitigation: (i) limiting runoff volumes through urban greening; (ii) reducing overflows by increasing the storage capacity of buffer tanks in sewers; (iii) decreasing pollutant load by specific treatment processes before the CSO is discharged into receiving water bodies; (iiii) real-time monitoring of the sewer network (Garofalo et al., 2017; Pistocchi et al., 2019; Botturi et al., 2021). Although there is no single effective solution and cost-benefit analysis should be carried out by evaluating the specific case (Casal-Campos et al., 2015; Dolowitz et al., 2018; Matzinger et al., 2011; Stovin et al., 2013), one of the most promising strategies to reduce the environmental pressure of CSOs can be found in Nature-Based Solutions (NBS) (Rizzo et al., 2020; Petrie, 2021). Indeed, NBS systems show several advantages compared to conventional approaches (first flush tanks), such as a continuous treatment of CSO (also including second flushes) and additional services in terms of flood protection, biodiversity increases and recreational activities (Liquete et al., 2016; Masi et al., 2017; Rizzo et al., 2021). Among the different 'green' solutions, constructed wetlands (CWs) present powerful and well-documented removal performances for different classes of pollutants. CWs can be classified into two sub-categories, which differ according to the type of flow: surface flow wetlands (also defined free water surface systems; FWS) and sub-surface flow wetlands. In the first case, water is generally shallow and macrophytes emerge or float freely, with treatment capacities similar to those of natural wetlands such as lakes or ponds. In the second case, instead, a porous medium (e.g., sand or gravel) and a more developed macrophyte root zone are present, allowing greater interaction between the roots themselves, the biofilms, and the water to be treated. Since, in the latter configuration, wastewater flows through the porous medium, there is also maximisation of the physical removal of solids by filtration, as well as suitable habitat for biofilm development. The first CWs for the treatment of CSOs (CSO-CWs), developed in Germany in the late 1980s, were in fact designed exclusively for total suspended solids (TSS) and chemical oxygen demand (COD) abatement, while providing an additional retention volume for CSOs (Grotehusmann et al., 1997; LfU, 1998; Liebeskind, 2001; DWA, 2019). Only later, CSO-CW design was optimised for the mitigation of a wider range of pollutants. Nowadays, CSO-CW technologies have been successfully applied on a full-scale in several European and US countries (Pálfy et al., 2017a, 2017b, 2017c; Masi et al., 2017; Tao et al., 2014), although with greatly variable designs depending on site-specific conditions. Variability is also emphasised due to the absence of international uniform regulatory guidelines. According to the recent review of Rizzo et al. (2020), six different approaches can therefore be distinguished for CSO-CW, each of which generally includes preliminary treatments (e.g., sand and grease trap) to handle the large amount of solid particles conveyed by CSOs: German approach, French approach, Italian approach, American approaches, Combination of CSO tanks and conventional CW solutions, and Aerated systems.

Finally, for a proper understanding of the wide variability of CSO-CWs in terms of design and operational characteristics, another relevant factor may be considered. Indeed, CSOs can take place at two different levels of the sewage system: in line with the sewer network or upstream the centralized WWTP. Therefore, the two types of overflows are distinguished by different hydraulic characteristics. The first category of CSO, which occur in line with the sewer network, is characterized by shorter concentration time of the sewer network and smaller water volume in comparison to the CSO events taking place upstream the centralized WWTP. For that reason, CW systems designed to treat the second class of overflows generally present different design features, e.g. they are usually dimensioned on a larger scale to be able to handle higher flow events. As a general observation, despite the demonstrated potential of CW systems for CSO treatment, the significant variability of possible schemes and the lack of available data on the temporal characterization of CSOs and treatment performances still represent a limitation to their extensive application. Most importantly, the only data reported in the literature refers to CSO-CW systems located along the sewerage network, with a total absence of information concerning CSO-CWs upstream of the centralized WWTP.

This study therefore aims to contribute to bridging this gap by providing data collected during a three-year monitoring campaign of the CSO-CW upstream the WWTP located in Carimate, province of Como (Italy). The analysis of the whole dataset allowed a characterization of the quality and quantity of CSOs and an estimation of the removal efficiencies of CSO-CW. This research represents, to the best of our knowledge, the first monitoring of a full-scale CSO-CW designed to treat the combined sewer overflow upstream of the WWTP, rather than the more common CSOs in line to the sewers, providing also interesting suggestions for future designers in this frontier of CW application.

2. Materials and methods

2.1. Characterization of CSO upstream the centralized WWTP

The experimental case study is located in Carimate, Italy (45° 42′N, 9° 07′E).

The centralized WWTP of Carimate treats the wastewater from the combined sewer serving 11 towns in Como province (70,040 inhabitants). Combined sewer overflows (CSOs) upstream of Carimate WWTP occur frequently, sometimes lasting for several days even during dry weather after the rain event, due to the long concentration time of the sewer network (see Table 1 and Table 2).

For design purposes, CSO events were assumed to be characterized by different pollutant loads depending on their duration and the sampling time: (i) CSO event A, CSO in the 24 h following the beginning of CSO events and occurring after a minimum 2-day dry period, where pollutant loads are expected to be higher due to washout effect of roads and sewer; (ii) CSO event B, CSO events below a 2-day dry period or the second fraction of the previous CSO event (collected >24 h after the beginning of the overflow), for which is expected a generally show lower contamination level, with a pollutant load assumed due only to diluted

Table 1
Statistics on the duration of CSO events and the dry time between events. Data from 2012 to 2014.

	Dry period [days]	CSO events duration [days]
Average	12	3
Std. Dev.	19	6
Min	1	1
Max	99	38
80° percentile	19	4

Table 2
Sewage quantity statistics used for the CSO-CW design, for all overflow events, CSO A and CSO B events only. Data from 2013 to 2014.

	Total events	CSO A	CSO B
Average [m^3 d^{-1}]	11,963	8137	13,269
Std. Dev. [m^3 d^{-1}]	6833	5655	6722
Min [m^3 d^{-1}]	895	895	1788
Max [m^3 d^{-1}]	29,403	27,137	29,403
80° perc. [m^3 d^{-1}]	18,038	13,236	18,984
Average annual No. of events	75	19	56
Annual volumes [m^3]	893,257	154,610	738,647

domestic wastewater. The characterization of the CSO event A and B were based on the monitoring data of wastewater influent to the WWTP from 2013 to 2014, in order to allow a proper design of the CSO-CW system. The CSO characterization is reported in Table 3 and Fig. 1, confirming the higher pollutant loads expected by CSO event A in comparison to CSO event B.

2.2. Constructed wetland for the treatment of CSO upstream the centralized WWTP

The centralized WWTP of Carimate is managed by the Water Utility Como Acqua Srl and its equipment is reported in Fig. 2. The WWTP is equipped to provide pre-treatment (grit removal) and a primary treatment of CSO (sedimentation) up to 3000 m^3 h^{-1}. According to permit that the WWPT has for the discharge in the Seveso River, the WWTP must treat a flow rate equal to 2700 m^3 h^{-1} during CSO event. Since the biological secondary treatment can receive a maximum of 2200 m^3 h^{-1}, a constructed wetland (CW) system was designed by IRIDRA to treat the remaining CSO required by the authorization as well as to intercept a portion of the diluted pollutant load, which was estimated equal to 104 t_{COD} $year^{-1}$ (contained in about 890.000 m^3 $year^{-1}$). As illustrated in Fig. 2, the CSO-CW system aims to ensure that the WWTP effluent mixed with the effluent from CW complies with the discharge limits set by Italian legislation for wastewater discharge in freshwater bodies, Legislative Decree 152/2006 (COD 60 mg L^{-1}; TP 1 mg L^{-1}; TN 15 mg L^{-1}; TSS 15 mg L^{-1}).

