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Exploring the performances of a new integrated approach of grey, green and blue infrastructures for combined sewer overflows remediation in high-density urban areas

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Abstract

Most sewage collection systems designed between 19th and early to mid-20[th] century use single-pipe systems that collect both sewage and urban runoff from streets, roofs and other impervious surfaces. This type of collection system is referred to as a combined sewer system. During storms, the flow capacity of the sewers may be exceeded and the overflow discharged into a receiving water body (RWB) through spillways without any control and remediation. Combined sewer overflows (CSOs) may, therefore, produce serious water pollution and flooding problems in downstream RWBs. Methodologies for a rational management of CSOs quantity and quality share many commonalities, and these two aspects should be considered together in order to maximize benefits and promote local distributed actions, especially in high urban density areas where the space availability for the construction of CSO storage tanks is often a limiting factor. In this paper, a novel strategy to control downstream flow propagation of a CSO as well as to improve its quality is tested on a real case study in the area of the metropolitan city of Milan. The approach is based on the combination of grey, green and blue infrastructures and exploits the integrated storage and self-depuration capacities of a first-flush tank, a constructed wetland and a natural stream to obtain admissible flow rates and adequate water quality in the RWB.

The results, evaluated through a modelling framework based on simplified equations of water and pollutants dynamics, show excellent performances for the integrated system, both in terms of flow control and pollution mitigation. The pollution, using biological oxygen demand concentration as a proxy of the whole load, was decreased by more than 90% and downstream flooding situations were avoided, despite the spillway was not regulated. Concerning the economic point of view, from a rough estimate of the costs, the system allows reducing the investment of 30 to 50% in respect to the traditional CSO controls based solely on flow detention tanks. The proposed approach, as well as the modelling framework for its effective implementation, appear strongly scalable in different world contexts and aim to fill the gap between urban and rural environments in the management of stormwater and CSOs, promoting the involvement of the water managers, the irrigation-reclamation agencies and regional authorities.

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See online Appendix for additional material.

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Introduction

The rapid and frequently disordered urban development of many areas in the world, associated with the tendency of increasing mean and maximum daily precipitation heights (Todeschini, 2012), affects rainfall-runoff processes and pollutants fate and transport in such areas, inducing a significant reduction of the efficacy of the existing urban sewerage systems. The consequences of these phenomena affect particularly the combined sewerage systems (CSSs), where a unique network of laterals, mains, and outfall sewers serves for all types of sewage and runoff. These sewerage systems are common in many urban areas, in Italy and elsewhere. U.S. EPA (2008) estimates that in the areas around the Northeast, Pacific Northwest and Great Lakes in the U.S.A. more than 700 communities with a total population of more than 40 million are served by a CSS. In Europe, about 2/3 of inhabitants are connected to CSSs in Germany, and in Italy about 60% of sewer networks consist in CSSs (Weyand, 2002; Carbone *et al.*, 2014; Utilitalia, 2017). During severe storms, the flow capacity of this kind of sewers can be exceeded, and the overflow diverted into a receiving water body (RWB) through spillways. An increase in the frequency of spillways activation has been observed in the last decades and this trend is expected to continue in the future. A recent study of Brzezińska *et al.* (2016), carried out on a study area of about 211 ha in the Region of Łódź (Poland), showed that the number of overflows was different every month and every year, and varied from 9 to 23 between 2012 and 2014. The total amount of untreated wastewater discharged to the RWB during one year ranged from about 3600 m^3 to 92,258 m^3. The frequent activation of spillways in the CSSs is in part due to their constructional characteristics. Indeed, they are usually designed to activate with a discharge greater than two times the amount of blackwater flow occurring on average during dry periods over the year. This flow, in turn, is estimated exclusively based on water endowment per capita, meaning that the activation of CSS spillways depends almost entirely upon the number of inhabitants at the time the sewerage system was designed. Accordingly, the design of spillway's threshold does not consider the real impervious area and future potential land use changes or rainfall pattern modifications. In the Padana plain, the spillway activations on average in a year can vary between 50 to 70 (up to 80-90 in the mountain regions) with an average discharge duration that is long enough for delivering about 70-80% of the total pollution load flowing in the sewer system (as reported in *Guidelines for first-flush management* of the Emilia-Romagna region no. 1860 of 18 December 2006). Consequently, combined sewer overflows (CSOs) in many cases produce significant water pollution and flooding issues in the RWBs. CSOs contain untreated or partially treated wastewater along with stormwater.

CSOs are a water pollution concern for municipalities served by CSSs, as it is the case for the metropolitan city of Milan, since uncontrolled and unmanaged CSOs are directly discharged in natural and artificial RWBs. In the context of the metropolitan city of Milan, the RWBs are often rural channels that are part of a dense and ramified network mainly intended for irrigation and drainage of rural areas. The continuous release of CSOs in these RWBs can increase the risk of a chronic pollution, affecting water used in agricultural and environmental contexts (*i.e.*, for crop irrigation and, indirectly, aquifer recharge).

