

Research papers

Analysis of the residual nutrient load from a combined sewer system in a watershed of a deep Italian lake

Laura Barone^a, Marco Pilotti^{a,b,*}, Giulia Valerio^a, Matteo Balistrocchi^a, Luca Milanese^a, Steven C. Chapra^b, Daniele Nizzoli^c

^a DICATAM, Department of Civil, Environmental, Architectural Engineering and Mathematics, University of Brescia, Brescia, Italy

^b Civil & Environmental Engineering Department, Tufts University, Medford, MA 02155, USA

^c Department of Chemistry, Life Sciences and Environmental Sustainability, University of Parma, Parco Area delle Scienze 11/A, 43124 Parma, Italy

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ABSTRACT

This paper investigates the residual nutrient load from a combined sewer system along the shore of a deep Italian lake, to provide data that can help explaining the contribution of combined sewers to lakes eutrophication. To this purpose, a stochastic methodology is applied to the analysis of the combined sewer overflows and pollutants, that provides reliable estimates, with related uncertainties, of the storage capacity to be supplied in order to mitigate the impact on the quality of receiving waters. The sewer is modeled by SWMM and two terminal combined sewer weirs are modeled in detail and instrumented for calibration purposes. A year-long campaign was accomplished, allowing to study the occurrence and relevance of the first flush. The calibrated model of the sewer network was used to extrapolate the results to a 10-years period, thus providing a statistically reliable estimate of the residual load delivered from this watershed to the lake. A conservative evaluation shows that up to 22% of phosphorus and up to 41% of nitrogen delivered to the sewer are still discharged into the environment. However, the results also show that in this case a relatively small capture volume would obtain a target pollution reduction, thus providing insights on the feasibility of this structural practice in similar watersheds along the shore of endangered lakes.

1. Introduction

Eutrophication is a major threat to lake waters quality worldwide, mostly due to phosphorus (P) and nitrogen (N) delivery from diffuse and point sources in anthropized watersheds (e.g., Schindler et al., 2008). The diversion of sewage through the development of combined urban drainage systems is a common practice in endangered lake areas but water quality improvements have often been less effective than expected.

Combined sewer systems are the prevalent sewage collection system in urban areas which evolved from the sprawl of old settlements. In these systems, under dry conditions sanitary waters supply the sewage discharge, while, under wet weather conditions stormwaters are collected and conveyed through the same conduits, mixing with sanitary waters. During heavy precipitations, sewage exceeding the conveyance capacity of the sewer network, or the treatment plant processing capacity, is discharged into surface waters as combined sewer overflows (CSOs). The actual amount of nutrients flushed by CSOs depends on the local climate, on the imperviousness of the drained catchment, on the

introduction of so-called best practices to deal with stormwater and on the operational management of the sewer in dry weather periods.

In general, the rationale supporting the technical acceptance of CSOs is that (1) a combined sewer cannot be sized to efficiently deal with both ordinary sewage flow and peak stormwater discharges; (2) the renewal time of the CSO receiving body is short; and (3) the sewage pollutant concentration during wet weather periods decreases due to dilution. Owing to violation of these assumptions, in the past the environmental impact of CSOs has often been underestimated. In fact, during wet weather periods, CSOs may deliver substantial amounts of contaminants such as nutrients, heavy metals, sediments, wastewater micropollutants and microorganisms (Bryan Ellis and Yu, 1995; Chebbo et al., 2001), whose impact on the quality of receiving water bodies cannot be overlooked (Sartor and Boyd, 1972; EPA, 1993, 2009; Tibbetts, 2005). Moreover, in strongly urbanized areas, stormwaters are themselves contaminated by diffuse sources (Novotny, 2002) so that, during wet weather periods, mixing often does not yield the assumed dilution.

Hence, this issue has been studied from various perspectives: assessing the occurrence of the first flush phenomenon, i.e. of the

* Corresponding author at: DICATAM, Department of Civil, Environmental, Architectural Engineering and Mathematics, University of Brescia, Brescia, Italy.
E-mail address: marco.pilotti@unibs.it (M. Pilotti).

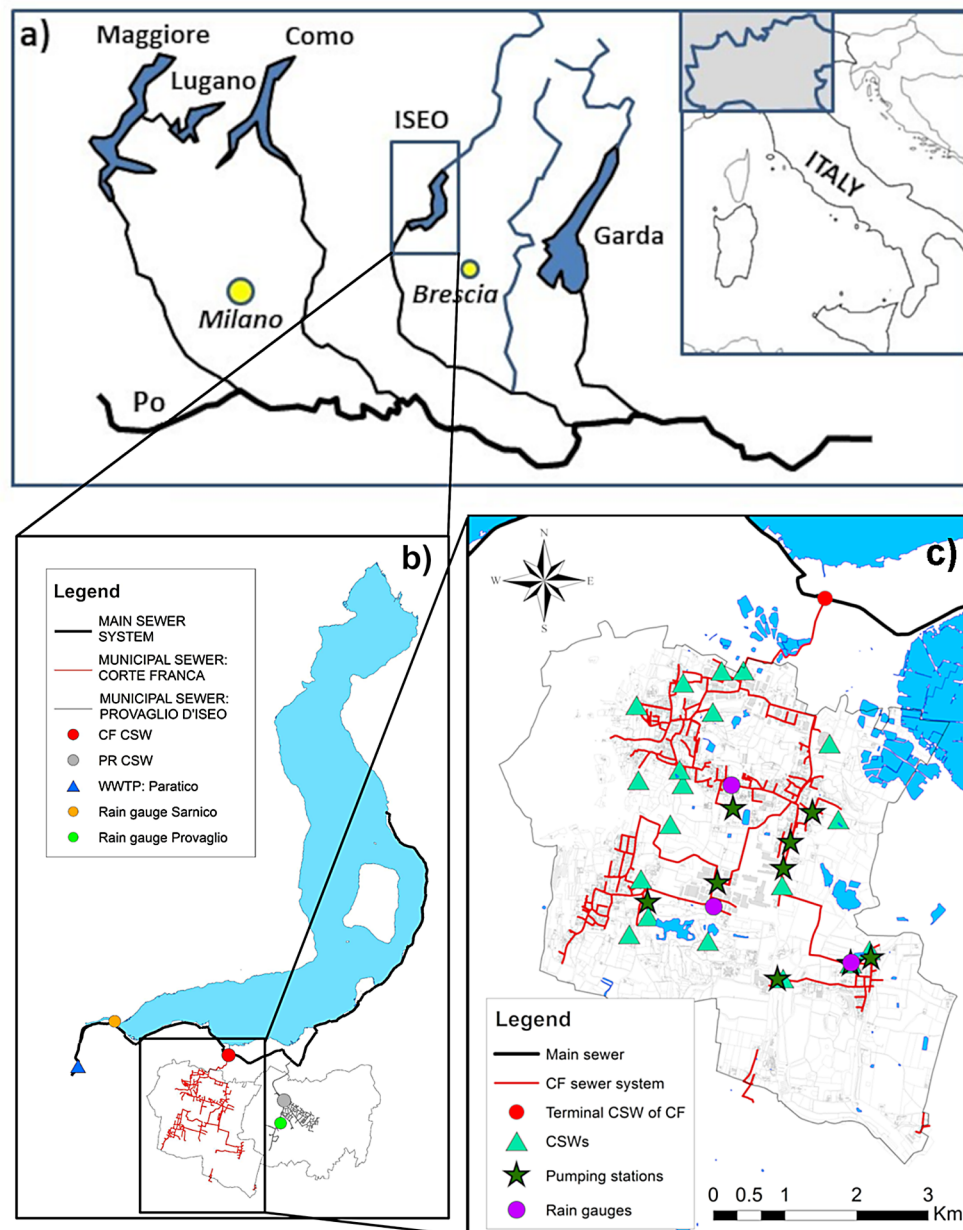


Fig. 1. Lake Iseo in Lombardy, northern Italy (panel a); outline of the municipal sewers of Corte Franca (CF) and Provaglio d'Iseo (PR), with the main sewer system around Lake Iseo (black solid line) and the 2 monitored CSWs (panel b). Detailed map of the CF sewer system with symbols referenced in the paper (panel c).

concentration of most pollutant mass during the first part of the overflow event (Saget et al., 1996; Bertrand-Krajewski et al., 1998; Deletic, 1998; Sansalone and Cristina, 2004; Bach et al., 2010), evaluating the efficiency of stormwater storage tanks (Balistrocchi et al., 2009; Wang and Guo, 2018), reducing the impact on receiving water bodies (Freni et al., 2010; Todeschini et al., 2011), improving sampling techniques for quality monitoring (McCarthy et al., 2018) and analysing the interaction with climate change (Salerno et al., 2018).