Due to limit in the available space for NBS implementation, the maximum CW size could not have received all the CSO events without a high risk of short term clogging. Since the only CSO A events were giving risk of not compliance with the permit for the discharge in Seveso River of the WWTP, a dedicated feeding strategy was proposed. The CW system was designed to treat the first and most polluted fraction of CSO A event, to fulfill the discharge limit of the WWTP, keeping the possibility of treating also a portion of the second and less contaminated CSO B events, for further pollutant load interception. The following feeding scheme was designed: (i) CSO event A, the maximum CSO flow rate is set to 1300 m^3 h^{-1} per maximum 7 h/day (maximum treated CSO: 9000 $m^3 event^{-1}$) for 20 CSO A event per year (180.000 m^3 $year^{-1}$–36 t_{COD} $year^{-1}$); (ii) CSO event B, the maximum CSO flow rate is set of 970 m^3 h^{-1} per maximum 6.5 h/day (maximum treated CSO: 6300 m^3 $event^{-1}$) for 50 CSO event per year (315.000 m^3 $year^{-1}$–32 t_{COD} $year^{-1}$). In this way, the CSO-CW is designed to intercept up to 500.000 m^3 $year^{-1}$ (about 58% of the total estimated average volume per year, designed hydraulic loading rate of 60 $m^3(m^2 y)^{-1}$) and a COD load of 60 t_{COD} $year^{-1}$ (about 60% of the total estimated COD load per year). In other words, the CSO-CW is planned to intercept a pollutant load of 7700 p.e. (expressed in terms of COD), which were previously discharged untreated in the Seveso River.

The CSOs are treated with a multistage CW system, with the layout illustrated in Fig. 3 and pictures in Fig. 4. The 1st stage comprises two vertical subsurface flow (VF) CW beds, each one further divided into two separated hydraulic sectors for a total area of 8500 m^2; the four sectors are planned to work alternate and regulated by Programmable Logic Controller (PLC) to guarantee sufficient dry periods for the VF beds. The 2nd stage is a free water surface (FWS) CW of 4500 m^2.

The infiltration rate within the VF beds is controlled by a throttle valve, sized according to common guidelines (0.015 l/d/m^2; Rizzo et al., 2020) and providing sufficient residence times for effective pollutant removal.

The technical specifications of the first VF stage are resumed in Table 4. The VF stage has been built with two beds of 4250 m^2, each bed is divided in 2 hydraulically separated sectors, resulting in 4 parallel sectors feed in pressure. A regulation manhole permits to set two operational mode: (i), full empty, in order to maximize the oxygen transfer and the aerobic removal efficiencies; (ii) 20 cm of saturated layer at the bottom of the bed, in order to provide an anoxic environment for denitrification and acting as reservoir of water for plants during drying

Table 3
Statistics on the quality of overflow water samples for CSO A, CSO B and all events (without distinction between A and B): chemical oxygen demand (COD), 5-day biochemical oxygen demand (BOD5), total suspended solids (TSS) results, total nitrogen (TN), ammonium (NH_4^+), and phosphorus (TP) results. Water quality data influent to the WWTP from 2013 to 2014, used for the CSO-CW design.

	COD [mg L^{-1}]			BOD5 [mg L^{-1}]			TSS [mg L^{-1}]		
	CSO A	CSO B	CSO All events	CSO A	CSO B	CSO All events	CSO A	CSO B	CSO All events
Average	186	101	140	53	32	42	107	53	76
Std. Dev.	118	42	95	42	13	33	70	24	56
Min	70	47	47	16	12	12	33	15	15
Max	534	208	534	200	60	200	318	116	318
80° perc.	191	129	164	62	42	52	135	71	90
No. of S.	30	31	65	28	27	55	26	34	60

	TN [mg L^{-1}]			N-NH_4^+ [mg L^{-1}]			TP [mg L^{-1}]		
	CSO A	CSO B	CSO All events	CSO A	CSO B	CSO All events	CSO A	CSO B	CSO All events
Average	20	15	18	11	8	9	3.2	1.9	2.5
Std. Dev.	8	4	7	5	4	5	2.3	0.7	1.7
Min	6	8	6	0	1	0	1.1	0.6	0.6
Max	44	24	44	26	15	26	10.5	3.5	10.5
80° perc.	25	19	20	14	11	13	3.8	2.5	2.9
No. of S.	29	31	60	29	35	64	30	36	67

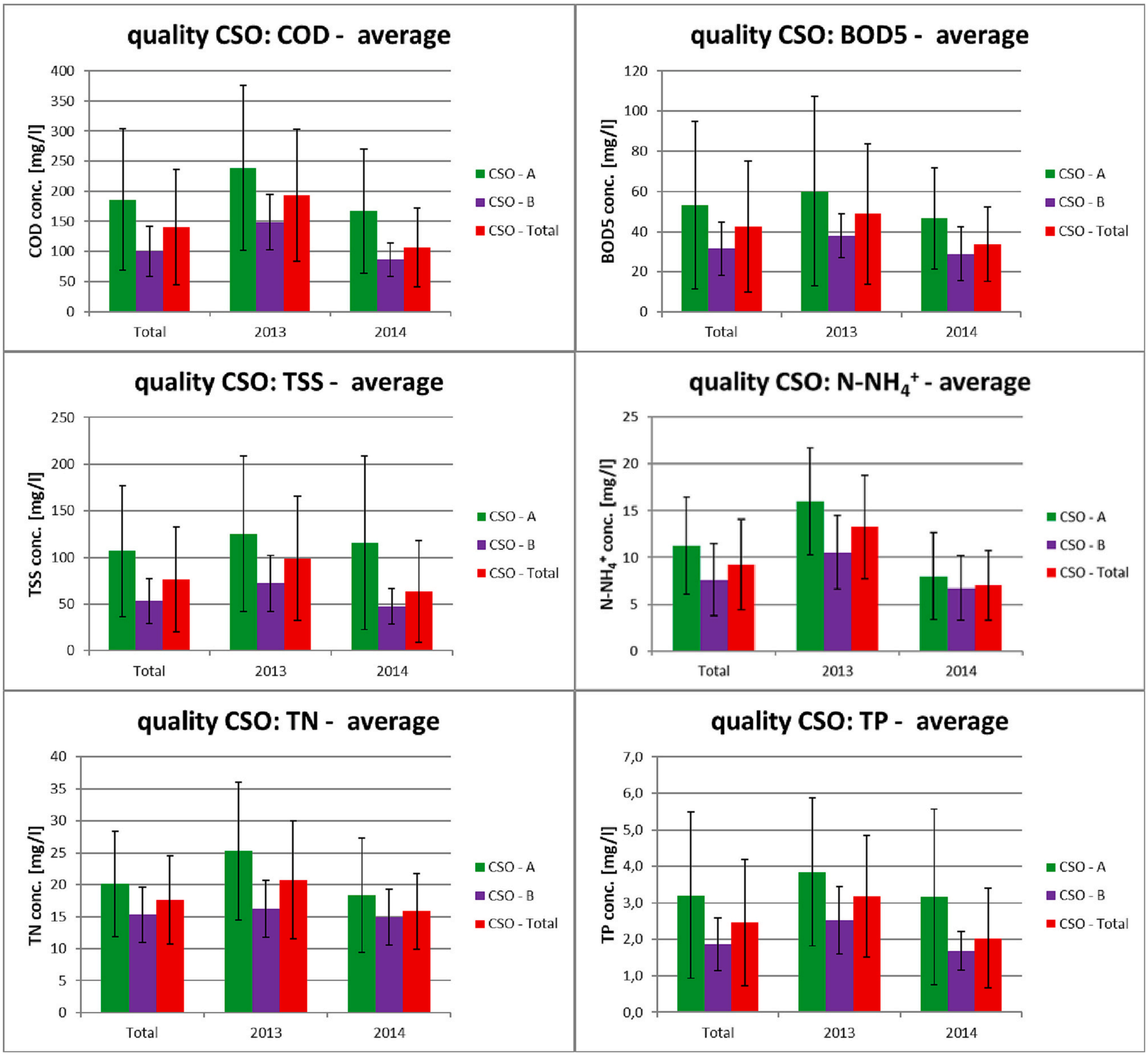

Fig. 1. Graphs showing the statistical analysis of effluent quality for CSO A, CSO B and all events (without distinction between A and B). Water quality data influent to the WWTP from 2013 to 2014, used for the CSO-CW design.

