

Hydrologic performance assessment of nature-based solutions: a case study in North-eastern Italy

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Abstract

The consequences of climate change are exacerbated by land-use changes, which influence rainfall-runoff relations and, consequently, flood risk. Effectively, urbanisation is steadily contributing to increasing impervious areas and reducing the time-to-peak. The effect of nature based solutions (NBSs) on mitigating these phenomena is recognised. Nevertheless, these kinds of sustainable infrastructures are still barely known and scarcely adopted in many parts of European Countries. The LIFE BEWARE project aims to enhance hydraulic safety and spread good practices in rainwater management by promoting and facilitating the adoption of NBSs in the Altovicentino area (Northern Vicenza Province, Veneto Region, Italy). To support the dissemination activities, some full-scale NBSs have been created within the municipality areas involved in the project. The hydrological impact of the structures is continuously monitored thanks to the installation of devices measuring inlet and outlet runoff and rainfall patterns. This study aims to analyse the monitoring data of the first two years of the built NBSs. Results show that the structures managed almost all the water runoff through processes of infiltration and retention, providing additional insights into understanding the real

behaviour of NBSs exposed to the specific environmental conditions of a very rainy foothills area. In particular, mean rain intensity and rainfall duration are the variables that mostly affected the structure performance, especially for events prolonged over time (2-3 days) with mean rainfall intensity in the range of 2-3 mm/h. Therefore, the overall outcomes from this analysis were useful for improving the design of NBSs and further promoting their installation in urban areas.

Introduction

Climate change affects the precipitation regime of different regions worldwide, increasing the frequency and magnitude of rainfall events (Brunetti *et al.*, 2009). This trend is expected to increase shortly as a consequence of global warming (Wilhelm *et al.*, 2012). Different trends have been identified in the Mediterranean region by analysing the rainfall events of the last decades in terms of duration and intensity. According to Alpert *et al.* (2002), the increase of events classified as heavy-torrential and a decrease of prolonged and less intense phenomena is highlighted on the Italian territory. In addition, the increasing population growth and land use change have exacerbated the consequences of intense rainfall events (Swain *et al.*, 2020) because an increasing number of people and goods are exposed to flood hazards (Hirabayashi *et al.*, 2013). In this context, different mitigation measures have been developed and applied to mitigate the hydrological risk and further increase the population's resilience against its consequences (Maragno *et al.*, 2018). Among these, natural water retention measures can play a fundamental role in moderating the climate-related challenges of flood hazards (Ruangpan *et al.*, 2020). They can reduce the surface runoff and peak discharge rate and increase the time lag between rainfall events and peak discharge (Bettella *et al.*, 2018; Ishimatsu *et al.*, 2017). The use of nature-based solutions is also favoured by different national and international communities (Faivre *et al.*, 2017) since they can significantly reduce the consequences of floods in urban areas and increase the resilience of citizens living in flood-exposed regions (Apollonio *et al.*, 2021; Ruangpan *et al.*, 2020).

Nature Based Solutions (NBSs) or LID (Low Impact Development) are measures designed to decrease the hydro-meteorological risk based on the different systems observed in nature (European Commission, 2015). They can be divided into small- and large-scale NBSs according to their extent and the total volume of water they can manage (Church, 2015). In urban areas, small-scale NBSs are preferred for their capacity to reduce the effects of water runoff generated by a certain city area (Chan *et al.*, 2018; Stanchi *et al.*, 2021). The effectiveness of NBSs depends on the frequency and magnitude of rainfall events and the type and design characteristics of NBSs. In particular, Ishimatsu *et al.* (2017) report that rain gardens have high efficiency in managing small discharges of water runoff, while swales and permeable sur-

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faces resulted more efficient in case of heavier rainfall events (Zölch *et al.*, 2017). However, other studies observed opposite trends, as reported by (Bortolini and Zanin, 2018; Jennings *et al.*, 2015), because many factors affect the efficiency of these kinds of structures. One of these is the moisture condition before the peak of rainfall that could significantly alter the effect of peak discharge reduction, as Bettella *et al.* (2018) demonstrated for green roofs.