Owing to their long renewal time (Pilotti et al. 2014), deep lakes are particularly sensitive to the pollution effects of CSOs, whose contribution has been identified as a constraint to water quality improvement in several large lakes in the world (e.g., Sekaluvu et al., 2018). A technical solution was found in extended storage capacities, such as the construction of deep tunnels and reservoirs for temporary CSOs storage (e.g., Lyandres and Welch, 2012). However, to our knowledge, very few studies have so far quantified the contribution of the CSOs to nutrients load in deep European lakes and none in the Italian area.

In Italy, all the great prealpine lakes (Lake Maggiore, Lugano, Como, Iseo and Garda, with maximum depths between 256 and 410 m; Fig. 1a) are surrounded by important urban settlements where combined sewers predominate, and are under scrutiny for the increase in nutrient concentrations and the decrease in hypolimnetic oxygen content. The case of Lake Iseo is particularly relevant. This lake 50 years ago used to be fully oxygenated as far as its maximum depth at 256 m, while is now anoxic under 100 m (Salmaso and Mosello 2010). Lake Iseo drains a large watershed (Valle Camonica, about 1450 km²) whose strong economic development led in the past to an uncontrolled pollution of Oglio River, its main tributary. In addition, the lake drains many small watersheds, whose combined sewers drain to a centralised wastewater treatment plant. About 20 years ago, a combined sewer pipe was completed along the eastern lake shore to improve its water quality (solid black line in Fig. 1b) which collects and delivers the sewage from 9 municipal sewer systems to the waste water treatment plant located at the lake outlet.

Since the capacity of the combined sewer was limited to low return period rainfall events, combined sewer weirs (CSWs) were located at the connection with the municipal sewers, on the assumption that the pollutant concentrations from the CSOs during wet weather periods were low. In fact, it was empirically reckoned that the overall contribution of CSOs to the P load could range between 0 and 3% of the overall yearly load to the sewer (Garibaldi et al., 1998). However, although no data has been measured or any modelling effort undertaken to actually quantify this process in Lake Iseo to the date of this research, these assumptions are presumably wrong.

Without quantitative data in the Italian prealpine area as in many other lakes elsewhere, it is difficult to step over a legislation that is based on the maximum effluent concentrations, in favour of an approach based on the nutrient cumulative effects that are particularly relevant for lakes. Therefore, we believe that every effort to increase the body of knowledge on this contribution is justified.

Bearing in mind the long renewal times of deep lakes, a long-term assessment of nutrient residual loads associated with CSOs is a crucial piece of information, that must be known before any restoration strategy is undertaken. Unfortunately, pollutant transport dynamic in combined sewer systems is affected by a number of physical, chemical, climatic, hydraulic and hydrologic factors, so that it configures as a very site-specific phenomenon. This requires complex and computationally intensive numerical simulations, conducted for long time periods. Further, simulation outcomes must be statistically characterised. In this paper, an alternative stochastic approach, based on Monte Carlo simulations, is suggested. To this purpose (1) we modeled in detail the hydraulic-hydrologic behaviour of two municipal sewer systems located along the shore of Lake Iseo, obtaining a calibrated modeling framework for the occurrence of CSOs; (2) we instrumented a representative CSW where we monitored eighteen CSO events, measuring total nitrogen (TN) and phosphorus (TP), chemical oxygen demand (COD), total suspended solids (TSS) and biological oxygen demand (BOD). Then, (3) the data measured during the experimental campaign were extrapolated to a longer period. By using the calibrated model with a 10-year long rainfall record, a probabilistic estimation of the sewage volumes disposed into lake by the sewer CSWs and of the corresponding TP and TN loads was accomplished. Finally, (4) the obtained results were used to estimate, by a Monte Carlo approach, the capture volume that would be needed in a detention tank to obtain a target reduction of the disposed pollution load.

Overall, we believe that this paper also provides important insights regarding other watersheds located in areas with similar climatic features and anthropic pressure, so contributing to a better understanding of the relevance of lakes eutrophication problem.

2. Materials and methods

2.1. Description of the study area

We considered two relatively small urban–rural catchments (Provaglio d'Iseo and Corte Franca) with similar municipal sewer systems, located along the eastern coastal area of Lake Iseo. The sub-alpine Lake Iseo (area of 61 km²; maximum depth of 256 m) is the fifth largest Italian lake in terms of volume. It is located in the region of Lombardy (see Fig. 1a), in an area characterised by the presence of several other deep and large lakes. During the second half of the 20th century it underwent a transition from oligotrophy to eutrophy and the oxygen content of the bottom waters decreased from 9 mg/l (in 1967) to zero from mid-1995 s till the mid-2000 s (Pilotti et al., 2014). Undoubtedly, the human pressure in the lake's watershed can be blamed for the gradual increase of the trophic level, coupled with the accumulation of nutrients deriving from the limited exchange of deep waters. From this viewpoint, the situation is further hindered by current climatic trends, that might completely prevent the regular overturn of deep waters (Valerio et al., 2015).

Having in mind the quantification of the residual load from the entire main sewer draining the eastern shore of the lake, we started from the contribution of the municipal sewers, whose hydrology is very similar. We focused our attention on the CSW located at the junction of the Corte Franca (CF in the following) municipal sewer with the main pipe (red dot in Fig. 1b). This CSW is one of the most important for the discharged volumes and its proximity to the lake in a protected natural wetland between two important touristic settlements. Accordingly, the contribution of this CSW in an area characterized by strong submerged macrophytes growth during summer could be relevant both for lake eutrophication and for potential bacterial pollution. To this end, we monitored the CSW, sampling CSOs, and implemented a model using EPA's SWMM (Storm Water Management Model) software, to better understand the hydraulics of the sewer.

2.2. The hydraulic-hydrological model of Corte Franca watershed

The Corte Franca (CF) combined sewer system (Fig. 1c) is composed of the main network and of two minor subnetworks (Nigoline and Borganato), which are connected to the main one by two pumping stations. Due to lack of geometric data, the hydraulics of these two subnetworks were not modeled and their contributions transferred directly from the pumping stations to the municipal network. The diameter of the conduits of the combined sewer system varies from 125 mm to 800 mm and they are made in concrete and PVC, for an overall length of 19 km. Along the sewer system, there are 20 small CSWs.

The total area drained by the sewer, provided by the public body in charge of the urban water cycle management ATO (Ambito Territoriale Ottimale), is 2.9 km². Considering that 45% of the area is served by separated sewer, the area that generates runoff during wet weather is 1.6 km². To obtain a careful quantification of the impervious surfaces, a land use classification was carried out through a colour band analysis of the recent satellite Sentinel-2 images, with a 10 m spatial resolution. The resulting land use map is shown in Fig. 2, where the urbanized areas drained by the sewer system is evidenced. This area totally amounts to 0.6 km² and approximately 40% can be regarded as totally impervious.

To compute the dry weather loads, the total area was divided in 191 sub-catchments, one for each sewer junction, by assuming that the population density is uniformly distributed in the basin. The dry weather loads were calculated by multiplying the measured per capita water supply, equal to 300 l/(p.e.d), by the number of equivalent inhabitants of the area of interest. The per capita water supply values were obtained by the analysis of the daily volume delivered by the drinking water plants of the municipalities. In addition to normal dry weather flow condition, the touristic seasonal loads were calculated by using data provided by the national institute of statistics (ISTAT), so that the dry weather flow presents a monthly pattern.

The actual geometrical characteristics of each conduit and manhole of the sewer were implemented in the model. The pumping stations functioning was described in detail by inserting the storage unit's dimensions, the pump characteristic curves, the geometrical data of delivery conduits and the startup and shutoff depths of pumps. The CSWs have a fundamental role and were included in SWMM by describing the characteristics of the weirs and the possible presence of sluice gates.

As infiltration model, we used a constant infiltration capacity f_p (mm/h) since during intense events that may cause a CSO, the reduction of infiltration capacity in urban areas is negligible. The value of f_p was obtained by calibration: we evaluated that 40% of the urban area is totally impervious, characterised by $f_p = 0$ mm/h, whereas in the remaining area $f_p = 3$ mm/h. Three Davis rainfall gauges with resolution of 0.2 mm and sensor type tipping bucket with magnetic reed switch were placed within the CF watershed (Fig. 1c) for more than a year, measuring cumulative rainfall every minute.