The possibility of controlling CSOs through an integrated management of CSSs and RWBs could be very promising, despite it has been explored to a very limited extent so far, also because very often different subjects are responsible for the management of the two systems (*i.e.* CSSs and RWBs). In the past, the increase of drainage capacity of the sewer systems appeared as the only viable measure for managing runoff discharged in the CSSs, removing the excess of water from the urban areas but, in many cases, increasing the risk of flooding and pollution impact on downstream natural streams (Piro *et al.*, 2010). However, this approach requires large investments and areas, making it barely feasible, especially in territories with high density of urbanisation (Carbone *et al.*, 2014). New approaches have been widely studied in the last years, in the quest for alternative ways to mitigate runoff from impervious surfaces as well as reducing flows and pollutant loads in urban drainage system, and, consequently, in CSOs (Dietz, 2007; Ahiablame *et al.*, 2012). Such approaches are identified by several acronyms [urban low impact development (LID), sustainable development systems, *etc.*; Fletcher *et al*., 2014]) and refer to systems and practices to manage stormwater as close to its source as possible that use or mimic natural processes resulting in the infiltration, evapotranspiration or use of stormwater in order to protect water quality and associated aquatic habitat. Despite many model-based results confirm the role of LID and similar solutions in restoring natural flow regime at the urban catchment scale, their effectiveness depends on their spatial distribution, that is often in conflict with the location of areas that could be requalified (Fry and Maxwell, 2017). Moreover, recent studies show that sustainable approaches are more effective for frequent storms of smaller magnitude than for rare storms of larger magnitude (Loperfido *et al*., 2014; Fry and Maxwell, 2017), which is partly in contrast with the evolution of the rainfall trends, that show a global increasing tendency in maximum daily precipitation height (Todeschini, 2012).

Therefore, it appears suitable to explore an integrated approach that exploits the benefits of different CSO control strategies, combining grey, green and blue infrastructures (GGBIs) and paying attention to the consequences of downstream flow and pollutant propagation. This approach is based on flow and pollutant load controls through natural water retention measures and constructed wetland (CW) systems. Such low-cost and low-energy treatment techniques through soil and vegetation (macrophytes) activity reproduces natural water purification processes (Toscano *et al.*, 2015), and in combination with small first-flush tanks (FFTs) provide significant reductions in flow and pollution load, preserving ecosystem from wastewater impacts (Masi *et al.*, 2017).

Such an integrated approach is also supported by water laws and regulations at the European (*e.g.*, Water Framework Directive 2000/60 CE), national (*e.g.*, Italian Legislative Decree. n. 152/2006), and local level (Lombardy Region Decree n. 48 of 23 November 2017). In this perspective, no single standardised solution can be considered conclusive at all locations and combined structures must be developed. The complexity of the processes involved, therefore, asks for models that are able to reproduce the behaviour of the different components (*i.e.* FFT, CW, RWB) for a correct design the whole system.

In the following, we present a tailored combination of GGBIs to mitigate the impact of CSOs flow and pollutant loads, as well as the setting up of a parsimonious simplified integrated model, which provides both water-quantity and water-quality simulations for each component of the system. In particular, the approach includes retrieving geomorphological characterisation of RWBs through LiDAR data analysis. The model framework and the approach proposed in this work would be scalable in different world contexts and, in particular, it is expected to respond efficiently to specific design questions frequently rising in high-density urban areas where the planning of CSOs mitigation measures is affected by the lack of available spaces.

Materials and methods

The combined grey, green and blue infrastructures approach

The proposed approach is mainly based on exploiting detention, infiltration and self-depuration capacities of CW and RWB components in order to mitigate respectively peak discharge, volumes and pollutions of CSOs. A FFT is also considered, especially to reduce the heavy metal concentrations, which are expected to be found in the very first foul flush, which might undermine survival of plants in the other two components and contaminate the environment. However, the volume of FFT is not derived from the traditional *a priori* criteria (*i.e.* based on harvesting of the first 2.5-5 mm of rainfall), usually adopted according to Italian standards

(Becciu and Paoletti, 2009). The volume of FFT is designed together with CW and RWB components in order to have a whole system providing a pollution abatement close to water quality requirements for agricultural and environmental uses (*e.g.* as imposed by ISO 16075 *Guidelines for treated wastewater in irrigation* or *Guidelines for interpretations of water quality for irrigation* provided by FAO56 manual).

The design phase is based on the application of a mathematical model of the water-quantity and water-quality interactions between FFT, CW and RWB. The three components are assumed to behave as well-mixed reservoirs connected in series (Figure 1), where FFT and CW have the shape of a parallelepiped, while RWB is constituted by a series of irregular shaped reservoirs with storage capacities and stage-volume relationships defined according to the RWB geometry.

The phytodepuration effect in the CW, as well as the RWB self-purification capacity, is represented by a first order degradation kinetic (Freni *et al.*, 2008). The interaction among the components is the following: the CSO is diverted to FFT until it reaches its full capacity (providing the so-called *vertical cut* of hydrograph and pollutograph), then it is by-passed. The water, therefore, flows into the CW through a weir. The CW is a vegetated free water surface system, not lined and provided with storage capacity, which allows both vertical fluxes (through infiltration) and horizontal runoff towards the RWB, similar to natural systems for agricultural drainage water treatment (Lavrnić *et al.*, 2018). In general, the RWB is part of an extensive and ramified network of artificial channels and natural streams, which in many cases may offer significant storage capacities. RWB is conceived as a reservoir achieved using a regulating weir able to maintain both upstream storages and downstream flow controls. The phytodepuration effect in the CW and RWB changes in accordance with the residence time of water in these two components. In the former, the residence time might be modulated changing the CW area or the weir height, while for the latter only changing the weir height. The goal of the model application is to evaluate the discharge and pollutant load abatements depending on the system design, *i.e.* on the size of the three components and on the flow regulation in the CW and RWB.