Consequently, monitoring NBSs is fundamental to adequately assess their performance in terms of mitigation of surface runoff, peak discharge, and facilitation of water infiltration (Biddoccu *et al.*, 2014; USEPA, 2000). Some studies reported the effectiveness of NBSs in terms of both hydraulic efficiency and pollutant reduction (Eckart *et al.*, 2017; Wilson *et al.*, 2015). In literature, several studies principally investigated NBSs analysing the managed water volume with respect to the total runoff, the infiltration rate, the peak discharge reduction, and the peak time delay. Such results depend on both the intrinsic characteristics of the structure and the precipitation pattern. The latter is used to size NBSs, with the aim to mitigate the volume of water derived by the first peak flush of the storm for a given return period, as reported in different guidelines (MNCPA, 2007; WIDNR, 2010).

Nonetheless, different rainfall patterns can also affect the efficiency of NBSs, especially when the duration of the events increases, as shown in Hunt *et al.* (2008). However, today, the evaluation of hydrological performances based on different types of rainfall patterns is seldom investigated. Therefore, more studies monitoring NBSs are necessary to improve the design and size of future facilities in different environmental settings and climatic regions (Jiang *et al.*, 2020). In particular, this study aims to investigate the relation between rainfall patterns and NBSs performance regarding water volume inflowing and outflowing. Within the Life project 'BEWARE' three NBSs have been designed, realised, and equipped with sensors to monitor the water volume constantly. In addition, a rain gauge has been appositely installed to detect the rainfall pattern. The relation between NBSs efficiency and the characteristics of the rainfall events recorded in two years has been statistically analysed, finding out the most critical conditions. Thanks to these outcomes, the research is dedicated to providing new insights into the design and size of NBSs, aiming to improve the control and management of the water runoff caused by different types of rainfall events.

Materials and Methods

Study area

The monitored NBSs are located in the northern Province of Vicenza (Veneto Region, north-eastern Italy) and, more precisely,

in the municipality of Santorso. In 2019 three structures funded by the BEWARE project were created to tackle local flooding problems by increasing water infiltration and reducing runoff water. The area of the Santorso municipality is located at the foot of the first mountains of the southern Alps, at an elevation of around 200 m a.s.l. (above sea level). The area is surrounded by mountain peaks to the north direction, while to the south, it faces the Veneto Plain. Due to the particular topography of the area, it is recognised as being among the rainiest sites in the Veneto Region. Mean annual temperature and precipitation are 12.3°C and 1566 mm, respectively, with a seasonal rainfall pattern showing two peaks in May and November (Braca *et al.*, 2021). Therefore, following the Köppen-Geiger climate classification system, the study area can be defined as humid subtropical (*Cfa*). The lithology of the area is mainly characterised by fluvial and glacial deposits with the size of the elements in the order of sand-gravel and a smaller component of clay. The Veneto environmental agency (ARPAV) classified the soil permeability in the range between 0.01 and 10⁻⁶ m/s. Regarding land use, the area where the NBSs have been built can be defined as moderately urbanised, characterised by a relative artificial cover of between 50% and 80% (except for one NBS located in an agricultural area). Before the installation of the structures, the water runoff generated by rainfall events was discharged to the underground pipelines of the municipality.

The investigated structures

The monitored structures consisted of three NBSs located in urban areas. Figure 1A shows the structures' (n.1-3) location, while Figure 1B-D report a picture of the interventions. Table 1 reports the main characteristics of the structures. Given their extent and storage volume, the structures can be classified as small-scale Nature Based Solutions (Ruangan *et al.*, 2020). NBSs have been sized by designers to manage the rainfall volume of an event characterised by a return period of 30 years through a statistical analysis of the historical rainfall events and adopting the runoff coefficient procedure to derive the expected runoff. Structure 1 is a rain garden (Figure 1B) realised next to the Libertà Square to improve the management of water runoff produced by the impervious paving of the parking lot. The drainage area has an extent of 784 m², and is completely covered by a layer of impervious tar.

Accordingly, in the design phase has been assessed that 90% of the water rainfall volume produces surface runoff. Therefore, the extent of the rain garden is equal to 67 m². To improve the infiltration process and create a storage volume, the natural soil has been replaced with a drainage layer of sand, gravel, and small boulders (maximum diameter equal to 150 mm) to a depth of 0.8 m. The resulting storage capacity of the rain garden is 42 m³. Structure 2 is a small waterway that delivers surface runoff to a bioretention

Table 1. Parameters of the structures analysed in the study.