The discharge delivered to the municipal sewer outlet, where the monitored CSW is located, was measured during the same period.

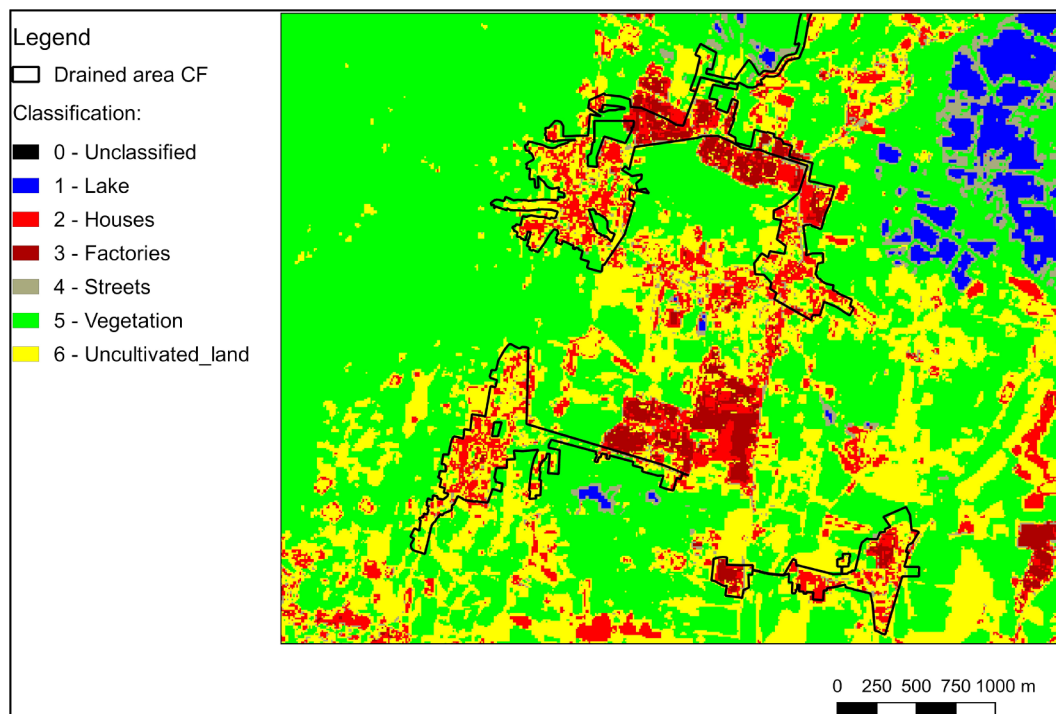


Fig. 2. Land use map of Corte Franca, calculated by satellite images analysis of Sentinel-2, 10 m spatial resolution.

Another raingauge station, managed by the regional agency for environmental protection (ARPA Lombardia) is located in Sarnico, about 4 km north-west of CF (see Fig. 1, panel b), and provided a continuous series from 2007 recorded at 10' time step. The monitoring of the terminal CSW at CF allowed us to firstly set up a hydraulic model of this device, and to calibrate the rainfall-runoff model of the sewer network. Despite the considerable level of complexity of the CSW, a 1-dimensional model was found to provide a satisfactory representation of the overflow process (see details in supplementary material SMI).

2.3. The hydraulic-hydrological model of Provaglio watershed

The Provaglio d'Iseo (PV) sewer system is characterised by the presence of a single CSW, located immediately upstream of the junction of the municipal sewer with the main sewer pipe. Thus, the measured inflow upstream of the CSW is the total flow entering the main sewer. This CSW discharges during wet weather in the wetland area called Torbiere d'Iseo, which is in close communication with Lake Iseo. Since the geometrical information of the municipal sewer systems under study was not available, a complete survey of sewer systems was carried out.

The industrial part of the basin is drained by a separated sewer system and its dry weather flow enters the municipal sewer downstream of the CSW.

The remaining drained PV area, equal to 1.1 km², was classified using the Sentinel 2 satellite images, as previously explained, obtaining an urbanized drained area of 0.45 km². The combined PV sewer is mainly made of concrete pipes; the diameters range from 160 mm to 1600 mm, for an overall length of 13 km. At each network junction, the value of drained area was assessed by visual inspection of the drained subcatchments. The dry period input discharges to the sewer were distributed along the network considering the local population density. Rainfall was measured at a rain gauge located inside the watershed (Fig. 1b).

The CSW of Provaglio consists in an oblique weir whose efficiency is increased by the backwater produced by a gate. By using monitoring data, a suitable 1-dimensional hydraulic model was set up and

calibrated for this device, as well (see details in supplementary material SMII).

2.4. Model calibration and validation

Due to the complexity of the CF sewer system, which has, inter alia, 20 CSWs distributed in the watershed and 6 pumping stations, we used for the CF watershed the parameters obtained by the calibration of the watershed and municipal sewer of PV, that has similar characteristics but only a single CSW, located at the outlet of the network.

To this purpose, rainfall in the PV watershed and discharge at the CSW were measured for a period of 7 months.

The hydrologic parameters of the PV model were calibrated by working on single rainfall-runoff events, comparing the measured discharge hydrograph at the CSW with the modelled one for the period 10/03/2018 – 13/03/2018 (Fig. 3a). The model was then validated for the period 01/03/2018 – 05/04/2018; an example of model validation is shown in Fig. 3b.

Fig. 3c and 3d show the comparison between the measured discharge hydrograph approaching the final CSW of Corte Franca (in blue) and the modelled discharge hydrograph (in red) for two rainfall events of (01/05/2017 – 03/05/2017) and (05/11/2017 – 06/11/2017), when the same set of optimized hydrologic parameters were applied to the CF model. As one can observe the match is very satisfactory, with a maximum error on the hydrograph volume of 4% in the event of panel d). The coefficients of linear correlation between measured and modelled data are: 0.882 (panel a), 0.844 (panel b) 0.919 (panel c) and 0.944 (panel d).

2.5. Nutrients dynamic assessment

In November 2017 we installed an automatic sampler ISCO 3700 at the CSW of Corte Franca (see green dot in Fig. SMI.1) to collect CSO samples, equipped with 24 ½-liter bottles. The sampling was carried out by aspiration using a peristaltic pump. The sampling interval was set equal to 10 min and the sampler was set up to collect two samples of 250 ml in each bottle. In this way, it was possible to characterize the