A detailed description of the model equations is provided in Appendix.

The case study

The case study area is included in the metropolitan city of Milan, which is about 2000 km^2 large and it is characterized by more than 70% of urbanized areas, 134 municipalities with about 3 million of residents in total. In most cases the urban drainage networks (managed by a single integrated water service manager -

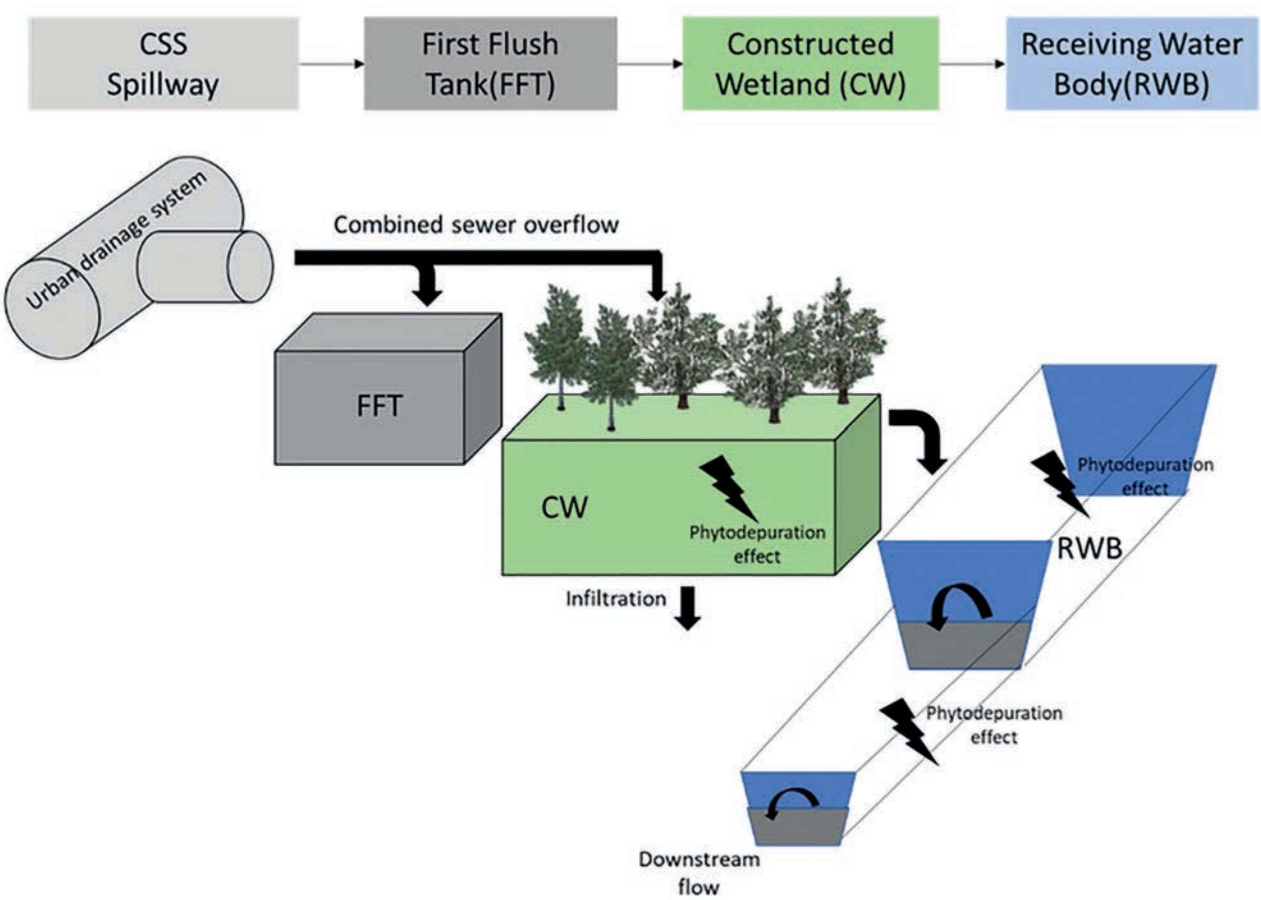

Figure 1. Schematic representation of the integrated grey, green and blue infrastructure system. In figure, the outline of each component and its connection with the other elements of the system is shown. In particular, the spillway of the combined sewer system (CSS), the first-flush tank (FFT), the constructed wetland (CW) and finally the receiving water body (RWB) are presented.

CAP Holding Ltd.) are constituted by CSSs, with a total of about 800 spillways in the whole area, where RWBs are very often rural channels. The presence of residual agrarian lands interconnected with the urban fabric makes this territory suitable for testing the proposed approach. In particular, in the municipality of Sedriano the water manager needs to deal with the problem of a CSO which discharges onto an area of about 1 ha (Figure 2), which is flooded several times every year and from which the overflow water mostly infiltrates into the soil and evaporates to the atmosphere. The area is close (about 150 m) to a semi-abandoned channel (named Fontanile Casa) that currently is not connected to the area, though the difference in elevation would allow gravity-driven flow (Figure 2).