	Structure 1 Libertà Square	Structure 2 Grumo Hill	Structure 3 Prati Street
Extent (m ²)	67	44	172
Upslope drainage area (m ²)	784	4200	1145
Storage volume, SV (m ³)	42	48	103
Runoff coefficient (-)	0.9	0.2	0.85
Mean depth of the draining layer (m)	0.8	0.9	1
Vegetation species	Perennial herbaceous plants, evergreen shrubs, and one tree (<i>Alnus glutinosa</i>)	Mowed lawn	Perennial herbaceous plants and evergreen shrubs

area (Figure 1C) realised on the slope of a hill - the Grumo Hill in Santorso - to mitigate the flood risk in a downstream residential area. The drainage area (extent of 4200 m²) is characterised by a surface cover of grassland and sparse young forest (broad leaves). Therefore, practitioners estimated a runoff coefficient of this area of 0.2. The surface of the NBS results is equal to 44 m² with a storage capacity of 48 m³. This volume has been realised by modifying the area's topography at the outlet of the grassed waterway and substituting the soil with a drainage layer of coarse gravel for a depth of 0.9 m. Structure 3 consists of a rain garden (Figure 1D) built in the parking lot of Prati Street (Santorso) to decrease the water runoff coming from the paved and cultivated upstream areas. The upslope drainage area is equal to 1145 m², considering only the parking lot. However, in the case of prolonged and intense rainfall events, an additional five hectares of upstream agricultural land partially contributes to the inlet volume of the rain garden. The designed drainage coefficient results equal to 0.85. The structure's total surface has an extent of 172 m² and a storage capacity of 103 m³. Also, in this case, the soil has been removed and substituted with a drainage layer of sand, gravel, and small boulders (maximum diameter equal to 150 mm) for a depth of 1 m.

Data acquisition and analysis

Data acquired in the study consisted of precipitation pattern and discharge flowing into the three structures and out of these. The precipitation pattern was recorded using a rain gauge installed on the roof of the elementary school of Santorso. The model installed is the HD2015 (Delta Ohm S.r.l., Italy), characterised by

a sensibility of 0.2 mm and an acquisition frequency of 5 min. The rain gauge is equipped with a data logger HD33-M transmitting the recorded data remotely via a built-in 4G/3G/GPRS modem. The distance between the rain gauge and the structures is less than 800 m. More precisely, the rain gauge is located 80 m southeast of structure 1, 130 m west of structure 2, and 770 m north of structure 3. Therefore, in this study, we assumed that rainfall recorded by the rain gauge represents the rainfall pattern that occurred in the monitored locations. Furthermore, since in this study, we were more interested in assessing the NBS performances in case of extreme events, we considered the rainfall events that have produced at least 10 m³ of inflow volume.

Concerning the inlet and outlet flow discharge measurements, an ad hoc setup was designed to precisely monitor the runoff inlet and outlet volume of the three monitored structures through a pressure transducer sensor measuring the water level associated with a crest-weir. The setup consists of a concrete pit (connected to the outlet of the drained area) equipped with an aluminium sharp-crested weir of a defined shape. The setup comprises different parts: in the first part, the runoff is intercepted and pre-treated (siphon) to remove sediment that might clog the second part, which functions as a weir pond. The weir installed in the concrete pit is necessary for the flow discharge measurement and was designed considering the range of inlet flow rates (assessed using the Rational Method adopting a runoff coefficient defined by the practitioners in the sizing phase, Table 1). To accurately measure the wide range of discharges and limit the head height flowing through the notch, a compound rectangular-rectangular sharp-



Figure 1. Aerial overview of the study area with location of the investigated nature based solutions (NBSs) (A) and photos of the investigated structures: Libertà Square (B), Grumo Hill (C), and Prati Street (D) (Santorso, IT).