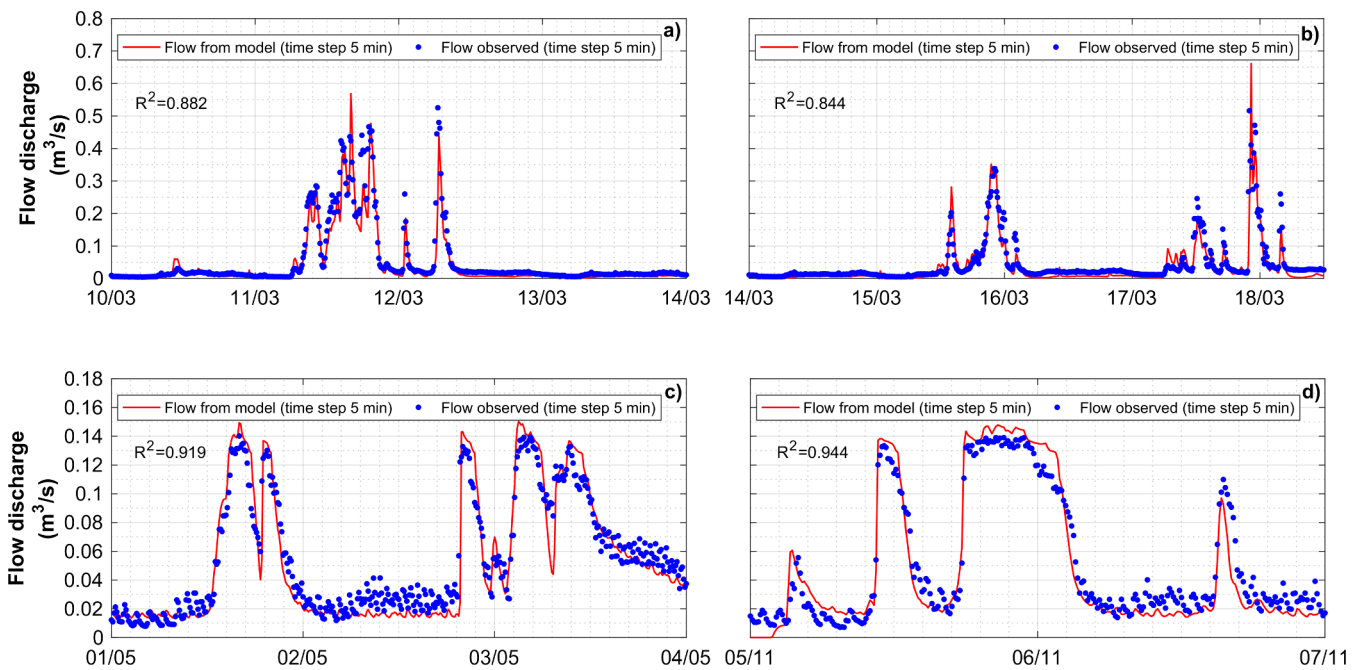


Fig. 3. Comparison between measured and modelled discharge hydrographs at the CSW of Provaglio and Corte Franca. (a) model calibration for Provaglio (10/03/2018 – 13/03/2018); (b) example of model validation for Provaglio (14/03/2018 – 18/03/2018). The calibration event was selected because it is a multi-peak event with a range of discharges typical of a wet period. The quality of the match between the observed and modelled series of (b) is well representative of the performance of the model for the other events in the validation period. (c), (d) examples of Corte Franca model validation for the period (01/05/2017 – 03/05/2017) and (05/11/2017 – 06/11/2017).

overflowing sewage during an 8-hour long event. After collection, the samples were transported through a portable refrigerator to the laboratory to quantify TP and TN concentrations. Since the sampler is not refrigerated, we took care to collect the samples as soon as possible after the end of the events. Overall, a total of 18 CSO events and 242 samples were analysed. Unfiltered water samples were analysed for TP and TN concentrations with standard spectrophotometric (Perkin Elmer, Lambda 35) methods as soluble reactive phosphorus and nitrate after alkaline peroxydisulfate oxidation (Valderrama, 1981).

When operative conditions made it possible, the laboratory carried out also analysis of COD (7 events, APHA 2012), BOD₅ (2 events, UNI EN 1899-1 2001) and total suspended solids TSS (4 events, APAT CNR IRSA 2090 B Man 2003), to identify possible correlations between the pollutants. The dates of CSO events when the stormwater runoff samples were collected are summarized in Table 1, along with the parameters measured in laboratory and the numbers of samples for each event. During all these events, the discharge hydrograph of the incoming flow and of the CSO was either measured or computed using the estimated stage-discharge relationship.

In order to study the phenomenon of first flush, the dimensionless diagrams of pollutant loads and discharge volumes, firstly proposed by Bertrand-Krajewski et al. (1998) and herein called Dimensionless Cumulative Load curves (DCL curves; see Fig. 4) were used. In these diagrams, the ratio ν between cumulative and total runoff volume is reported on x axis and the ratio λ between cumulative pollution load and total pollution load is reported on y axis. The empirical DCL curves can be fitted by the power function in Eq. (1) (Ma et al., 2011), where the greater the first flush, the smaller the value of the exponent b is. When the first flush is absent, $b = 1$.

$$\lambda = \nu^b \quad (1)$$

This approach was preferred to other solutions, despite the deficiencies regarding its arbitrary definition of first flush which can be overcome by using non-parametric statistical analyses (Bach et al. 2010). Actually, Eq. (1) makes it possible to implement Monte Carlo simulation procedures, to size the capture volume needed to mitigate

the impact of the CSOs with reference to a performance target. The first flush analysis focused on total phosphorus and total nitrogen, that are widely recognised as responsible for the eutrophication process in lakes.

2.6. Estimation of nutrients residual load to the lake

The calibrated hydrodynamic model of CF's sewer network was used to perform a 10-year-long (from 2007 to 2016) continuous simulation to assess the wet and the dry weather sewage produced in the long-term period. To this purpose, we used the rainfall data of the Sarnico rain gauge, recorded with a 10 min time step. In this way, a continuous time series of CSOs, directly discharged into Lake Iseo through the monitored CSW, was computed.

In the absence of a calibrated quality model, Monte Carlo simulation techniques (Kottogoda and Rosso, 2008) offered an effective alternative to predict the nutrients residual load associated with these overflow discharges. Indeed, samples of overflow events along with their qualitative and quantitative characteristics, can be generated, by assuming that the parameters describing the pollutant dynamics are random variables. Their variability was expressed by suitable probability distributions, fitted with respect to a sample of independent events derived from the simulated series.

To this purpose, the continuous series of overflow discharges was discretized into individual independent overflow events through a peak-over-threshold criterion corrected with a minimum inter-event period (Lang et al., 1999; Bacchi et al., 2008) implemented into two phases:

1. Individual overflows were sampled from the continuous series as the part of the overflow hydrograph exceeding a discharge threshold used to eliminate from the sample minor overflow events, that convey negligible volumes.
2. Two subsequent individual overflows were assumed to be independent when separated by an inter-event period longer than the minimum one; otherwise, they were joined in a single event.

In the following, a threshold discharge of 10.01/s and a minimum inter-event period of 3.0 h were adopted. When relevant detention

Table 1

Dates of monitored CSO events, parameters analysed in laboratory and number of samples for each event; main characteristics of the rainfall events triggering the monitored CSOs and corresponding quality parameters: antecedent dry weather period a , wet weather duration d , rainfall depth h , maximum rainfall intensity i_{max} , overflow discharge volume V , event mean concentration EMC and exponent b of the DCL curves for TN and TP, and summary statistics of quality parameters.

Event	Event start date dd/mm/yyyy hh:mm	Event end date dd/mm/yyyy hh:mm	Samples nr	Analysed parameters					a (h)	d (h)	h (mm)	i_{max} (mm/h)	V (m ³)	EMC (mg/l)		b	
				TN	TP	COD	BOD ₅	TSS						TN	TP	TN	TP
1	05/11/2017 10:30	05/11/2017 13:20	9	x	x			x	343.7	2.2	7.0	8.4	337	29.8	5.1	0.71	0.65
2	05/11/2017 17:40	06/11/2017 02:50	2	x	x			x	4.3	8.7	35.8	10.8	1399	17.4	2.5	1.00	1.00
3	06/11/2017 15:00	06/11/2017 16:20	3	x	x			x	12.0	1.0	2.2	3.6	117	25.9	2.8	1.05	1.03
4	12/11/2017 22:00	13/11/2017 01:00	9	x	x				149.5	1.7	10.0	28.8	408	21.2	3.3	0.73	0.69
5	25/11/2017 09:10	25/11/2017 16:50	22	x	x				296.2	6.3	12.0	4.8	740	15.2	2.8	0.57	0.57
6	11/12/2017 10:50	12/12/2017 02:00	24	x	x				378.0	8.7	15.6	4.8	1700	13.2	2.1	0.50	0.47
7	09/01/2018 01:20	09/01/2018 06:40	15	x	x				181.2	2.5	18.4	32.4	645	13.5	2.1	0.50	0.47
8	03/03/2018 13:30	03/03/2018 18:50	15	x	x	x			156.2	5.3	8.4	3.6	310	22.6	3.7	0.70	0.72
9	11/03/2018 08:00	13/03/2018 00:50	30	x	x	x			180.5	17.3	46.4	7.2	4075	14.3	1.4	1.00	0.60
10	15/03/2018 13:40	16/03/2018 16:20	22	x	x				62.2	11.0	23.8	4.8	1608	9.8	1.9	0.63	0.74
11	03/04/2018 21:10	04/04/2018 04:50	15	x	x	x			127.5	6.5	9.6	2.4	14	9.6	1.7	0.95	1.05
12	09/04/2018 19:10	10/04/2018 01:50	8	x	x	x			117.8	3.0	9.8	13.2	269	16.0	3.7	0.69	0.63
13	11/04/2018 17:10	12/04/2018 01:20	20	x	x				21.2	5.5	9.6	3.6	559	8.8	1.2	0.72	0.72
14	29/04/2018 20:00	30/04/2018 04:00	12	x	x				379.7	3.0	7.6	8.4	198	27.4	5.0	0.39	0.30
15	09/05/2018 16:20	09/05/2018 21:10	13	x	x				16.0	1.8	6.2	12.0	367	12.3	1.8	0.89	0.79
16	16/05/2018 21:40	17/05/2018 01:00	9	x	x				57.7	3.7	8.0	4.8	298	15.3	2.6	0.77	0.70
17	04/06/2018 07:30	04/06/2018 14:40	6	x	x	x	x	x	144.5	2.8	29.6	50.4	609	12.9	1.8	0.53	0.45
18	03/07/2018 20:10	03/07/2018 23:00	8	x	x	x	x		375.7	2.3	6.4	6.0	281	26.4	4.6	0.67	0.57
Mean														17.3	2.8	0.72	0.68
Minimum														8.8	1.2	0.39	0.30
Maximum														29.8	5.1	1.05	1.05
Variation coefficient														0.37	0.43	0.26	0.29

capacities are not present in the watershed, two subsequent CSOs can be considered independent if they are separated by a period almost equal to the time of concentration. In this watershed, such a time is far shorter than the minimum interevent period suggested for urban application, which is set at 3.0 h (Adams and Papa, 2000). The threshold flow discharge was selected in order to have a CSOs minimum volume slightly greater than 1.0 m³ but also considering that the choice of a greater threshold would have yielded a significant underestimation of the total annual overflow volume.