The Fontanile Casa channel is about 3.2 km long and at the end the water is spilled directly into a field. In some points of its distal side, the Fontanile Casa is interconnected to the irrigation channel network. In particular, through a bridge-channel and a straight side weir (section 5-5 and section 7-7 in Figure 3, respectively) the irrigation channel network spills water into the underlying Fontanile Casa, as shown in Appendix Figure 1. These interconnections aim to increase the flow of the Fontanile Casa in order to provide a sufficient amount of water for the irrigation requirements of the surrounding fields. Moreover, along the Fontanile Casa there are gates, to allow water diversion to the fields, and culverts at the crossings with road infrastructures (Appendix Figure 2); hydrodynamic simulations using EPA-SWMM model (Huber and Dickinson, 1988) showed that they do not significantly affect the flow propagation.

Technical configuration

The Fontanile Casa and the new requalification project based on the combination of grey (FFT), green (CW) and blue (RWB) infrastructures are sketched in Figure 2. In order to take into account that channel width and height progressively decrease from the start to the end of its path, the RWB was subdivided in five portions according to changes in shape and pattern, each one represented by a linear reservoir. In particular, referring to Figure 3, portion I is from section 1-1 to 2-2, portion II from 2-2 to 3-3, portion III from 3-3 to 5-5, portion IV from 5-5 to 7-7, and finally portion V from 7-7 to the end. At the end of each portion the flow is supposed to be regulated through a weir, whose height is designed in order to control both flow and pollution level.

The FFT volume and CW area are mainly designed to reduce the pollutant load, whereas for the RWB (*i.e.* Fontanile Casa) the maximum storage capacity of each portion was detected by LiDAR data (*i.e.* DTM with 1x1 m of resolution). Stage-volume relationship of each portion was calculated using *Drainage Channel Builder* plugin of QGis and DTM information, sectioning vertically each portion of the channel at different height-steps (Cazorzi *et al.*, 2013). LiDAR data was also employed to detect cross sections of the channel, especially where inaccessible, and the procedure was validated through in-situ surveys carried out by portable GPS (GR-5, Topcon, Ancona, Italy) and total station (GT500, Topcon). The geomorphological analysis and related results are described in detail in the following.

Dataset and model settings

The model requires in input time series of flow and pollutants concentration. In this work, a real CSOs event occurred at Sedriano spillway on 5th August 2016 was used for testing the model and the approach. The overflow was caused by a rainfall event of about 20 mm falling in 1 h on Sedriano urban basin, and which led to a CSO peak of about 2500 L/s. The flow was measured at the spillway at 1-min time-step by a flow meter (KaptorMulti, BM Tecnologie, Milano, Italy). Since quality measurements of CSO were not available (a water quality sampler has been installed only recently), the potential pollution was derived from literature data (Freni *et al.*, 2008) obtained for an urban catchment of the city of Bologna (San Lazzaro), whose characteristics are very similar to those of Sedriano. In particular, both sites drain a urban area of approximately 100 ha, about 60% of which are impervious, with around 10,000 inhabitants.

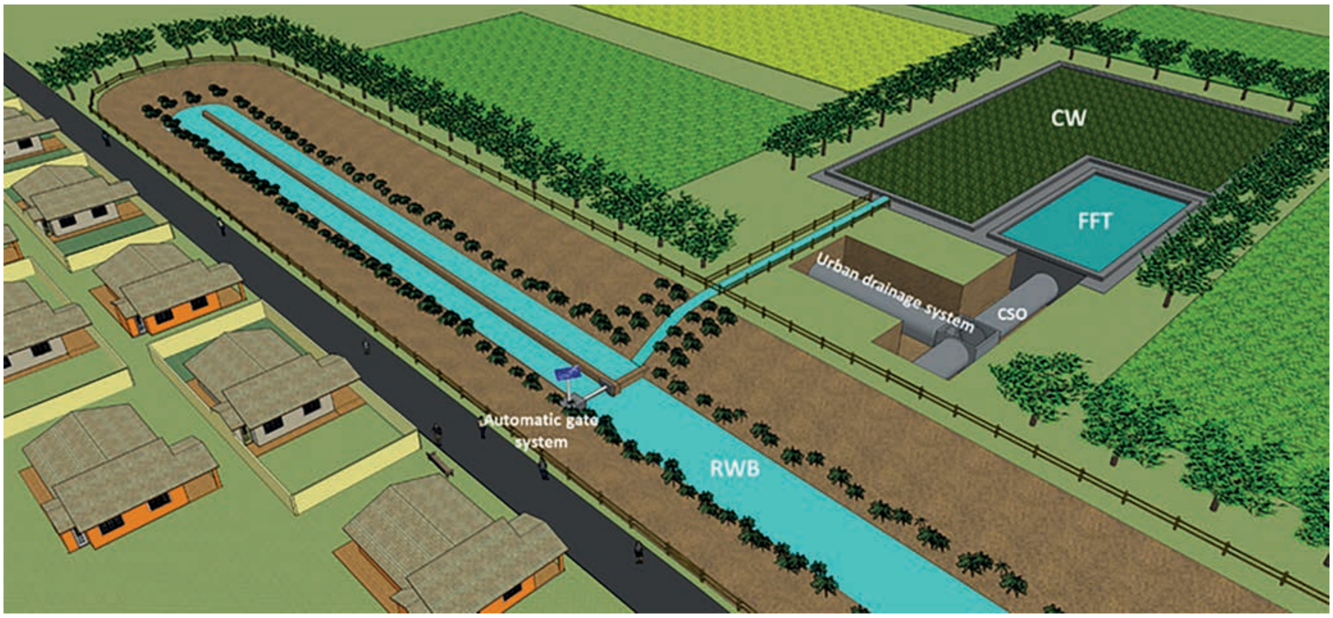

Figure 2. Rendering of the potential integrated system of grey, green and blue infrastructures in the case study of Sedriano. CW, constructed wetland; FFT, first flush tank; CSO, combined sewer overflow; RWB, receiving water body.