crested weir (CRRSC weir) was designed (Figure 2A). We chose a rectangular shape because a triangular weir would have resulted in an excessive lowering of the rain garden/bioretention bottom surface with respect to the elevation of the drainage area. Therefore, the CRRSC weir can be considered a combination of two simple rectangular sharp-crested weirs (Martínez *et al.*, 2005). Assuming this, the discharge-head relationship for the symmetric CRRSC results from a linear combination of two rectangular weirs, and it can be written as:

$$Q = C_{d1}\sqrt{2g}(2b_1)h_1^{3/2} + C_{d2}\sqrt{2g}(b_2)h_2^{3/2} \quad (1)$$

where C_{d1} and C_{d2} are the discharge coefficients that can be set at 0.415 if the upstream flow velocity is equal to zero as reported in Ferro (2011), b_1 is the width of the right/left side rectangular weir (175 mm, that is equal to the symmetrical right weir), b_2 is the width of the central rectangular weir (400 mm), h_1 is the head of the left and right rectangular weir (90 mm), and h_2 is the head of the middle rectangular weir (70 mm). Experimental calibration of the weirs was performed using a full-scale prototype. Experimental data confirmed the validity of the theoretical coefficients used in Eq. 1. A linear regression performed every two consecutive measurements was adopted, obtaining a broken line (based on 15 points) that was successively used to derive the discharge values. The final relation adopted to convert flow head values into discharge values is reported in Figure 2B.

To accurately measure the flow head over the weir crest and consequently derive the inlet and outlet flow discharge of the structures, a pressure transducer was installed inside the concrete pits containing the weirs. The water level sensor is a Datalogger Dipper PT (SEBA Hydrometrie GmbH, Germany) equipped with an external battery compartment. The SEBA Data Loggers type Dipper-PT are used for digital data recording of ground and surface water levels. The robust ceramics pressure measuring cell makes measuring the water level above the probe (hydrostatic pressure) possible. Combining the referential pressure sensor and the special measuring cable (with integrated air pressure compensation capillary) compensates for air pressure fluctuations. Therefore, the instru-

ment's sensitivity results equal to 1 mm in terms of water level above the sensor. A measurement has been acquired every hour when the water depth is lower than the weir height or 2 minutes when it is higher.

Thanks to the implemented setup, data acquired and analysed in this study are the precipitation pattern measured with the rain gauge and inlet and outlet discharge pattern derived with water level pressure transducers located upstream of the CRRSC. Firstly, the original data have been grouped for rainfall events, deriving the start and end time of rainfall, inlet, and outlet discharge. Then, for each event, the total rainfall volume (V_p), representing the maximum potential inflow to the structure, is derived by multiplying the cumulative sum of the rain gauge measurements for the upslope drainage area (Table 1). The effective runoff volume (V_{pe}) is then calculated by scaling the precipitation volume (V_p) according to the runoff coefficient adopted at the design stage. Finally, the inlet (V_{in}) and outlet (V_{out}) volumes of the monitored NBSs have been derived by the measurements of the water level sensors installed in the concrete pit.

Moreover, the maximum rainfall intensity (considered in a period of 5 minutes) and the mean rainfall intensity have been derived for every rainfall event. The inlet and outlet volumes are also calculated together with the time lag between the rainfall start and activation of the structure. Since the study aims to provide new insights into the effectiveness of NBSs for significant rainfall events, small rain events characterised by a total inlet volume lower than 10 m³ were not considered.

Regarding the analysis, a paired correlation matrix was performed, and then the best relations were further investigated. Finally, we analysed the performance of the structures in terms of inlet volume managed by the NBS. The so-called structure effectiveness (SE) is calculated following (Eq. 2):

$$SE = \frac{V_{in} - V_{out}}{V_{in}} 100 \quad (2)$$

We defined a good performance of the structure when the SE value is greater than 95%.