periods. During the monitoring period presented in this paper, the VF beds worked with 20 cm saturated layer at the bottom. The VF beds are planted with *Phragmites australis.*

One free water surface (FWS) bed has been designed. Variable water depth (from 0.0 to 1.5 m), with an average depth equal to 0.4 m, was designed in order to place different autochthonous aquatic plants (*Schenoplectus lacustris, Menyanthes trifollata, Typha minima, Nimphea alba, Lythrum salicaria, Nuphar iutea, Iris pseudacorus, Carex riparia, Typha latifolia,* and *Pesicria amphibia*), maximizing biodiversity.

2.3. Water quantity and quality dataset and statistical analyses

From the beginning of 2018 until the end of 2020, a sampling campaign was carried out to temporally characterize the quality and quantity of CSOs and to estimate the ecosystem service of CSO-CWs in terms of water quality improving.

About CSO quantity, the CSO flow rates sent to the VF beds have been measured by counters, from January 2018 (after the start-up phase) to October 2020.

Regard CSO quality, a total of 27 samples were collected from the 31st January 2019 up to 27th October 2020 by the Water Utility without a specific frequency, following the most relevant CSO events during the monitoring period. More samples were taken in 2019 and fewer in 2020 (8 and 5 months per year, respectively). The water quality dataset was used to calculate mean, standard deviation, minimum, and maximum values for each pollutant parameter at different stages of the CSO-CW: influent (IN); effluent from the 1st stage VF CW (OUT VF); effluent from the 2nd stage FWS (OUT FWS).

Analyzed water quality data regards chemical oxygen demand (COD), total nitrogen (TN), ammonium nitrogen (N-NH_4^+), and total phosphorous (TP). Metals were also measured for some samples (Cu, Fe, Ni, Zn, Al, Si, As). Influent TSS was also started to be monitored in 2020 for monitoring possible long term clogging risk according to indications from recent guidelines (Rizzo et al., 2020). The samples were analyzed by internal certified laboratory, according to standard methods (American Public Health Association, 2005). Composite samples covering overflow hours (for a maximum of 24 h) have been collected at the inlet of the VF stage by an automatic sampler, starting from the beginning of

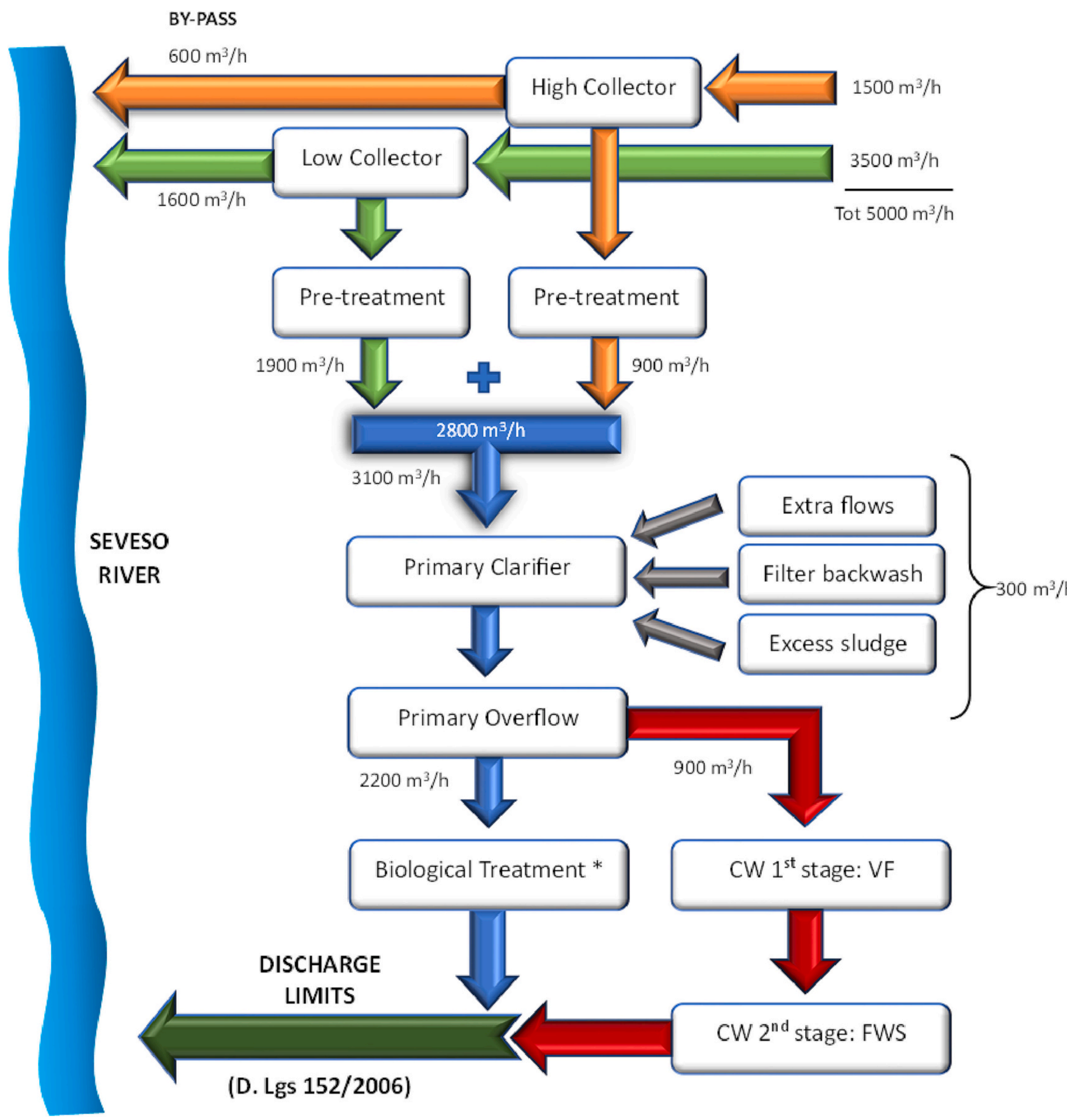

Fig. 2. Flow estimation of the various outflows during major storm events and functional diagram of the WWTP and CSO-CW systems components.
* Biological treatment is constituted by an oxidation tank and a secondary clarifier, followed by a sand filtration and a sodium hypochlorite disinfection stage.

CSO event in order to capture the washout effect and to estimate the most relevant pollutant loads in the influent. Grab samples for CSO quality monitoring of the first VF stage and the second FWS stage outflows were taken.

The statistical analyses are done with Microsoft Excel.