Accordingly, the average annual number ω of individual independent events was computed, along with the volume V of total

overflow discharge occurring during the event, that is, including the flow discharge below the threshold.

Typical TP and TN concentrations were already known by the analysis of measured overflow events.

In order to run Monte Carlo simulations, a sample of ω overflow events was generated for each simulation year. Each event was featured by the overflow volume V , the event mean concentration (EMC) and the exponent b of the DCL curve, randomly varying according to their univariate probability distributions. As customary in Monte Carlo simulation procedures, this assumption is justified if the different variables are mutually independent, as supported in this case by the

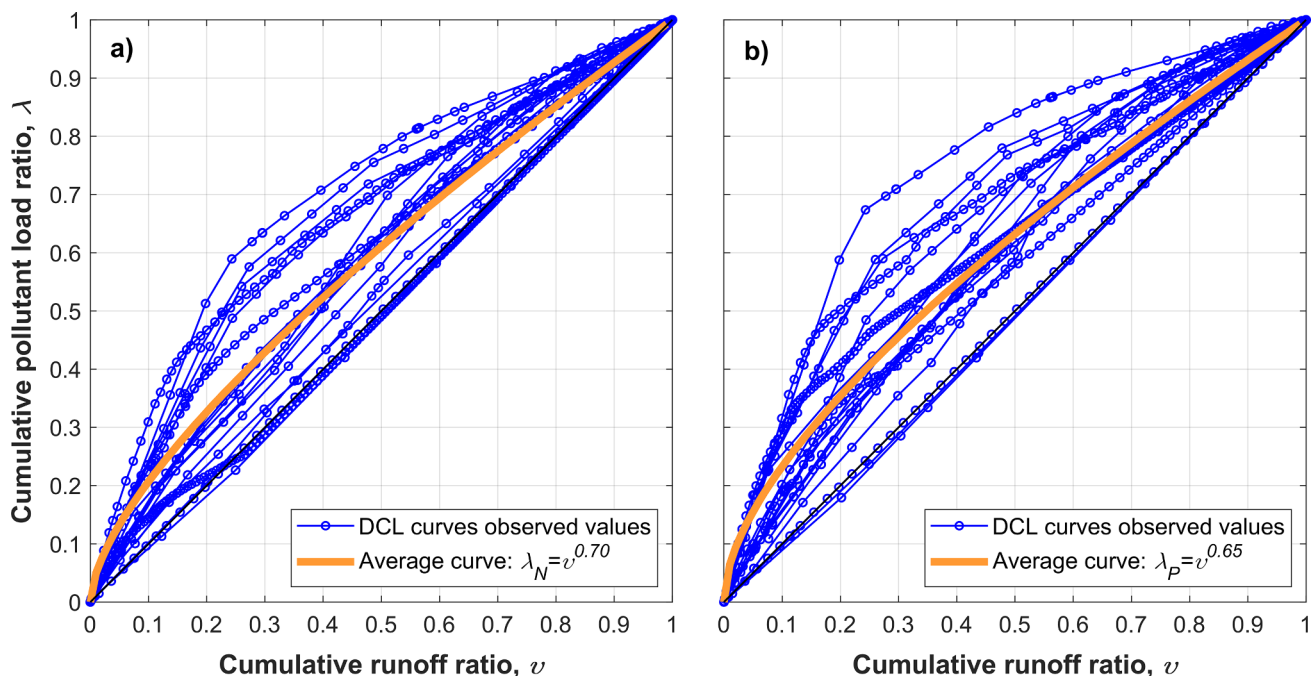


Fig. 4. TN (panel a) and TP (panel b) DCL curves observed at the monitored CSW and power functions approximating the average behaviours; λ is the ratio between cumulative pollution load and total pollution load and ν is the ratio between cumulative and total runoff volume.

empirical evidence presented in the following. In this way, if a sufficiently long time series is used, annual balances of nutrient loads and overflow volumes can be computed with reliable estimates of their expected value and uncertainty (herein quantified in terms of standard deviation).

3. Results and discussion

3.1. Nutrients dynamic assessment

The main characteristics of the monitored CSO events are reported in Table 1, where the rainfall events are delineated in terms of depth, duration, maximum intensity and antecedent dry weather period, while the pollutant dynamic is summarized by the observed EMC of TN and TP and the exponent b of the power functions (1), fitted to the empirical DCL curves (Fig. 4). Statistics of these quality parameters are reported, as well. The measured samples reflect a wide range of rainfall events and initial conditions in the network and the analysed nutrients show very similar pollutant dynamics. Apart from the order of magnitude, EMCs aleatory variability are comparable, since the variation coefficient estimates show analogous dispersions around the mean and statistics of exponent b have almost identical values.

TP and TN concentrations are within the upper range of concentrations measured in other CSOs (Gervin and Brix, 2001; Barco et al., 2008; Brombach et al., 2005; Salerno et al., 2018) and were from 30 to 7 times higher compared to those previously measured in the lake's tributaries (Garibaldi et al., 1999). In general, the pattern of both DCL curves shown in Fig. 4 ranges from the proportional transport (when b is equal to 1.00) to a moderate-strong first flush (b equal to 0.39). According to the first flush definition proposed by Bertrand-Krajewski et al. (1998), no DCL curve shows a strong first flush, as 80% of the pollutant load is always transported by a percentage of the overflow volume greater than 30%. On average, a moderate-weak first flush, featured by an exponent b value of 0.70, is experienced for both nutrients.

A correlation analysis was carried out to identify significant statistical relationships between the quality parameters and the rainfall characteristics. To this end, the Kendall rank correlation coefficient and the Pearson linear correlation were used. Since the Kendall coefficient is independent of the marginal distributions, it can effectively measure the association degree of not necessarily elliptic dependence structures. The estimated coefficients are listed in Table 2, where values significantly different from zero are underlined and boldface. This condition is satisfied if the p -value of the independence test is less than 5%.

A general mutual independence of the analysed variables is evidenced by low coefficient values, which cannot be considered significantly different from zero. The only exception is given by the couples of the antecedent dry weather period a and the exponent b of both nutrients. These correlations indicate quite strong and significant discordant associations. Thus, the greater the antecedent dry weather period, the strongest the nutrients first flush is. The results obtained when the TP EMC is coupled with the antecedent dry weather period, a , the wet weather duration, d , and the rainfall depth, h , nevertheless deserve a brief discussion. In the first two cases, the Pearson coefficient

is significantly different from zero, while the Kendall coefficient, the most reliable one, is not. In addition, the Kendall coefficient value is low. Therefore, this appears to be a spurious linear correlation, related to the very small variability of the TP EMCs with respect to that of the antecedent dry weather period. In the third case, the contrary occurs, yet the discordance strength detected through the Kendall coefficients is quite low and its significance, slightly less than 5%, could be due to the small sample size, which yields high estimation variance.

It is worth highlighting that, in this climate, the antecedent dry weather period is independent of the other variables of the rainfall process (Balistocchi and Bacchi, 2011). On the one hand, a simple stochastic modelling relying on independent univariate distributions is therefore suitable to represent the nutrient transport dynamic. On the other hand, independence is basically an expression of a strong natural variability, so that mean annual values could not be representative of trend values and a suitable estimate of the uncertainty is mandatory to achieve meaningful assessments.