The phytodepuration effect is tested considering biological oxygen demand (BOD) as a proxy of the whole pollution level in the CSO. The same range of degradation constants, from 20 to 60 day^{-1}, is assumed for both the CW and the RWB, as suggested in Freni *et al.* (2008).

A flow *vs* pollutant concentration linear regression analysis was performed in order to obtain a general law for deriving BOD levels in the CSO based on flow rate (Barco *et al.*, 2008). The slope of cumulative mass concentration against cumulative flow was about 7 kg/m^3 (null intercept and R^2 equal to 0.89) with pollution peaking about 20 min before the peak flow. The hydrograph of Sedriano CSO (observed) and the corresponding BOD pollutograph (derived) are shown in Figure 4. The pollution peak is of about 1100 mg/L 7 min after the beginning of precipitation. Similar results were obtained by Suarez and Puertas (2005) for BOD in different urban catchments in Spain.

In the last two portions of the channel, a constant external water inflow of about 50 L/s was considered in order to evaluate the hydraulic behaviour of channel when CSOs occur during the irrigation period.

Results and discussion

Comparison between LiDAR data and *in situ* measurements

The channel longitudinal profile was derived directly from DTM and the results are shown in Appendix Figure 3. The overall height difference is about 1 m (mean slope of about 3‰) with a highly irregular profile and some stretches in counter-slope.

Good concordance between LiDAR data and in-situ cross-section measurements is obtained from the analysis, as shown in Figure 5. Two types of channel morphological characteristics were tested in order to validate the cross-section estimation procedure over different channel features (*i.e.* lined - Figure 5A and B - and unlined - Figure 5C and D - one). In both situations, LiDAR data slightly underestimate the surveyed channel cross-sections, as well as it is evident that the DTM constraint (*i.e.* the limited resolution 1x1 m) makes inapplicable the reading of cross-section geometry especially when the channel width becomes smaller than 1 m (Figure 5D). However, linear regression technique indicates that, in general, a good agreement between LiDAR data and *in situ* elevation measurements occur, as shown in Appendix Figure 4, where all detected points are compared. The points are classified according their RWB portion membership, showing outliers especially in portion I and III

Figure 3. The case study and the structure of the integrated system of grey, green and blue infrastructures constituted by first flush tank (FFT), constructed wetland (CW) and the channel receiving water body.

namely where dense vegetation on the banks could have affected the quality of LiDAR data. Nevertheless, the linear regression coefficient is very close to 1, while the determination coefficient (R^2) is about 0.75. This indicates that the proposed methodology based on detection of channel geometrical features by high-resolution LiDAR data is accurate and robust for detecting channel cross-sections especially where low-vegetated ditches occur.

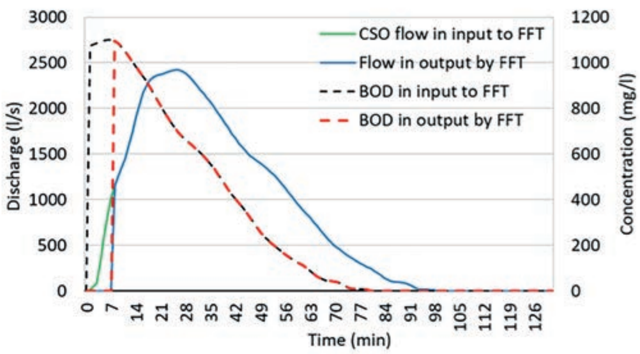

Figure 4. Flows and concentrations in input and in output to first flush tank (FFT). CSO, combined sewer overflow; BOD, biological oxygen demand.

Stage-volume relationships from portion I to III have been calculated directly by DTM data (Appendix Figure 5A-C), whereas the cross-sectional shapes of portion IV and V have been detected by in-situ surveys, and approximated with a triangular section as a result their small width and height (Appendix Figure 5D and E). Maximum storage volume for each portion was calculated taking into account the constraints of: i) avoiding backflows in CW concerning the portion I; and ii) considering a free board of about 20 cm in portion II and III and 10 cm in portion IV and V. The values are 2500 m^3 (I portion), 608 m^3 (II portion), 593 m^3 (III portion), 627 m^3 (IV portion) and 407 m^3 (V portion). Therefore, the maximum free water level in each portion is respectively 1.25 m (I portion), 1.16 m (II portion), 0.77 m (III portion), 0.63 m (IV portion) and 0.55 m (V portion).