3. Results and discussion

3.1. Treatment performance

Influent and effluent COD, total nitrogen (TN), ammonia nitrogen (N-NH_4^+) and total phosphorus (TP) concentrations measured from 31st January 2019 to 27th October 2020 at three sampling points of Carimate CSO-CW are shown in Fig. 5, with statistical analysis of the performance in Table 5. The concentration trends clearly highlight a good level of performance for the treatment of the all target contaminants, showing stable and satisfactory removal for N-NH_4^+ and TN and even increasing efficiency, during the monitored period, for COD and TP.

The CW system under investigation ensured that the water discharged into the Seveso River, consisting of the combination of the WWTP effluent and the FWS second-stage effluent, complied with the local regulation limits for the whole duration of the monitoring campaign, including the start-up and management phases.

Table 6 underlines how the treatment performances level of Carimate CSO-CW for the main target pollutants (mean values: COD 83.2%, TP 64.6%, N-NH_4^+ 63.8%) are consistent with those observed in similar national and European experiences. Nevertheless, it should be noted that the literature data available refers to CW systems treating CSO in line to the sewer and not upstream of centralized WWTP, as in the case of the Carimate plant. Data clearly highlight how, despite the different application, a different hydraulic operation and a larger scale compared to in-line systems, the CSO-CW upstream the Carimate WWTP still guarantees similar and satisfying purification performance. Moreover, another consideration can be added in terms of variability of CSO-CW systems. Indeed, the natural based solutions adopted in the previous studies, except for the Italian experience reported by Masi et al. (2017), are partially different in terms of filling material, layout and operation of the plant. Neither the German nor the French experience adopts a FWS as a second stage. Furthermore, the German overflow treatment plants are filled with coarse sand, leading to higher expected efficiencies in

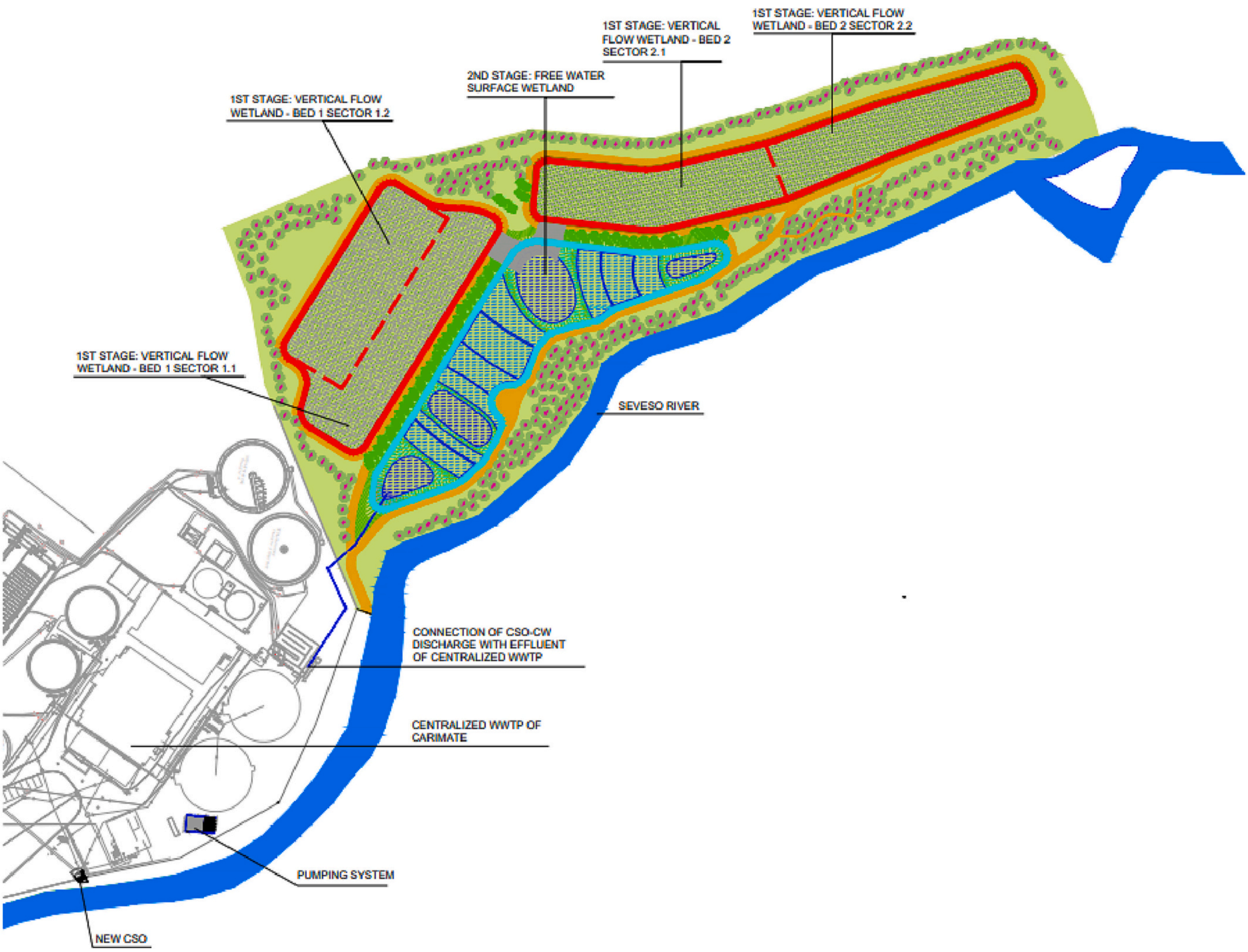

Fig. 3. Layout of the CSO-CW system upstream of wastewater treatment plant (WWTP) in Carimate (Italy). 1st stage: 2 vertical subsurface flow CW beds (delimited by solid red lines), each bed is divided in 2 hydraulically separated sectors (separated by dashed red lines); 2nd stage: free water surface wetland (delimited by solid light blue line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 4. Photos from the CSO-CW of Carimate (Spring 2019): VF 1st stage, left; FWS 2nd stage, right.

terms of filtration effect on COD and nitrification for ammonium, but requiring lower yearly loading rate to reduce the risk of long-term occlusion.

The saturated bottom of Carimate first VF stage and second FWS stage have been also demonstrated to provide partial denitrification, with a mean TN removal equal to 43.6%.

Table 7 shows the concentrations of metals and semimetals detected in the wastewater samples at the three different stages of the CSO-CW

Table 4
Technical specifications of the 1st stage VF CW of Carimate.

First Stage VF CW	
n° of parallel line	4
n° of VF sector per line	1
Total surface area VF	8500 m^2
Surface area of each VF line	2125 m^2
Average surface area of each VF sector	2125 m^2
Total height of the filter media	0.9 m
VF filter media layers (from the bottom)	
• coarse gravel – Ø 20–40 mm	15 cm
• gravel – Ø 5–10 mm	15 cm
• Pea gravel – Ø 1–5 mm	60 cm

system and the mean treatment performance for each studied contaminant. Interestingly, metal removal reaches promising levels across a broad spectrum of pollutants, with average percentage removal ranging from 84.1 to 93.6% for copper, iron, zinc, and aluminium, in agreement with the removal efficiencies reported from the Marcy-L'Etoile system in France (Pálfy et al., 2017a).

3.2. Hydraulic and pollutant loads

As shown in Table 8, the CSO-CW system provided satisfactory performance in terms of intercepting pollutant loads during the entire monitoring phase. The amount of COD load removed, estimated from 2018 to 2020, ranged between 123 and 198 $t_{COD}\ y^{-1}$, exceeding the 60 $t_{COD}\ y^{-1}$ set as a target during the theoretical design analysis.