In consideration of the gentle slopes and the low degree of impermeable covers featuring the catchment surfaces, the most compelling cause for the significant discordant association, relating to the antecedent dry weather period and the DCL parameters, is the accumulation of organic sediments in the sewer pipes in dry periods. Actually, simulations reveal a generalized problem of low sewage flow velocities in most of the network. More precisely, in dry periods flow velocities are averagely equal to 0.55 m/s, but in many pipes (almost 30% of the total network length), located primarily in the upstream portions of the network and next to its outlet, velocities less than 0.30 m/s are computed. When the critical shear stress is exceeded due to the storm water wash off (see for instance Ahyerre et al., 2000 and references therein), it is reasonable to suppose that the sudden re-suspension of settled particulate matter and nutrients is the leading cause of the first flush occurrence. On the other hand, the poor correlation of the first flush occurrence with respect to maximum rainfall intensity can be explained considering that the conveyance capacity of the sewer in wet periods is insufficient, so that the shear stress limit is exceeded even by low return period storms (less than 5 years).

Finally, plots in Fig. 5 show correlations between measured pollutant concentrations during CSOs events. A significant linear correlation between TP and TN concentrations is observed, with a TN/TP ratio of about 5, which is consistent with the expected range for civil sewage. This strong correlation further confirms the previously discussed similarities between the TN and the TP transport dynamics.

Moreover, in passing by and marginally with respect to the main objective of the paper, we observe that good correlations are obtained also for the other three couples (see Fig. 5b–d). These regressions, that are only indicative of a potential trend affected by a certain degree of uncertainty (related to sampling procedure and, in the case of BOD, the limited sample size), must be investigated in more detail but could indicate that also the transport dynamics of the organic matter and of the total suspended solids are basically analogous to those of nutrients.

3.2. Nutrients residual load estimate

The 10 years long modeling of the rainfall-runoff transformation along the CF network showed that on average the CSW at the outlet of the watershed delivers about 62,000 m³/year to the lake. The overall volume discharged by all the CSWs of Corte Franca sewer system (i.e., including the unmonitored ones within the watershed), is on average about 365,000 m³/year, so that the terminal CSW discharges 17% of the total CSO volume. 83% of the CSO volume is delivered at locations that do not directly drain into the lake but that, eventually, contribute to the overall load coming to the lake.

The volumetric efficiency of the sewer, i.e. the percentage of volume that reaches the main collector and, presumably, the terminal wastewater treatment plant, with respect to the total volume entering the combined sewer system is 66%.

Table 2

Kendall coefficients and Pearson coefficients, in round brackets, obtained by coupling rainfall event characteristics and quality data parameters (coefficients significantly different from zero are underlined and boldface).

	EMC		b	
	TN	TP	TN	TP
a	0.25 (0.47)	0.31 (0.59)	<u>−0.53</u> (−0.62)	<u>−0.62</u> (−0.69)
d	−0.31 (−0.43)	−0.34 (<u>−0.47</u>)	−0.03 (0.23)	0.01 (0.05)
h	−0.30 (−0.38)	<u>−0.35</u> (−0.46)	−0.14 (0.17)	−0.18 (−0.08)
i_{max}	0.10 (−0.11)	0.10 (−0.12)	−0.18 (−0.33)	−0.34 (−0.37)

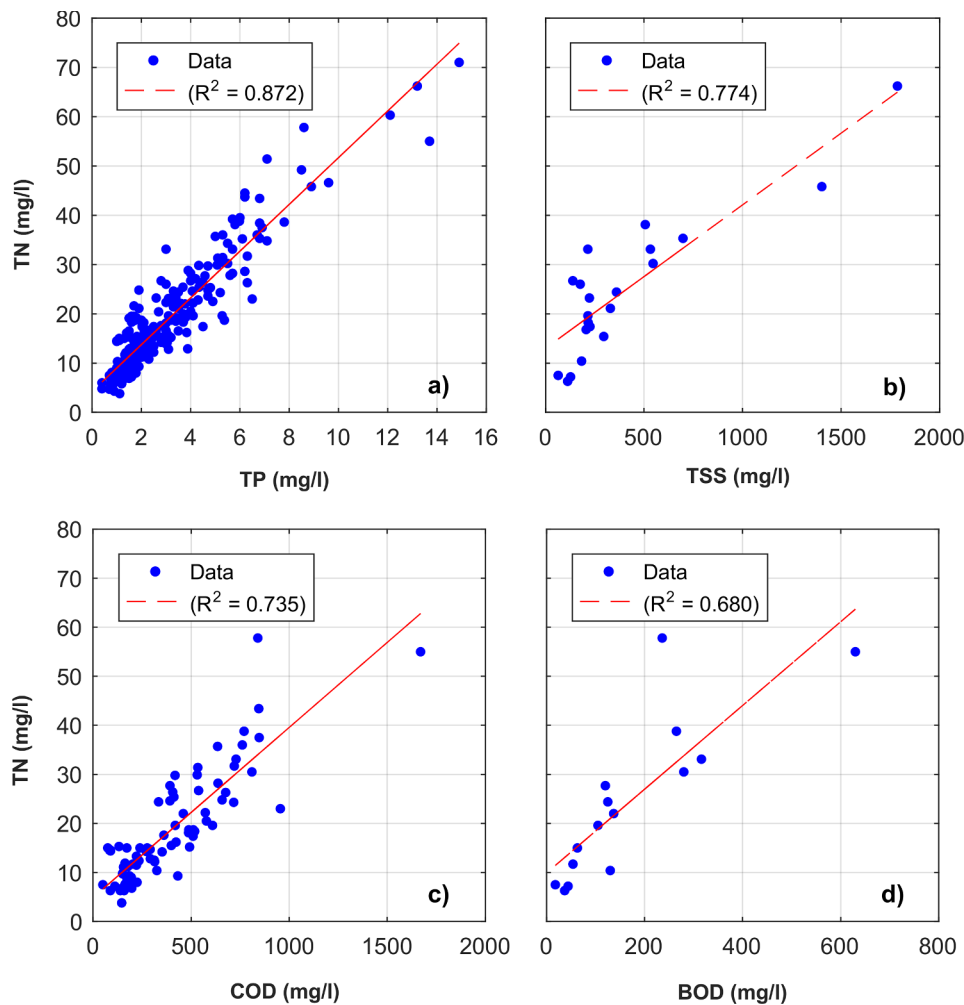


Fig. 5. Linear regressions between TP, TSS, COD, BOD concentrations and TN concentrations detected in the analysed sample bottles.

A more detailed statistical description of the 10 year-long simulated overflow discharge series was accomplished using the events sampling and analysis procedure detailed in the Methods section: the sample probability density of the overflow event volumes is shown as a bar diagram in panel a) of Fig. 6. The sampled CSOs are characterized by an average volume of about 640 m^3 , a standard deviation of 960 m^3 and a variation coefficient of 1.50. Moreover, the estimated average annual number of overflows above the introduced threshold ω is 95.3, and the average annual overflow volume amounts to about $61,000 \text{ m}^3$ (i.e., $2300 \text{ m}^3/\text{ha}_{\text{imp}}$ with respect to the impermeable catchment area).

As evident from the variation coefficient and the significant upper tail, the variability is large and the distribution is satisfactorily fitted by a Generalized Pareto (GP) distribution function (Kottegoda and Rosso, 2008). In Fig. 6a, the theoretical density function, fitted by means of the maximum likelihood criterion (shape parameter 0.33, scale parameter 440.5 m^3 , lower limit 0.0 m^3), is overlapped to the sample one. In the same Figure the cumulative distribution function is shown. The goodness-of-fit of the GP distribution to data is shown in Fig. 6b, where confidence boundaries for 10% significance are drawn: since all sample occurrences are included in the boundary region, the null hypothesis cannot be rejected.

These results delineate a systematic insufficiency of the conveyance capacity of the municipal sewer network, featured by high number of overflows, mainly related to small volumes. Indeed, the non-exceedance probability of an overflow volume of 100 m^3 is 22.5%, that is almost one fourth of total annual events. This probability rises to 37.5% if an overflow volume of 200 m^3 is considered.

To estimate the average annual nutrients load discharged through the monitored CSW, suitable distribution functions must be chosen for the EMC of TN and TP. However, the sample size does not allow to carry out an inference analysis as detailed as the overflow volume one and a lognormal distribution was selected, whose parameters were estimated by the maximum likelihood criterion (mean 2.75 mg/l and standard deviation 0.37 mg/l for TN, mean 0.90 mg/l and standard deviation 0.42 mg/l for TP).