Components design

We carried out a modelling experiment in order to assess the impact of each of the three system components on the flow and water quality downstream from the CSO outfall. Particular attention was dedicated to reduce as much as possible the dimension of the FFT in order to: i) cut costs; ii) reduce the environmental impact of the grey infrastructure; and iii) promote the use of natural components (*i.e.* CW and RWB) and their self-depuration capacity. Following these criteria, the volume of FFT was designed in order to store the first foul flush just after the peak of the concentration in input. A FFT volume of 180 m^3 is sufficient to store

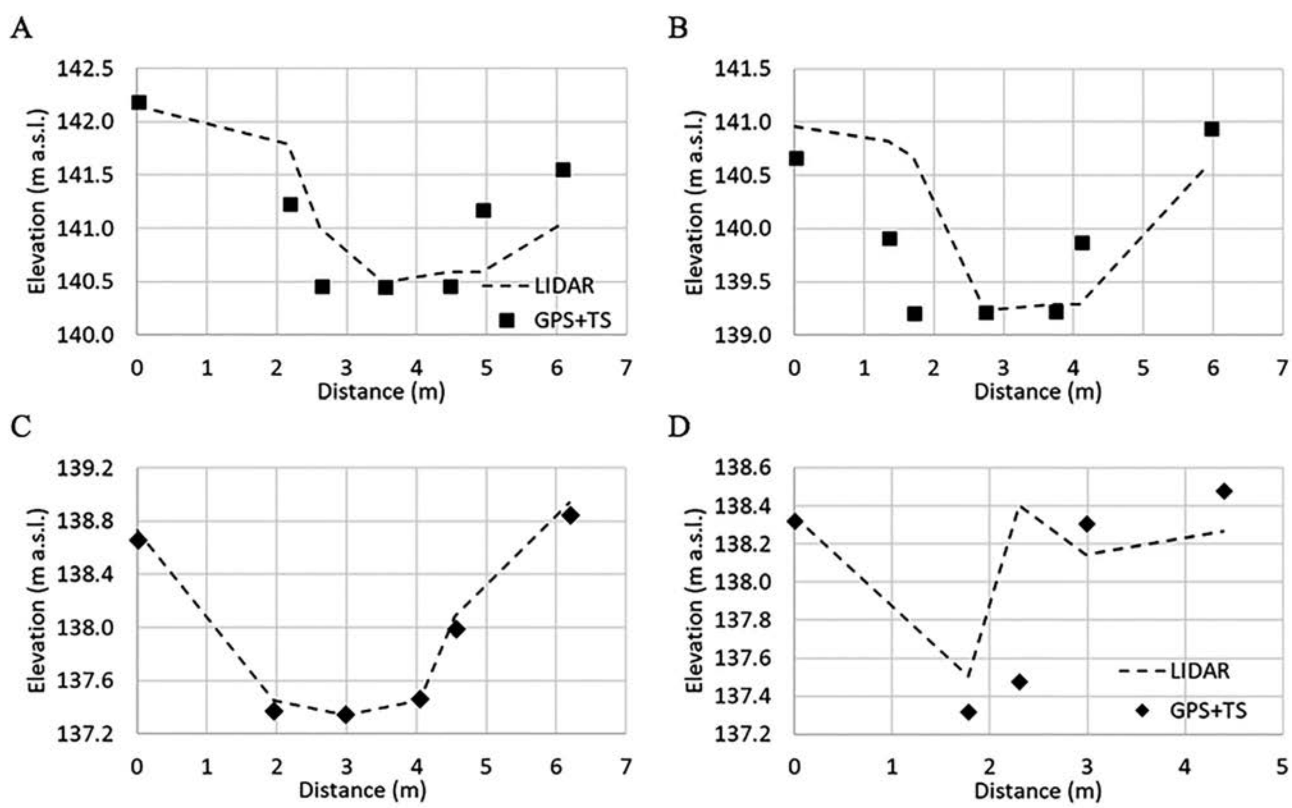

Figure 5. Example of cross section geometry as depicted by the LiDAR (dotted line) compared to the surveyed ditch geometry (black points). (A) Section A-A (lined channel), (B) section B-B (lined channel), (C) section 3-3 and (D) section 8-8 (both unlined channel). GPS, global positioning system; TS, total station.

the pollution load from the beginning of the spill up to reaching the peak concentration of 1100 mg/L (Figure 5). The FFT allows then storing about 22% of the total BOD discharged by the CSO. The volume of FFT is well below the operational standards of about 25-50 m^3 per hectare of impervious area (Becciu and Paoletti, 2009), which in the considered case would amount to a FFT of about 2250-4500 m^3.

CW was designed as a vegetated pond (*i.e.*, as a free surface flow constructed wetland) of about 3500 m^2 with an overflow weir 1 m high and 2 m long. The infiltration was modelled by Horton equation with a maximum and minimum infiltration rate of 250 mm/h and 25 mm/h respectively, and a decay constant equal to 2 h^{-1} (soil belonging to the group A of the SCS table) (SCS, 1956). The input hydrograph has a peak of about 2500 L/s, while the peak of concentration is about 1090 mg/L (Figure 6). The CW stores about 3400 m^3 of water, 660 m^3 of which infiltrate into the soil. The peak of the outflow from the CW component is about 900 L/s (about 62% of reduction), and the corresponding peak of concentration ranges from about 500 to 700 mg/L (45-62% of reduction). The remaining part of flow is delivered to RWB that was designed as a sequence of segments separated by overflow weirs. As a first approximation, the overflow weirs were considered fixed at 0.6, 0.5, 0.4, 0.3 and 0.2 m respectively from segment I to V. These heights were chosen according the cross-section characteristic of each segment, its maximum height and width. In Figure 7 the water and mass balances for each RWB portion are shown. In all cases the water level in each segment is well below the maximum storage capacity, whereas in portion IV and V the hydraulic and quality effects of the constant surplus flow of 50 L/s spilled in the channel are shown. The peak outflow from the last segment is only about 150 L/s, with a peak of pollutant load ranging from 4.7-6.9 mg/L (99.4% reduction with respect to the initial BOD peak concentration). These values are well below the BOD threshold for *good quality* water bodies according to the Italian regulation (D.Lgs 152/2006), *i.e.* 25 mg/L.