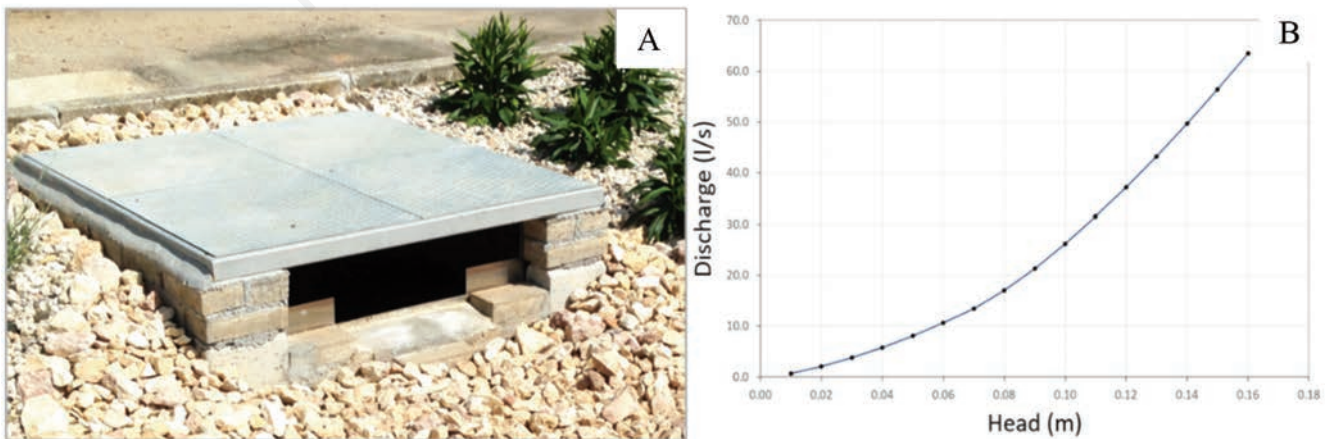


Figure 2. The compound rectangular-rectangular sharp-crested weir used to monitor the discharge of the structures (A), and the plot of the relation used to derive the discharge value from the head value (B).

Results

The installed instruments monitored the structure's hydrological effectiveness, recording two years (2020-2021) of measures. The rainfall events considered in the analysis are 92, 38 of which occurred in 2020 and 54 in 2021. The mean rainfall height per event equals 60 mm (50th percentile is 43 mm), with four events characterised by long duration (between 96 and 133 hours) yielding cumulated rainfall heights between 200 and 300 mm. As to the intensity of the events, the mean value is equal to 5.5 mm/h. More intense events (intensity greater than 20 mm/h) have been recorded for rain durations between 0.5 and 2.7 hours. Comparing the most severe recorded rainfall events to the historical series (period 1980-2020, analysed with EVI-Gumbel probability distribution), we observed an event with a return period equal to 15 years and seven events characterised by an estimated return period greater than 1.5 years. The features of these events are listed in the *Appendix, Table 1A*. Regarding the antecedent moisture condition (AMC) of the rainfall events, only 12 are characterised by AMC greater than one. However, regarding these events, the precedent rainfalls occurred in 2 to 5 days, with respect to the investigated one.

The correlations between rainfall variables and the inlet and outlet volumes are reported in Figure 1A. As a first result, we observed that the outlet volume for structure 2 was not measured for any rainfall event, meaning that the whole input volume was adequately managed through infiltration and retention processes. From *Figure 1A (in the Appendix)*, the analysis moved on, investigating the relations between pairs of variables. Firstly, the correlation between the total volume of the rainfall event (V_p) and inlet volume (V_{in}) was performed to assess the reliability of the adopted drainage coefficients used in the design phase (reported in Table 1). Figure 3 shows the scatterplot between V_p and V_{in} and the estimated linear rainfall-runoff model per structure (solid lines). Looking at the linear model coefficients, they resulted equal to 0.761, 0.247 and 1.411 for structures 1, 2, and 3, respectively. The coefficient of the fitted linear model involving structure 3 (referred to as the rain garden in Prati Street) resulted greater than 1, meaning that the structure collects runoff coming from outside the paved upslope drainage area, as was considered in the design phase. In addition, some recorded events for structure 1 show higher values of inlet

volume compared to the rain volume, but they are due to occasional (forced) water inputs from the surrounding area.

Analysing the *SE* value, representing the structure's performance in terms of water storing and ground infiltration, it is evident a very high performance of the three structures. In particular, the minimum *SE* value was equal to 98.7%. The rainfall variable that most influences the performance of the structures is maximum rainfall intensity (Figure 4). The scatterplot of Figure 4 shows that the lowest values of *SE* have occurred for rainfall events for which the maximum precipitation intensity per 5 minutes was between 20 and 70 mm/h. Therefore, in this range, structures 1 and 3 showed a relatively slight decrease in performance.