Hence, for every i -th simulation year, an overflow event sample having size ω is generated. Each j -th event is defined in terms of overflow volume V and EMCs for TN and TP. The annual load L_i discharged by the CSW is therefore given by equation (2). An accurate estimate of L_i variability has been achieved by using 100,000 simulation years, yielding the sample density functions illustrated in Fig. 7a-b for TN and TP respectively.

$$L_i = \sum_{j=1}^{\omega} EMC_{ij} V_{ij} \quad (2)$$

The annual loads probability distributions are less skewed and more concentrated around the mean than the CSO ones, as expected when random variables are derived by integration with respect to long time periods. The variation coefficients are estimated at 0.24, while the expected annual loads of nutrients disposed into Lake Iseo and their uncertainties amount to $1050 \pm 250 \text{ kg}$ of TN, $170 \pm 40 \text{ kg}$ of TP.

In absence of more accurate results from a direct monitoring at the other CSWs and of a quality model of the CF network, considering that the investigated CSW provides approximately 1/6 of the overall volume

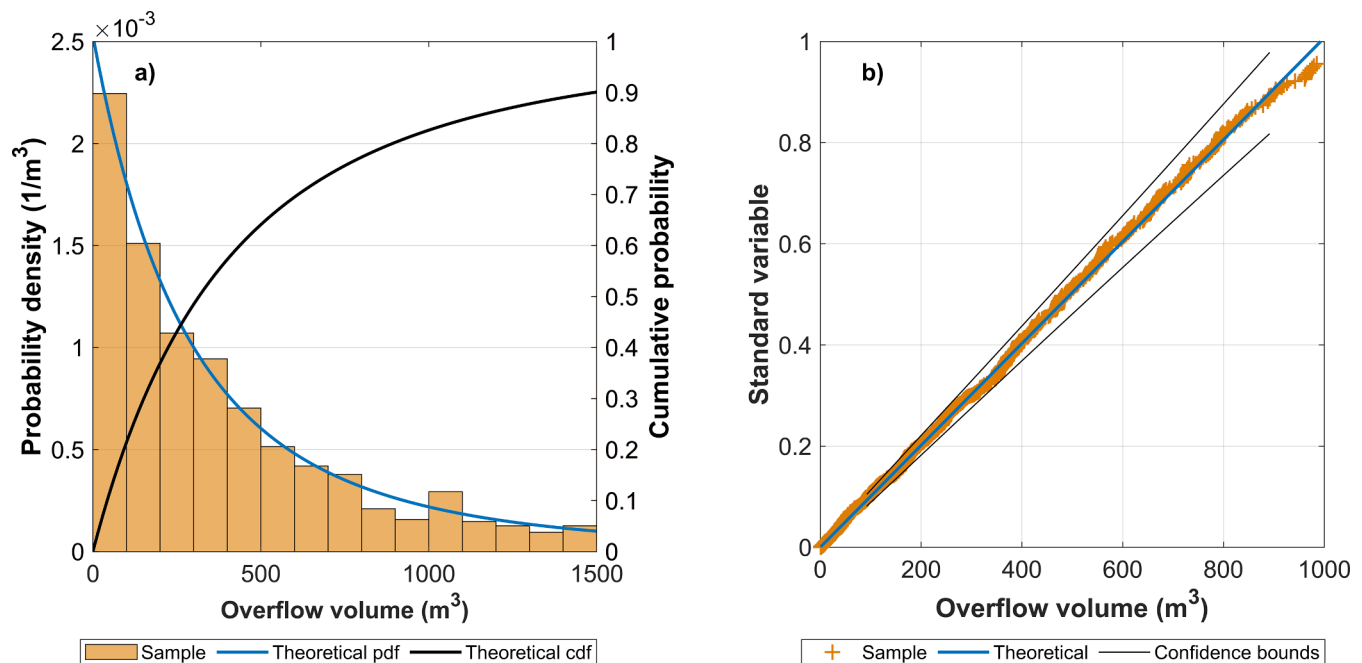


Fig. 6. Empirical and theoretical probability densities (light brown bar and blue solid line) and cumulative distribution (black solid line) functions of overflow volumes from the CSW at the outlet of the CF network a), goodness-of-fit test for 10% significance of the Pareto distribution function b). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

delivered to the environment each year, a “back of the envelope” evaluation on the actual amount of phosphorous released to the environment by the CF sewer is about 1 tonne each year.

The calculation of the overall percentage of nutrients loads, delivered to the main sewer with respect to the total nutrients entering the network, requires knowledge of the concentration of dry weather sewage. To this purpose, a set of measurements over a dry weather day provided average concentrations of 3.01 mg/l for TP and 30.37 mg/l for TN that could be affected by sedimentation in the conduits. By assuming typical literature concentration values for dry weather sewage, that varies in the range 6:10 mg/l for TP and 20:40 mg/l for TN, the 7000 equivalent inhabitants for CF and the per capita water supply of 300 l/(p.e.d), the percentage of loads discharged to lake with respect to loads produced is equal to 13.3–22.2% for TP and to 20.5–41.1% for TN. These values are much larger than the ones reckoned during the initial design of the main sewer around the lake.

Based on recent measurements along the two main lake's tributaries, we estimate an overall contribution of 84.7 tonnes of P in a year from the whole Valle Camonica watershed. The measurements also show that

about 50% of this load is delivered to the lake during rain events, when the CSOs in Valle Camonica are overflowing in the tributaries. According to this evaluation, the CSOs by Corte Franca increases by about 1% the whole phosphorous mass delivered to Lake Iseo. Although negligible in itself, one must consider that other 16 municipalities, with similar local network are located around the lake. Moreover, the relevance of the Corte Franca CSOs is amplified by their location within an environmentally protected area and the proximity to important touristic areas.

3.3. Sizing of a detention storage

The CF watershed lies inside the moraine arch produced by the ancient glacier of the Valle Camonica, so that the soils include large amounts of clay and fine grains. Several ponds located inside the watershed and the proximity of Lake Iseo and Sebino natural wetlands indicate the presence of a shallow water table with abundance of peat. As a consequence, infiltration capacities are generally low, suggesting the choice of storage structures for urbanization mitigation practices,

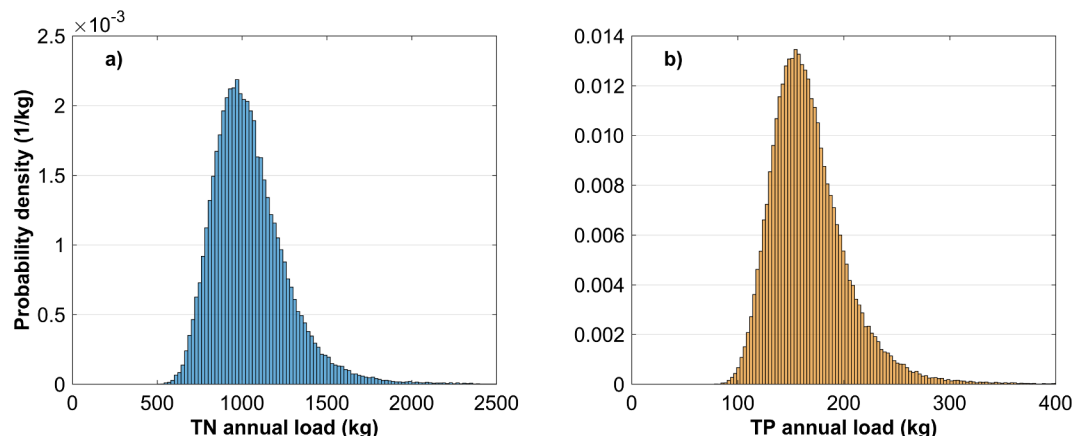


Fig. 7. Sample probability density function of annual TN load a), and annual TP load b).

rather than source or end-of-pipe infiltration practices.

Consequently, to mitigate the impact of the CF CSOs on the lake, an off-line overflow detention storage, downstream of the monitored CSW, could be designed to intercept the first part of the CSO. After the storage capacity is filled, the further overflow discharge would be completely delivered to the receiving water body. During the dry weather periods, the stored volume would be pumped back into the sewer network, to be delivered to the wastewater treatment plant.

Storage capacity, the intensity and recurrence of the first flush phenomenon and the average detention time (Balistocchi et al., 2009) are crucial parameters for a capture tank performance. According to the Italian law, the emptying process must begin after a dry weather period longer than 48:96 h, in order to avoid intercepting overflow events conveying small pollutant loads, due to the short antecedent dry weather period, and overcharging a network where the falling limb of a flood might still be flowing. On the other hand, the longer the detention time is, the greater the probability that the storage capacity is filled during a following CSO. This implies that the capture tank performance decreases with a growing average detention time.