Interestingly, since the start-up phase to date, the system is still in operation and has never shown any signs of clogging, despite the high hydraulic loading rates (HLR) shown in Table 8, with a peak of 95 $m^3(m^2 y)^{-1}$ registered in 2020. This confirms the evidence reported in the most recent literature. In fact, although according to the first guidelines set for German RSFs a maximum hydraulic load of 40–60 $m^3(m^2 y)^{-1}$ is recommended (Uhl and Dittmer, 2005; Rizzo et al., 2020), this threshold should be considered valid for systems filled with coarse sand, such as the German Retention Soil Filters (e.g. Tondera et al., 2017). For gravel-based systems, typical for instance of the French approach, on the contrary, it seems to be possible an increase of the HLR without incurring clogging phenomena (Rizzo et al., 2020). Indeed, the monitoring data and the modelling analysis from the full-scale French system described by Pálfy et al. (2017a, 2017b, 2017c), where HLR up to

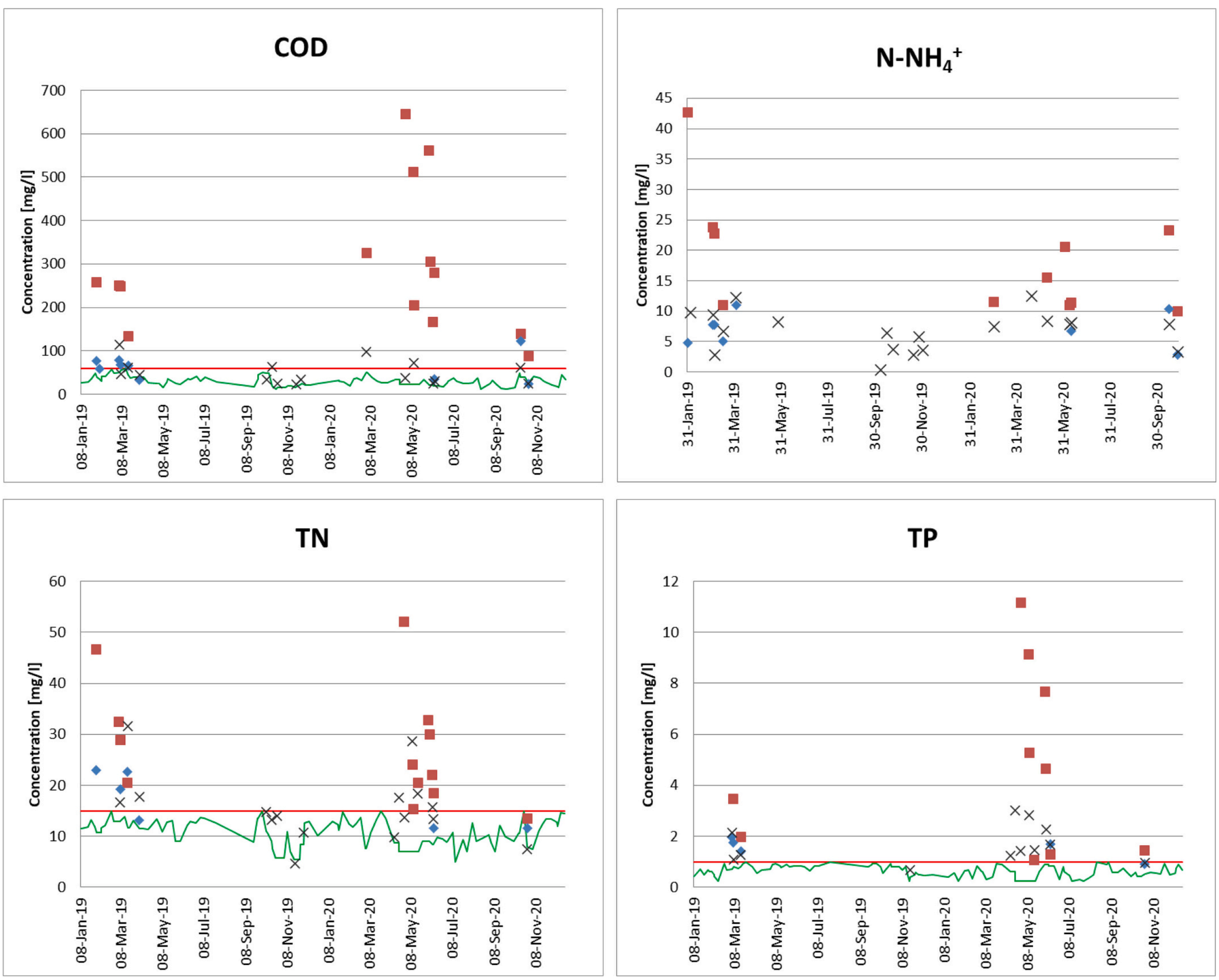

Fig. 5. COD, N-NH_4^+, TN, and TP concentrations of treated wastewater effluent from the CSO-CW system upstream of the WWTP of Carimate from 31st January 2019 to 27th October 2020. IN: influent to first VF stage (red squares); OUT VF: effluent from the 1st VF stage (blue diamonds); OUT FWS: effluent from the 2nd FWS stage (black crosses), effluent discharged into Seveso River (green lines); local regulation limits (red lines). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 5
Statistical analysis of pollutant concentrations of wastewater treated by the CSO-CW upstream of the WWTP located in Carimate at the different stages: influent (IN); effluent from the 1st stage VF wetland (OUT VF); effluent from the 2nd stage FWS wetland (OUT FWS). Data from 31st January 2019 to 27th October 2020.

		IN	VF OUT	FWS OUT
COD [mg L^{-1}]	Mean	294	62	50
	Std. Dev.	168	30	27
	Min	87	24	22
	Max	645	123	114
	80° perc.	400	77	63
	No. of s.	14	9	16
TP [mg L^{-1}]	Mean	4.7	1.6	1.7
	Std. Dev.	3.6	0.4	0.7
	Min	1.1	0.9	0.7
	Max	11.2	2.0	3.0
	80° perc.	8.0	1.8	2.3
	No. of s.	10	5	12
N-NH_4^+ [mg L^{-1}]	Mean	18.5	7.0	6.7
	Std. Dev.	9.7	2.8	3.3
	Min	10.0	2.9	0.4
	Max	42.6	11.1	12.5
	80° perc.	23.3	9.3	8.8
	No. of s.	11	8	19
TN [mg L^{-1}]	Mean	27.4	16.8	15.5
	Std. Dev.	11.6	5.4	6.8
	Min	13.5	11.5	4.6
	Max	52.1	22.9	31.6
	80° perc.	32.6	22.6	17.8
	No. of s.	13	6	16

Table 6
Mean treatment performances of Carimate CSO-CW in comparison with literature data.

Parameter	Mean treatment performances of Carimate CSO-CW	Masi et al. (2017) Italy	Uhl and Dittmer (2005) Germany	Tondera et al. (2017) Germany	Pálfy et al. (2017a) France
Scheme	VF + FWS	VF + FWS	VF (RSF)	VF (RSF)	VF
Size	13,000 m^2	7000 m^2	N/A	from 300 m^2 to >5000 m^2	500 m^2
COD	83.2% (54.1–94.3%)	74–98%	> 84%	mean 49%	mean 79%
TP	64.6% (33.6–87.4%)			mean 34%	45–75%
N-NH_4^+	63.8% (28.9–87.8%)	72–99%	> 96%		mean 72%

250 $m^3(m^2{*}y)^{-1}$ were tested, suggest that for CSO-CWs using gravel and alternate feeding proposed by the French approach, occasional maximum peaks of cumulative hydraulic loading of 100 $m^3(m^2{*}y)^{-1}$ can be achieved, still guaranteeing normal operation of the system over time (Rizzo et al., 2020). Therefore, considering the stochasticity of CSO events and results from the CSO-CW of Marcy-L'Etoile and Carimate, it could be considered an HLR range equal to 60–100 $m^3(m^2{*}y)^{-1}$ for the future design of CSO-CWs involving French systems, in order to maintain satisfactory treatment efficiencies without occurring in clogging effects. Important to remark is that the threshold value of 100 $m^3(m^2{*}y)^{-1}$ should represent a maximum peak with just a sporadic occurrence frequency.