Figure 5 represents the rainfall duration against the mean intensity for those rainfall events that activated the structures. Firstly, it is possible to identify that the NBS structures have been activated by different rainfalls characterised by different intensity-duration relations. In particular, structures 1 and 3 indicated similar rainfall conditions for their activation, while structure 2 was activated when the events were more intense. Moreover, some rainfall events activated just one structure, while others activated two or more structures (note the overlapping points in Figure 5). Indeed, some of the extreme events in terms of precipitation volume did not activate the three structures simultaneously. Moreover, looking at the ratio between inlet volume (V_{in}) and structure storage capacity (S_V), the highest values are reported for events characterised by a duration greater than 36 hours and for a duration of around 10-12 hours associated with a mean intensity equal to 8 mm/h.

Finally, we investigated the predictability of the outlet volume of the structures. The analysis was performed excluding data from structure 2 since no output volumes were recorded. Among the different variables characterising the rainfall event, the mean rain intensity and duration affected the outlet volume of structures 1 and 3. In particular, the two variables significantly ($P < 0.001$) predicted the outlet volume by adopting a statistically linear model approach. Figure 6 shows the influence of mean intensity and rain duration on the outlet volume. Even if the observed outlet volume is very low, the highest values correspond to measures of mean rain intensity between 0.7 and 3 mm/h associated with an event duration longer than 40 hours. The structures performed well outside this range of values, producing outlet volumes lower than 0.1 m³.

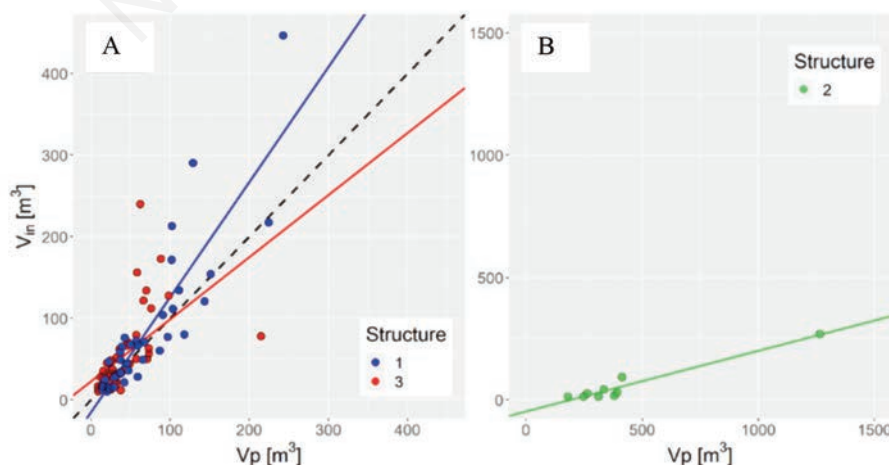


Figure 3. Scatterplot of rainfall volume event (V_p) and inlet volume for structures 1 and 3 (A) and 2 (B). Solid lines represent linear models, while the dashed line is the theoretical maximum admitted inlet volume ($V_{in}=V_p$).

Discussion

The characteristics of the investigated NBSs and the implemented monitoring setup correlated with rainfall precipitation data provided supplementary information for evaluating the effectiveness of such infrastructures. In the literature, such data are seldom reported, but they are of great interest to technicians (Cording *et al.*, 2017; Bai *et al.*, 2019).

The monitoring results of the three NBS structures showed overall good effectiveness in capturing and managing the water runoff through infiltration and surface retention processes. In particular, it was observed that structures 1 and 3 have a *SE* value greater than 98%, while only for two rainfall events the values were between 98 and 99%. Moreover, structure 2 never produced outflows, meaning its efficiency was always equal to 100% for the monitoring period. The lack of significant rain events has not facilitated the good performance. Indeed, in 2020 and 2021, intense events have been recorded, as the rainfalls occurring on 4th-9th December 2020 and 23rd August 2020 were associated with a return period of 15.0 and 16.5 years, respectively. The maximum volume of outflow measured for the three structures equals 0.7 m³, highlighting the conservative approach adopted at the design stage. Indeed, NBSs usually show outflow discharges even for rainfall events of low magnitude (Davis, 2008; Géheniau *et al.*, 2015). Based on the design features of the 3 structures, we could conclude that the choice of the generous thickness of the drainage layers - a minimum of 0.7-0.8 m - resulted in being the key factor for their successful performance. This proves that the selection of such a design variable should be scaled according to local rain aggressiveness, avoiding considering this variable as a constant standard thickness but rather as an additional to-be-sized subsurface storage volume.