The RWB alone was able to reduce about 50% of the total BOD discharged by CSO after just 3 h from the initial input. The sequence of weirs in the RWB provides, moreover, a control of the flow velocity, obtaining a maximum value of about 0.6 m/s. In the last two portions of the Fontanile Casa (IV and V portion) the added constant inflow of 50 L/s causes a significant increase of the water level in the channel, up to 0.4 m in segment V (however well below to the safety limit of 0.55 m).

The high BOD removal efficiency achieved by GBBI system is mainly contingent upon the capacity of each component to store CSO as well as to modulate the effluent flow. Moreover, the combination of long residence times, water removal by infiltration in CW and, finally, dilution in the last part of the RWB appear the most effective factors that allow obtaining, at the end of the treatment process, BOD concentration below the limits of law. A rough estimate of the costs shows that the total construction cost of the proposed system amounts to approximately 650,000 € (70,000 € for FFT, 210,000 € for CW and 370,000 € for RWB requalification), compared to the ca. 870,000 - 1,500,000 € of the traditional approach considering a FFT of an estimated capacity between 2250 and 4500 m^3.

Concluding remarks

This study was aimed at providing evidence about the possibility to adopt low-cost and low-energy grey-green-blue infrastructures for mitigating peak flow, volume and pollution loads of CSOs in high density urban areas. In particular, the proposed approach exploits detention, infiltration and self-depuration capacities of natural systems already existing in peri-urban areas, in order to achieve a tailored solution that is suited to the specific context.

The main findings of the case study presented in this work show that: i) high-resolution (1 m) DTM derived from LiDAR data allowed rapid mapping of the main geomorphological features of the channels, especially for low-vegetated channels with width of the same order of the DTM resolution; ii) the combination of FFT with a constructed wetland system (CW) and finally the management of the flows in the receiving water body (RWB) allowed to obtain more than 90% of pollutant load abatement avoiding, furthermore, the risk of downstream flooding situation. The peak of pollutant load decreased from about 1100 mg/L to 6 mg/L well below the Italian regulation limit for environmental protection (*i.e.* 25 mg/L), whereas the flow peak decreased from about 2500 L/s to 160 L/s despite a water surplus of 100 L/s was spilled between por-

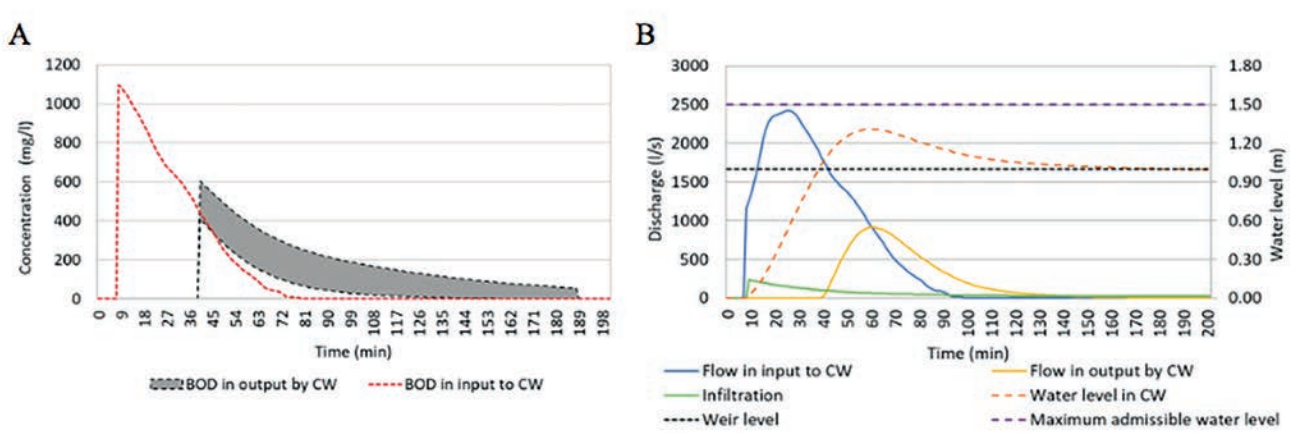

Figure 6. Flows and concentrations in input and in output to constructed wetland (CW). Mass (A) and water (B) balances. BOD, biological oxygen demand.