Similar considerations can be made for the solid loading rate (SLR). Based on the evaluation of more than fifty systems designed according to the standards set by the guidelines for RSFs (Grotehusmann et al., 2017), the initial HLR-based design approach has been revised from the hydraulic aspect to pollutant loading rates, namely fine solids, with a tolerable annual loading of fine solids (TSS_{fine}, defined as TSS < 0.63 μm) which should not exceed 7 $kg_{SS*}m^{-2}\,y^{-1}$(Rizzo et al., 2020). Also in

Table 7
Statistical analysis of metal and semimetals concentrations of wastewater treated by the CSO-CW upstream of the WWTP located in Carimate at the different stages and mean treatment performances of CSO-CW for metals and semimetals detected: influent (IN); effluent from the 1st stage VF CW (OUT VF); effluent from the 2nd stage FWS (OUT FWS). Data from 31st January 2019 to 27th October 2020.

		IN	VF OUT	FWS OUT
Cu [mg L^{-1}]	Mean	0.07	0.02	0.01
	Std. Dev.	0.06	0.02	0.01
	Min	0.00	0.00	0.00
	Max	0.16	0.04	0.04
	80° perc.	0.12	0.04	0.02
	No. of s.	10	5	12
	Mean treatment performance	84.1%		
Fe [mg L^{-1}]	Mean	3.88	0.34	0.46
	Std. Dev.	3.76	0.25	0.47
	Min	0.20	0.10	0.10
	Max	10.25	0.76	1.84
	80° perc.	7.14	0.39	0.54
	No. of s.	9	5	12
	Mean treatment performance	88.2%		
Ni [mg L^{-1}]	Mean	0.02	0.02	0.02
	Std. Dev.	0.02	0.02	0.02
	Min	0.00	0.00	0.00
	Max	0.06	0.05	0.06
	80° perc.	0.03	0.03	0.03
	No. of s.	10	5	12
	Mean treatment performance	31.2%		
Zn [mg L^{-1}]	Mean	0.16	0.02	0.02
	Std. Dev.	0.13	0.02	0.02
	Min	0.00	0.00	0.00
	Max	0.37	0.05	0.05
	80° perc.	0.28	0.04	0.03
	No. of s.	10	5	12
	Mean treatment performance	89.9%		
Al [mg L^{-1}]	Mean	0.65	0.05	0.02
	Std. Dev.	0.57	0.04	0.02
	Min	0.00	0.00	0.00
	Max	1.51	0.11	0.06
	80° perc.	1.17	0.07	0.04
	No. of s.	10	5	12
	Mean treatment performance	93.6%		
Si [mg L^{-1}]	Mean	4.92	3.72	4.29
	Std. Dev.	1.63	0.11	0.97
	Min	2.41	3.64	2.95
	Max	7.32	3.79	5.77
	80° perc.	6.24	3.76	5.02
	No. of s.	8	2	9
	Mean treatment performance	12.9%		
As [mg L^{-1}]	Mean	0.01	0.02	0.01
	Std. Dev.	0.01	0.01	0.01
	Min	0.00	0.02	0.00
	Max	0.03	0.03	0.03
	80° perc.	0.02	0.03	0.03
	No. of s.	10	5	12
	Mean treatment performance	16.7%		

this case, however, the CSO-CW system in Carimate did not show any clogging effects despite reaching estimated SLR levels above this threshold (10.4–16.8 $kg_{SS*}m^{-2}\,y^{-1}$, Table 8), probably due to the use of gravel rather than sand. Long term monitoring of Carimate CSO-CW and other gravel-based CSO-CWs is needed to confirm this threshold value.

3.3. *Additional ecosystem services and operational and maintenance*

One of the additional advantages of treating CSOs with NBS systems is undoubtedly the possibility of integrating other ecosystem services, such as increased biodiversity or flood protection. These benefits are especially relevant for CSOs upstream of wastewater treatment plants, due to the larger size of these systems compared to CSO-CWs in line with the sewage network.

Table 9 shows the efficiency levels in terms of flood reduction by detailed analyses of CSO events from 2018 to 2019. Carimate CSO-CW

Table 8
Annual statistical analysis of hydraulic and pollutant loads for the first three year of operation. HLR: hydraulic loading rate; SLR: solid loading rate.

	2018	2019	2020
Hydraulic load IN [m^3 y^{-1}]*	503,314	645,320	810,938
Solid load IN [t_{TSS} y^{-1}]**	89	114	143
COD load IN [t_{COD} y^{-1}]***	148	190	238
TP load IN [t_P y^{-1}]***	2.4	3.0	3.8
TN load IN [t_N y^{-1}]	13.8	17.7	22.3
COD load OUT [t_{COD} y^{-1}]***	25	32	40
TP load OUT [t_P y^{-1}] ***	0.8	1.1	1.4
TN load OUT [t_N y^{-1}] ***	7,8	10,0	12,6
COD load removed [t_{COD} y^{-1}]	123	158	198
TP load removed [t_P y^{-1}]	1.5	2.0	2.5
TN load removed [t_N y^{-1}]	6.0	7.7	9.7
HLR [$m^3(m^2y)^{-1}$]	59	76	95
SLR [kg_{SS} $(m^2y)^{-1}$]	10.4	13.4	16.8

* Monitored CSO volume treated by the CSO-CW of Carimate.
** Assuming average influent concentration of TSS from monitoring analyses of 2020 (TSS influent concentration 176.2 mg L^{-1} – six samples from 3rd March 2020 to 27th October 2020, standard deviation 125.8 mg L^{-1}).
*** Assuming average concentrations of pollutants from monitored data of 2019–2020, as reported in Table 6.

system proved to be considerably efficient, being able to intercept 45–100% (with an average value equal to 82%) of the CSOs upstream of the centralized WWTP, in line with results from Rizzo et al. (2018). These performance levels are guaranteed by the retention capacity of approximately 5000 m^3 provided by the NBS system, retaining significant CSO volume and slowly discharging into Seveso River.

In general, compared to other water purification systems, constructed wetlands entails lower long-term maintenance costs, without generating significant waste for disposal (Mannino et al., 2008). Indeed, in terms of reed biomass management, most wetlands, both natural and constructed, function in the absence of routine harvesting or thinning, except through seasonal die-off (Avellána and Gremillion, 2019). Interestingly, despite the larger size required for the treatment of CSO upstream of WWTPs, Carimate CSO-CW confirm the simplicity and low operating and maintenance costs of NBS. (See Fig. 6)

In fact, one reed harvest delayed just before the start of new vegetative season (about 5 months before the start of yellowing) resulted in the production of only 3 tons biomass per 4250 m^2 of VF. This amount, corresponding to 0.7 kg m^{-2}, is significantly lower than the average value of 1.9 kg m^{-2} presented in the descriptive statistical analysis of above ground biomass in mature stands of wetlands by Avellána and Gremillion (2019), with consequently strong containment of management expenses. Indeed, the waste disposal cost for the first VF stage is equivalent to 500 € for the whole 8500 m^2 surface. In other words, considering a total of 70,000 PE, a cost of 0.7 cent € per PE can be estimated.