Focusing on the runoff coefficient, the differences between the values adopted in the design and those estimated from field data (linear models, Figure 3) were similar for structures 1 and 2. Conversely, the structure 1 runoff coefficient, derived from field data, resulted equal to 1.41. This means that the water runoff collected and managed by the structure derived from an area larger than the upslope drainage area formally adopted in the design (anyway, the generated volume from different rainfall events was well managed by structure 3). At the same time, this finding suggests that particular attention should be paid to estimating the upward drainage area since it is a fundamental input for adequately managing water in urban areas (Stander *et al.*, 2010). Input volume can also be derived from groundwater fluxes, as Line and Hunt (2009) reported. Therefore, we suggest deriving the expected water amount by a comprehensive study of water processes through the analysis of remote sensing data (LiDAR, photogrammetry), field surveys (to detect the micro-topography or terrain peculiarities affecting water flow), data provided by the urban water management authorities and even eyewitnesses of past flooding events. Attention should be paid particularly in case of mixed land uses nearby the water retention NBS and when low terrain slopes are in play making unclear the flow paths. This was the case of our structure 3 for which the contribution from a much larger agricultural area could be added to the primary paved urban area. This kind of comprehensive analysis has to be reported in manuals in order to improve the design of NBSs, since actual guidelines are commonly stressing the estimation of runoff coefficient, giving less importance to the preliminary analysis on runoff fluxes (Majidi *et al.*, 2019; Zhang *et al.*, 2020).

Based on the analysis of the structure effectiveness through the *SE* coefficient (Figure 5), it is possible to notice a decrease in performance for rainfall, showing a maximum intensity in the range

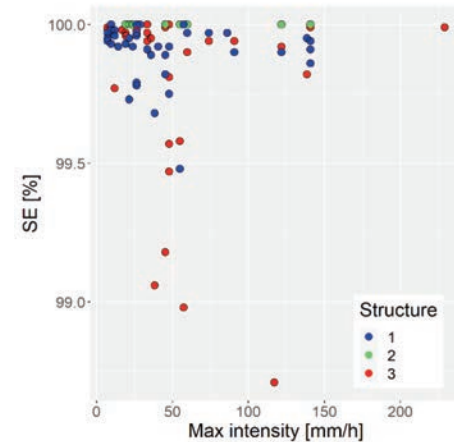


Figure 4. Scatterplot of maximum rainfall intensity and structure effectiveness (*SE*) for structures 1, 2 and 3.

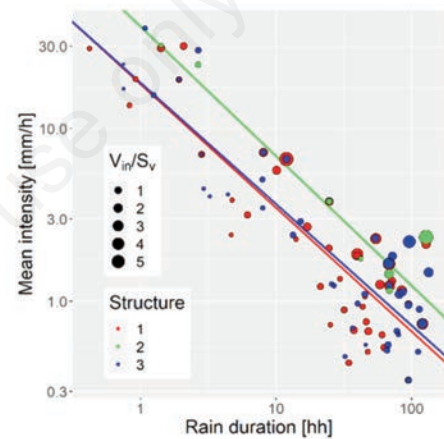


Figure 5. Scatterplot of rain duration *versus* mean rain intensity of the rainfall events for which the structures have been activated. The size of the dots represents the ratio between the inlet volume V_{in} and storage capacity S_V of the structure. The solid lines represent the log-linear fitting between the plotted variables for the three structures. The axes are on a logarithmic scale.

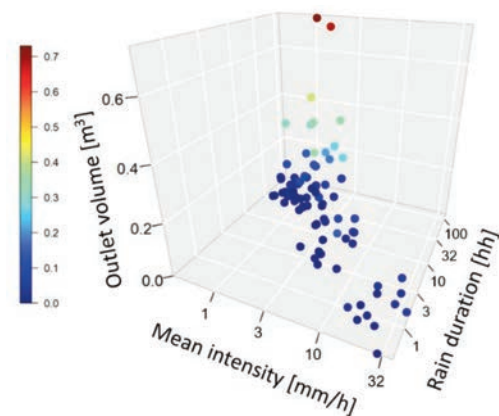


Figure 6. 3D scatterplot representing the outlet volume linked to mean intensity and rainfall duration. The colour intensity represents the outlet volume. The X and Y axes are on a logarithmic scale.