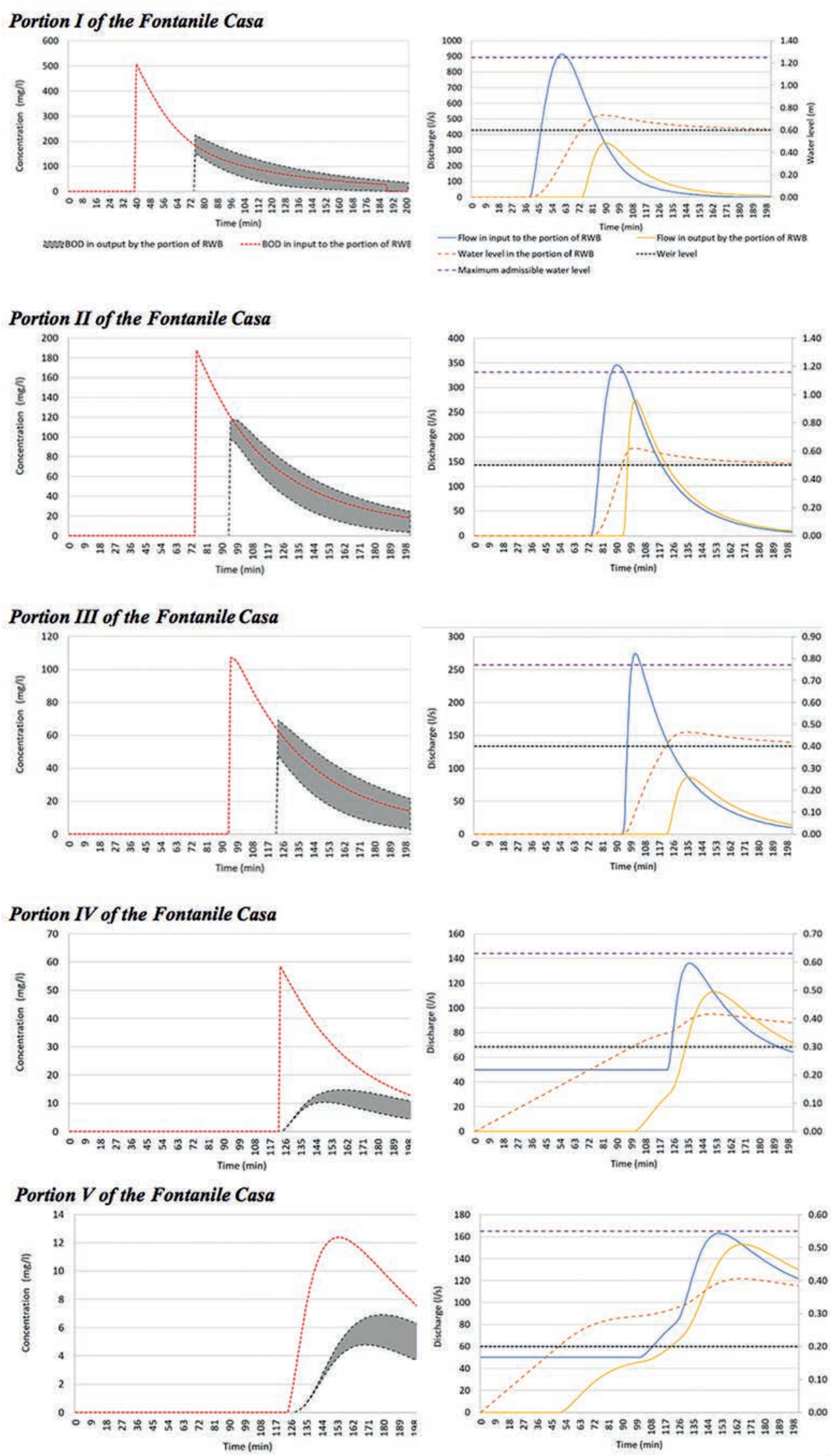

Figure 7. Flows (on the left) and concentrations (on the right) in input and output to the different portions of the Fontanile Casa. BOD, biological oxygen demand; RWB, receiving water body.

tion IV and V of the channel. Therefore, the system can be simultaneously designed to pursue flood risk reduction (abatement of flow peak) and improvement of receiving water quality objective; iii) the use of already existing grey, green and blue infrastructures allowed to reduce the space needed for CSOs storages from 1 ha in the current status to about 0.3 ha (sum of CW and FFT areas, the latter supposing a tank of 2 m height); iv) the overall cost for the construction of the integrated system is estimated to range from about 30 to 50% less than the traditional alternative solution of constructing of a larger CSO detention tank only. Nevertheless, further economic analysis need to be performed in order to evaluate the maintenance costs of each component.

Each component of the proposed system has some peculiarities. For example, CW performs a dual function, *i.e.* on one hand it cuts the peak of flow thanks to its storage capacity, while on the other hand it reduces the volume thanks to its infiltration capacity. These features are most important especially in the context of *hydraulic-hydrologic* invariance measures (that are becoming more and more present at local scale in Italy and elsewhere) (Masi *et al.*, 2017) where the reduction of peak discharge has necessarily to be accompanied by a reduction of volumes. Further improvements can be obtained through the control of flow in the RWB aimed to maintaining a correct ratio between upstream accumulation and downstream flow according to: i) the variability of flow in input to the RWB; and ii) the downstream channel hydraulic capacity. Improved flow control could be achieved by installing smart gates that operate automatically based on flow sensors and software-based actuators. Finally, the additional ecosystem services that can be provided by the green components of the system combined with the relatively low-cost of the interventions make the approach particularly attractive for small municipalities where large investments are seldom possible.

Therefore, results show the potential of exploiting natural systems and their self-depuration capacities in CSOs management, controlling both water and pollution loads by combining flow controls and storage mechanisms. Moreover, the adoption of a simplified mathematical model supported by LiDAR data analysis appears very useful in the design phase of the integrated system, allowing the exploration of the performances of each component in terms of remediation and flow control.

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