Alternatively, it would be possible to anticipate harvesting in order to maximize the biomass production for circular economy recovery (e.g., for energy production). However, recovery of biomass as an energy source requires consideration of the effects of harvesting on the wetland community (Avellána and Gremillion, 2019), as well as careful management of the higher biomass humidity.

4. Conclusion

As a general observation, this study has contributed to bridging the lack of available data regarding the potential of CW systems for CSO treatment, investigating for the first time, to the best of our knowledge, the operational conditions and treatment performances of a full-scale CSO-CW upstream of a centralized WWTP.

Indeed, the present research has provided an interesting set of information regarding the design and efficiency of the CW system upstream of the centralized WWTP of Carimate, located close to an urbanized area of the Northern Italy, for the treatment of the combined sewer overflow.

The observed removal rates during the 3 years monitoring campaign (mean values equal to 83.2%, 64.6%, 63.8% for COD, TP, and N-NH_4^+ respectively) confirmed the capability of CW system to reach satisfactory outlet concentrations for all the investigated parameters. Indeed, despite its large scale and different hydraulic characteristics, the CSO-CW upstream the centralized WWTP showed treatment performance levels consistent with literature data for systems in line with the sewerage network. Due to that efficiency, the water discharged into the Seveso River, consisting of the combination of the WWTP effluent and the CW effluent, has always shown COD, TN, N-NH_4^+, and TP concentrations below the national regulation limits for the whole duration of the monitoring campaign, with a significant pollutant load removed from the receiving water body.

The system also ensured the integration of additional ecosystem services such as flood mitigation, with an average CSO interception of 82%, enhancement of biodiversity and a low operational and maintenance cost.

In other words, the findings presented is this paper confirm that NBSs for CSOs treatment can provide an efficient answer to this concerning environmental issue, without highlighting significant negative side effects or reduction in expected purification performance as a consequence of the "upscale" from in line to upstream of centralized WWTP, also providing multiple additional ecosystem services.

CRediT authorship contribution statement

F. Masi: Project administration, Supervision, Writing – review & editing. **C. Sarti:** Writing – original draft, Formal analysis. **A. Cincinelli:** Writing – review & editing. **R. Bresciani:** Data curation, Writing – review & editing. **N. Martinuzzi:** Writing – review & editing. **M. Bernasconi:** Resources, Writing – review & editing. **A. Rizzo:** Formal analysis, Data curation, Writing – original draft.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Table 9
Analysis of flood reduction and CSO interception data, collected from April 2018 to May 2019.

		Apr-2018	May-2018	Jun-2018	Jul-2018	Jan-2019	Feb-2019	Mar-2019	Apr-2019	May-2019	Total
Out	m^3d^{-1}	2442	2619	3137	3275	1988	2149	2041	3629	4118	
CSO-CW	m^3m^{-1}	73,270	81,184	94,111	101,516	61,624	60,180	63,281	108,865	127,655	
In VF	m^3m^{-1}	66,484	67,522	51,579	58,381	16,117	30,729	25,056	71,536	51,195	
Out WWTP to FWS*	m^3m^{-1}	6786	13,661	42,532	43,134	45,507	29,451	38,225	37,329	76,460	
Out WWTP to VF*	m^3m^{-1}	6786	13,661	42,532	43,134	0	0	0	0	0	
CSO in VF	m^3m^{-1}	59,698	53,861	9047	15,247	16,117	30,729	25,056	71,536	51,195	194,633
CSO tot	m^3m^{-1}	131,725	69,171	9047	22,582	16,117	30,729	25,056	71,536	51,195	225,136
% CSO to CW		**45%**	**78%**	**100%**	**68%**	**100%**	**61%**	**100%**	**86%**	**100%**	**82%**

* Data sampled in 2018 come from the start-up phase, in which a small continuous flow of secondary WWTP effluent was maintained to support the start-up phases of VF and FWS stages.

Fig. 6. Photos from the harvesting of the 1st stage VF of Carimate (April 2019): harvested biomass, left; post-harvested VF beds, right.

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Data availability

Data will be made available on request.

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References

Al Aukidy, M., Verlicchi, P., 2017. Contributions of combined sewer overflows and treated effluents to the bacterial load released into a coastal area. Sci. Total Environ. 607, 483–496.

APHA; AWWA; WEF. Standard Methods for the Examination of Water and Wastewater, 21st ed.; American Public Health Association: Washington, DC, USA, 2005.

Avellána, A., Gremillion, P., 2019. Constructed wetlands for resource recovery in developing countries. Renew. Sust. Energ. Rev. 99 (2019), 42–57.

Barceló, D., Sabater, S., 2010. Water quality and assessment under scarcity: prospects and challenges in Mediterranean watersheds. Hydrology 383 (1), 1–4. https://doi.org/10.1016/j.jhydrol.2010.01.010.

Botturi, A., Ozbayram, E.G., Tondera, K., Gilbert, N.I., Rouault, P., Caradot, N., Gutierrez, O., Daneshgar, S., Frison, N., Akyol, Ç., Foglia, A., 2021. Combined sewer overflows: a critical review on best practice and innovative solutions to mitigate impacts on environment and human health. Environ. Sci. Technol. 51 (15), 1585–1618.

Casal-Campos, A., Fu, G., Butler, D., Moore, A., 2015. An integrated environmental assessment of green and gray infrastructure strategies for robust decision making. Environ. Sci. Technol. 49 (14), 8307–8314.

Crocetti, P., Eusebi, A.L., Bruni, C., Marinelli, E., Darvini, G., Carini, C.B., Bollettini, C., Recanati, V., Akyol, C., Fatone, F., 2021. Catchment-wide validated assessment of combined sewer overflows (CSOs) in a mediterranean coastal area and possible disinfection methods to mitigate microbial contamination. Environ. Res. 196, 110367.

Dolowitz, D.P., Bell, S., Keeley, M., 2018. Retrofitting urban drainage infrastructure: green or grey? Urban Water J. 15 (1), 83–91.

DWA, 2019. Retentionsbodenfilteranlagen. Retention soil filter sites. DWA-A 178,. German Water Association. ISBN: 978-3-88721-826-3.

European Commission, 2019. Evaluation of the Urban Waste Water Treatment Directive. SWD, Brussels.

Fu, X., Goddard, H., Wang, X., Hopton, M.E., 2019. Development of a scenario-based stormwater management planning support system for reducing combined sewer overflows (CSOs). Environ. Manag. 236, 571–580.

Garofalo, G., Giordano, A., Piro, P., Spezzano, G., Vinci, A., 2017. A distributed real-time approach for mitigating CSO and flooding in urban drainage systems. Network Comput. Appl. 78, 30–42.

Giakoumis, T., Voulvoulis, N., 2023. Combined sewer overflows: relating event duration monitoring data to wastewater systems' capacity in England. Environ. Sci.: Water Res. Technol. 9, 707–722.

Grotehusmann, D., Kerpen, T., Ruß, H.-J., 1997. Mischwasserbehandlung in Bodenfilteranlagen. Treatment of combined sewage in soil filter plants. Umweltqualitäten und Wirtschaften? Was wurde erreicht? Wo geht es hin?. In: 38th Essener Tagung für Wasser- und Abfallwirtschaft, Aachen, Germany. 158. Gewässerschutz, Wasser, Abwasser, pp. 10/1–10/14 (in German).