of 25-60 mm/h (Figure 5). Further improving this analysis, we observed that the most critical conditions for the monitored structures (highest output volumes) occurred for rainfall events characterised by a mean intensity of 2.5 mm/h and a duration of 65 hours. In agreement, the studies of Line and Hunt (2009) and Shuster *et al.* (2017) found that cumulative rainfall depth is a variable heavily affecting urban structure performances. Accounting for all these results at the design stage, importance should be placed on the analysis of probable rainfall events with long duration and thus generating large volumes of water runoff. This scenario, even if not managed by the NBS structure, will also provide valuable insights into the residual hazard of flooding and increase inhabitant awareness (Pagliacci *et al.*, 2020). All these attentions can effectively improve the calculation of the expected water volume in accordance with the rainfall events characterising the study area. Other studies analysed similar rainfall variables as reported in the review of Eckart *et al.* (2017). Following the study of Hunt *et al.* (2008), we found out that the increase in precipitation height decreases the rain garden performance. We refined this outcome by adding the precipitation intensity as similarly reported in Gülbaz and Kazezyılmaz-Alhan (2017). In addition, we identified the precipitation characteristics in terms of rainfall height and mean intensity limiting the rain garden performance. We concluded that the design hypothesis should not only consider a rain duration maximising the peak discharge flowing into the NBSs as suggested by several guidelines but also an additional design rainfall scenario characterised by a mean intensity of 2.5 mm/h for 2-3 days (Figure 6). The outcome corroborates design guidelines (MNCPA, 2007; WIDNR, 2010), generally indicating that rain gardens should be sized to mitigate the first peak flush of the storm. Thanks to the accurate monitoring setup, we found that prolonged rainfall events (2-3 days) affect at the most the hydraulic performance of NBSs.

Looking at the inflow volume with respect to the designed stored volume (Figure 5), we can assert that the structures can also mitigate the effects of some extreme rainfall events. This result is also observed in other studies involving monitoring NBS structures (Nichols, 2018). Particularly in these cases, to assess the performance of the structures under extreme rainfall scenarios, using numerical models (*i.e.* HYDRUS-1D) might represent a precious integration (Nichols *et al.*, 2021). Furthermore, thanks to the installation of an ad-hoc measurement setup, data collected in this project can be used in the next studies investigating the reliability of numerical models.

Conclusions

The study investigated the monitoring data collected from three NBSs built in the Alto-Vicentino area (IT), which is featured by a very high cumulative precipitation height within the Veneto region. Overall, we observed good structure performances in terms of the fraction of water runoff managed by the structures, also concluding that the adoption of a drainage layer of at least 0.8 m demonstrates to be a valid design choice. The volume of water flowing out from the structures was really low (maximum observed value equal to 0.7 m³) even if precipitation events were of medium-high magnitude. Thanks to rainfall data and inflow/outflow measurements, we further identified the most critical rainfall characteristics in terms of unmanaged volume. Results showed high outlet volumes with rainfall durations of 2-3 days and mean intensity of 3 mm/h.

Moreover, for the design phase, the identification of water contributing to the inlet volume has to be assessed through a compre-

hensive analysis since, in urban areas, runoff can also derive from areas outside the identified drainage area, which could lead to an inappropriate functionality of the NBS. Therefore, the precise evaluation of the NBSs through the *ad hoc* measurement setup associated with the rainfall pattern collected for two years can be of high relevance for improving guidelines on functionality and best size characteristics of NBSs, so promoting the installation of such infrastructures, especially in the territorial context of North Italy. The experimental setup is still acquiring data to detect the NBS performance over time and evaluate the mitigation function for more severe events. In addition, further research can benefit from the presented data to validate numerical models and support the assessment of the hydrological benefits of NBS at catchment level.

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Online supplementary material:

Table 1A. Occurrence date and characteristics of the most intense rainfall events recorded during the two years of the monitoring period of the LIFE BEWARE project.

Figure 1A. Scatterplot of matrices, with bivariate scatterplots below the diagonal, histograms on the diagonal, and the Pearson correlation above the diagonal of the variables analysed involving the three structures.