The storage capacity of the capture tank can be defined in terms of water quality volume (WEF, ASCE, 1998), stochastically defined as the average CSO volume that must be stored and treated, to achieve a target abatement of the pollutant load. Monte Carlo simulation techniques can be utilized to estimate this volume, as well.

However, to sample from the continuous overflow discharge series CSO events that are independent, it is now necessary to select a minimum inter-event period that is set according to the storage detention time, so that the storage is empty when the subsequent overflow occurs. Consequently, in the following, minimum inter-event periods of 48 h and 96 h were selected.

In addition, the occurrence and the intensity of the first flush is modelled by assuming the exponent b of the power function approximating the DCL curves as a random variable, whose variability is described by a normal distribution fitted to the TP power function exponent, reported in Table 1. Phosphorous is chosen because in Lake Iseo it likely controls trophic conditions (Garibaldi et al., 1999; Salmaso and Mosello 2010).

The ratio between the storage capacity W and the overflow event volume V , generated by the GP distribution, provides a dimensionless event volume that can be transformed through the DCL curve into a ratio between the captured load and the overall overflow one, that is an event capture efficiency. By multiplying this event efficiency for the CSO event load, the actual event load captured by tank is estimated. Finally, if for each i -th simulation year, several events are generated in accordance with the average annual number of overflows ω , the total annual loads discharged and captured are computed. The ratio between these loads supplies the annual capture efficiency of the tank η_i , as indicated in equation (3):

$$\eta_i(W) = \frac{\sum_{j=1}^{\omega} EMC_{ij} V_{ij} (W/V_{ij})^{b_{ij}}}{\sum_{j=1}^{\omega} EMC_{ij} V_{ij}} \quad (3)$$

Finally, the expected value and variability can be assessed through a sufficiently large number of simulation years. The results of 100,000 simulations are illustrated in Fig. 8, where the expected values of the annual capture efficiency are reported along with confidence boundaries centred on the mean and equal to the double of the standard deviation. The efficiency curves in Fig. 8 are referred to the specific storage capacity, a customary concept for sizing the water quality volume, that is the ratio between the tank capacity W and the product of the total urban catchment area A and the catchment impermeability I . The conventional storage capacity of a capture tank in Lombardy is $50 \text{ m}^3/\text{ha}_{\text{imp}}$.

Relatively small storage capacities, ranging between 1000 m^3 and 2000 m^3 (about $40:80 \text{ m}^3/\text{ha}_{\text{imp}}$ with respect to the impermeable catchment area), are associated with quite large capture efficiencies:

58:74% for the 48-h detention time, 51:68% for the 96-h detention time. With reference to the rules established by local regulations (storage capacity $50 \text{ m}^3/\text{ha}_{\text{imp}}$ and detention time 96 h), the expected efficiency is equal to 60%, with an uncertainty of 10%. The small volumes featuring most of overflow events can explain such large efficiencies. The detention time exerts a moderate influence on the expected efficiency, when it varies in this usual range. Uncertainties are however significant, since they are estimated at about 10% between 1000 m^3 and 2000 m^3 for both average detention times.

In addition, expected volumetric capture efficiencies are reported in Fig. 8, to evidence the efficiency gain determined by the first flush with respect to a hypothetical pollutant dynamic, characterized by a proportional transport. Owing to the moderate first flush detected for this urban catchment, such an efficiency gain is quite small. Its values decrease with the storage capacity W , from 10% down to 7% and are slightly greater when a 96-h detention time is adopted, so that, for the conventional storage capacities of $50 \text{ m}^3/\text{ha}_{\text{imp}}$, the volumetric efficiency curve is included in the uncertainty region of the load efficiency curve.

4. Conclusions

In this paper, the residual nutrient load discharged into Lake Iseo through a CSW located at the outlet of a small rural-urban watershed has been assessed by coupling a year-long monitoring campaign with long-term simulation techniques and a Monte Carlo approach. The results have been extended to the whole sewer network, where several CSWs are present. This allowed the determination of statistically reliable estimates of the overall average annual overflow volumes and of the corresponding nutrient loadings, along with their uncertainties.

In this regard, a general independence of the residual nutrient loads with respect to the rainfall variables was evidenced, except for the concordant correlation of the first flush strength and the antecedent dry weather period. This behaviour can however be explained by considering the peculiar combination of the sewer network hydraulics, the pollutant parameters, the catchment hydrology and the climate characteristics, and it confirms once more the site-specific nature of the pollutant transport dynamics.

Despite alternative approaches were recently advanced to detect and quantify the first flush phenomenon, the cumulative dimensionless load curves still maintain a general validity for practical application purposes. Indeed, the difficulty of relating the single curve to the overflow volume can be easily overcome, when such curves are implemented inside Monte Carlo simulations. Conversely, more sophisticated approaches, namely non-parametric statistical analyses, can provide deep insights of observed pollutographs, but they are hardly implementable in verification and design procedures and are computationally intensive.

With regard to the case study, this analysis suggests that, despite the construction of a combined sewer pipe along the eastern lake shore, which collects and conveys the sewage outside the lake watershed, significant amounts of TN and TP are still delivered to the lake during most rainfall events due to the occurrence of CSOs along the municipal sewers. A conservative evaluation of the percentage of nutrients loads delivered from the Corte Franca sewer that are still discharged to the lake ranges between 13.3% and 22.2% for TP and to 20.5%–41.1% for TN. These values are much larger than the ones reckoned during the initial design of the main sewer around the lake and the results provide, for the first time in this environmentally fragile area of Italy, a sound basis to propose and design valuable mitigation measures.

On average, the measured first-flush phenomenon showed to be moderate-weak, though its strength is significantly correlated with the duration of the antecedent dry-weather period. This statistical relationship can be justified by the very low sanitary sewage flow rates during dry weather conditions, leading to the accumulation of significant deposits of organic matter in various parts of the sewer network.

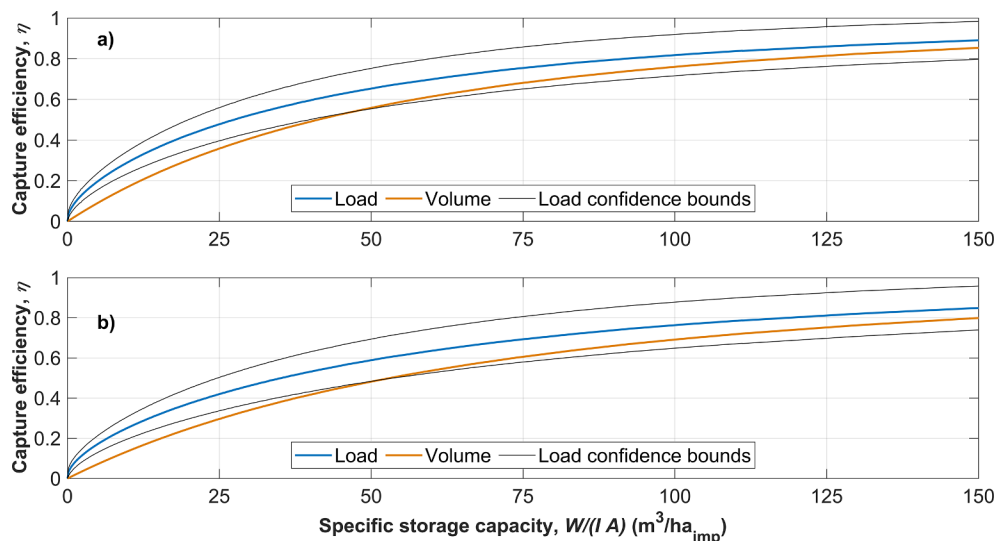


Fig. 8. Efficiency curves of a capture tank for different detention periods 48 h (a) and 96 h (b).

However, despite the large annual overflow volume and the absence of a systematically strong first flush, a small water quality volume must be provided downstream of the monitored CSW for a capture storage tank to be effective. This outcome is mainly due to the high number of overflow events, which convey modest discharge volumes (less than 200 m³). A tank sized according to the standards enforced by regional regulations, that is a capacity of 50 m³/ha_{imp} (1300 m³) and an average detention time of 96 h, could be able to achieve a mean capture efficiency equal to 60%. A storage capacity of 75 m³/ha_{imp} (2000 m³) managed by using a more reasonable detention time of 48 h, would increase the efficiency to 75%. Accordingly, also considering the generally low permeability of this moraine watershed, which hinders the general adoption of alternative urbanization mitigation practices, an end-of-pipe storage structure emerges as a technically sound solution to mitigate the impact of CSOs on the lake.

Declaration of interests

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

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Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jhydrol.2019.01.031>.

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