Grotehusmann, D., Lambert, B., Fuchs, S., Uhl, M., Leutnant, D., 2017. Erhebungsuntersuchung zur Optimierung der Retentionsbodenfilter in NRW. In: Ministry of Environment, Nature Conservation, Agriculture and Consumer Protection of the German Federal State of North Rhine-Westphalia (Ed.), Investigation to Optimize Retention Soil Filter in NRW Final Report. Düsseldorf. https://www.lanuv.nrw.de/fileadmin/tx_mmkresearchprojects/Abschlussbericht_RBF_NRW.pdf. Accessed date: 6 August 2019 (in German).

Keupers, I., Willems, P., 2013. Impact of urban WWTP and CSO fluxes on river peak flow extremes under current and future climate conditions. Water Sci. Technol. 67 (12), 2670–2676.

LfU, 1998. Bodenfilter zur Regenwasserbehandlung im Misch- und Trennsystem. In: Soil Filters for Stormwater Treatment in Combined and Separate Sewer System. Handbuch Wasser 4 Band 10. Landesanstalt für Umweltschutz Baden-Württemberg, Karlsruhe 95 p. + annexes (in German).

Liebeskind, M., 2001. Untersuchung der Leistungsfähigkeit von Bodenfiltern in NRW. In: Investigation on Efficiency of Retention Soil Filter in NRW. Final Report. Forschungsinstitut für Umwelttechnik und Umweltanalytik, Wasserlaboratorien Roetgen GmbH (un-published (in German).

Liquete, C., Udias, A., Conte, G., Grizzetti, B., Masi, F., 2016. Integrated valuation of a nature-based solution for water pollution control. Highlighting hidden benefits. Ecosyst. Serv. 22, 392–401.

Mannino, I., Franco, D., Piccioni, E., Favero, L., Mattiuzzo, E., Zanetto, G., 2008. A cost-effectiveness analysis of seminatural wetlands and activated sludge wastewater-treatment systems. Environ. Manag. 41, 118–129.

Masi, F., Bresciani, R., Rizzo, A., Conte, G., 2017. Constructed wetlands for combined sewer overflow treatment: ecosystem services at Gorla Maggiore, Italy. Ecol. Eng. 98, 427–438.

Matzinger, A., Riechel, M., Rouault, P., Steen, O.P., Pawlowsky-Reusing, Erika, Heinzmann, B., 2011. IMPACT-BASED MANAGEMENT of combined sewer overflows–Introduction to a flexible planning instrument. Blue Facts 2–9.

Meehl, G.A., Tebaldi, C., 2004. More intense, more frequent, and longer lasting heat waves in the 21st century. Science 305 (5686), 994–997.

Pálfy, T.G., Gerodolle, M., Gourdon, R., Meyer, D., Troesch, S., Molle, P., 2017a. Performance assessment of a vertical flow constructed wetland treating unsettled combined sewer overflow. Water Sci. Technol. 75 (11), 2586–2597.

Pálfy, T.G., Gourdon, R., Meyer, D., Troesch, S., Olivier, L., Molle, P., 2017b. Filling hydraulics and nitrogen dynamics in constructed wetlands treating combined sewer overflows. Ecol. Eng. 101, 137–144.

Pálfy, T.G., Gourdon, R., Meyer, D., Troesch, S., Molle, P., 2017c. Model-based optimization of constructed wetlands treating combined sewer overflow. Ecol. Eng. 101, 261–267. https://doi.org/10.1016/j.ecoleng.2017.01.020.

Petrie, B., 2021. A review of combined sewer overflows as a source of wastewater-derived emerging contaminants in the environment and their management. Environ. Sci. Pollut. Res. 28 (25), 32095–32110.
Pistocchi, A., Dorati, C., Grizzetti, B., Udias, A., Vigiak, O., Zanni, M., 2019. Water Quality in Europe: Effects of the Urban Wastewater Treatment Directive. A Retrospective and Scenario Analysis of Dir. 91/271/EEC, EUR 30003 EN. Publications Office of the European Union, Luxembourg. https://doi.org/10.2760/303163, 978-92-76-11263-1.
Quaranta, E., Fuchs, S., Liefting, H.J., Schellart, A., Pistocchi, A., 2022a. Costs and benefits of combined sewer overflow management strategies at the European scale. J. Environ. Manag. 318, 115629 https://doi.org/10.1016/j.jenvman.2022.115629.
Quaranta, E., Fuchs, S., Liefting, H.J., Schellart, A., Pistocchi, A., 2022b. A hydrological model to estimate pollution from combined sewer overflows at the regional scale. Application to Europe. J. Hydrol. Regional Stud. 41 (2022), 101080. https://doi.org/10.1016/j.ejrh.2022.101080.
Rizzo, A., Bresciani, R., Masi, F., Boano, F., Revelli, R., Ridolfi, L., 2018. Flood reduction as an ecosystem service of constructed wetlands for combined sewer overflow. J. Hydrol. 560, 150–159.
Rizzo, A., Tondera, K., Pálfy, T.G., Dittmer, U., Meyer, D., Schreiber, C., Zacharias, N., Ruppelt, J.P., Esser, D., Molle, P., Troesch, S., Masi, F., 2020. Constructed wetlands for combined sewer overflow treatment: a state-of-the-art review. Sci. Total Environ. 727, 138618 https://doi.org/10.1016/j.scitotenv.2020.138618.
Rizzo, A., Conte, G., Masi, F., 2021. Adjusted unit value transfer as a tool for raising awareness on ecosystem services provided by constructed wetlands for water pollution control: an Italian case study. Int. J. Environ. Res. Public Health 18 (4), 1531.
Schreiber, C., Rechenburg, A., Koch, C., Christoffels, E., Claßen, T., Willkomm, M., Mertens, F.M., Brunsch, A.F., Herbst, S., Rind, E., Kistemann, T., 2016. Two decades of system-based hygienic–microbiological research in Swist river catchment (Germany). Environ. Earth Sci. 75 (21) https://doi.org/10.1007/s12665-016-6100-9.
Stovin, V.R., Moore, S.L., Wall, M., Ashley, R.M., 2013. The potential to retrofit sustainable drainage systems to address combined sewer overflow discharges in the Thames Tideway catchment. Water Environ. J. 27 (2), 216–228.
Tao, W., Bays, J.S., Meyer, D., Smardon, R.C., Levy, Z.F., 2014. Constructed wetlands for treatment of combined sewer overflow in the US: a review of design challenges and application status. Water 6 (11), 3362–3385.
Tondera, K., 2019. Evaluating the performance of constructed wetlands for the treatment of combined sewer overflows. Ecol. Eng. 137, 53–59. https://doi.org/10.1016/j.ecoleng.2017.10.009.
Tondera, K., Koenen, S., Pinnekamp, J., 2013. Survey monitoring results on the reduction of micropollutants, bacteria, bacteriophages and TSS in retention soil filters. Water Sci. Technol. 68 (5), 1004–1012. https://doi.org/10.2166/wst.2013.340.
Tondera, K., Klaer, K., Roder, S., Brueckner, I., Pinnekamp, J., 2017. Improving the microbiological quality of the Ruhr River near Essen: comparing costs and effects for the reduction of *Escherichia coli* and intestinal enterococci. Water Sci. Technol. 75 (11), 2659–2668.
Uhl, M., Dittmer, U., 2005. Constructed wetlands for CSO treatment: an overview of practice and research in Germany. Water Sci. Technol. 51 (9), 23–30. https://doi.org/10.2166/wst.2005.0280.
Yu, D., Dian, L., Hai, Y., Randall, M.T., Liu, L., Liu, J., Zhang, J., Zheng, X., Wei, Y., 2022. Effect of rainfall characteristics on the sewer sediment, hydrograph, and pollutant discharge of combined sewer overflow. J. Environ. Manag. 303, 114268 https://doi.org/10.1016/j.jenvman.2021.114268.