Standard Issue – Article

Journal of Agricultural Engineering

https://www.agroengineering.org/

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

Tommaso Baggio, Francesco Bettella, Lucia Bortolini, Vincenzo d'Agostino

Publisher's Disclaimer

E-publishing ahead of print is increasingly important for the rapid dissemination of science. The *Early Access* service lets users access peer-reviewed articles well before print/regular issue publication, significantly reducing the time it takes for critical findings to reach the research community.

These articles are searchable and citable by their DOI (Digital Object Identifier).

Our Journal is, therefore, e-publishing PDF files of an early version of manuscripts that undergone a regular peer review and have been accepted for publication, but have not been through the typesetting, pagination and proofreading processes, which may lead to differences between this version and the final one.

The final version of the manuscript will then appear on a regular issue of the journal.

Please cite this article as doi: 10.4081/jae.2023.1485

©The Author(s), 2023
Licensee PAGEPress, Italy

Submitted: 22/07/2022
Revised: 10/09/2022
Accepted: 14/09/2022

Note: The publisher is not responsible for the content or functionality of any supporting information supplied by the authors. Any queries should be directed to the corresponding author for the article.

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article or claim that may be made by its manufacturer is not guaranteed or endorsed by the publisher.

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

Tommaso Baggio, Francesco Bettella, Lucia Bortolini, Vincenzo d'Agostino

Department of Land, Environment, Agriculture and Forestry, University of Padova, Legnaro (PD), Italy

Correspondence: Tommaso Baggio, Department of Land, Environment, Agriculture and Forestry, University of Padova, via dell'Università 16, 35020 Legnaro (PD), Italy.

E-mail: tommaso.baggio@unipd.it

Key words: Nature-based solutions; low impact development; hydro-meteorological hazards; risk mitigation and adaptation; field-scale experiment; hydrological monitoring.

Funding: this research was funded by *BEWARE Life project*, grant number *LIFE17 GIC/IT/000091*.

See online Appendix for additional Figure and Table.

Abstract

The consequences of climate change are exacerbated by land-use changes, which influence the rainfall-runoff relations and consequently the flood risk. Effectively, urbanization is steadily contributing to the increase of impervious areas and reducing the time-to-peak. The effect of Nature Based Solutions (NBSs) on the mitigation of these phenomena is recognized. Nevertheless, these kinds of sustainable infrastructures are still barely known and scarcely adopted in many parts of the 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 pattern. 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 resulted as being useful to improve the design of NBSs and further promote their installation in urban areas.

Introduction

Climate change is affecting the precipitation regime of different regions worldwide, increasing both the frequency and magnitude of rainfall events (Brunetti et al., 2009). This trend is expected to increase in the near future as a consequence of global warming (Wilhelm et al., 2012). In the Mediterranean region different trends have been identified by analysing the rainfall events of the last decades in terms of duration and intensity. According to Alpert et al. (2002) on the Italian territory, the increase of events classified as heavy-torrential and a decrease of prolonged and less intense phenomena is highlighted. 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 hazard (Hirabayashi et al., 2013). In this context, different types of mitigation measures have been developed and applied to mitigate the hydrological risk and further increase the population 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 rate of surface runoff, peak discharge and increase the time lag between rainfall event 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 in accordance with their extent and the total volume of water that 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 area of the city (Chan et al., 2018; Stanchi et al., 2021). The effectiveness of NBSs depends on the frequency and magnitude of rainfall events as well as on 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 surfaces resulted more efficient in case of heavier rainfall events (Zölch et al., 2017). However other studies observed opposite trends as reported in (Bortolini and Zanin, 2018; Jennings et al., 2015), because of 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 demonstrated by Bettella et al. (2018) for green roofs. Consequently, the monitoring of 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 respect to the total runoff, the infiltration rate, the peak discharge reduction and 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, also different rainfall patterns can affect the efficiency of NBSs, especially when the duration of the events increases, as shown in Hunt et al. (2008). Still 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 pattern and NBSs performance in terms of water volume inflowing and outflowing.

Within the Life project “BEWARE” three NBSs have been designed, realized and equipped with sensors to constantly monitor the water volume. 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 a period of two years has been statistically analysed, finding out the most critical conditions. Thanks to these outcomes, the research is dedicated to provide new insights into the design and size of NBSs, with the aim to improve the control and the management of the water runoff caused by different types of rainfall events.

Materials and method

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 through the increase of water infiltration and reduction of the amount of 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 on the Veneto Plain. Due to the particular topography of the area, it is recognized as being among the rainiest sites of 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 characterized by fluvial and glacial deposits with the size of the elements in the order of sand-gravel and a smaller component of clay. The soil permeability is classified by the Veneto environmental agency (ARPAV) in the range between 0.01 and 10^{-6} m/s. As regards the land use, the area where the NBSs have been built can be defined as moderately urbanized, characterized by a relative artificial cover of between 50% and 80% (except for one NBS that is located in an agricultural area). Before installation of the structures, the water runoff generated by rainfall events was basically 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 Figures 1B-1D report 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 (Ruangpan et al., 2020). NBSs have been sized by designers to manage the rainfall volume of an event characterized 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) realized 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 m^2 and it is completed 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. The extent of the raingarden is equal to 67 m^2. 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 of 150 mm) to a depth of 0.8 m. The resulting storage capacity of the raingarden is 42 m^3. Structure 2 is a small waterway that delivers surface runoff to a bioretention area (Figure 1C) realized on the slope of a hill – the Grumo hill in Santorso – with the aim of mitigating the flood risk in a downstream residential area. The drainage area (extent of 4200 m^2) is characterized by a surface cover of grassland and sparse young forest (broadleaves). Therefore, practitioners estimated a runoff coefficient of this area of 0.2. The surface of the NBS results equal to 44 m^2 with a storage capacity of 48 m^3. This volume has been realized modifying the topography of the area 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 m^2, 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 raingarden. The designed drainage coefficient results equal to 0.85. The total surface of the structure has an extent of 172 m^2 and a storage capacity of 103 m^3. Also in this case, the soil has been removed and substituted with a drainage layer of sand, gravel and small boulders (maximum diameter equal of 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) characterized 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 south-east 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 is representative of the rainfall pattern that occurred in the monitored locations. 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 m^3 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 the use of 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 (Figure 3a). The setup is composed of different parts: in the first part, the runoff is intercepted and pre-treated (siphon) to remove sediment that might clog the second part that 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-crested weir (CRRSC weir) was designed (Figure 2a). We chose a rectangular shape because the choice of a triangular weir would have resulted into an excessive lowering of the rain garden/bioretention bottom surface with respect to the elevation of the drainage area. The CRRSC weir can be considered as 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:

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

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 height of the left and right rectangular weir (90 mm) and h_2 is the height of the middle rectangular weir (70 mm). An 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 were 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 water level in ground water and surface water. The robust ceramics pressure measuring cell makes it possible to measure the water level above the probe (hydrostatic pressure). The combination of the referential pressure sensor and the special measuring cable (with integrated air pressure compensation capillary), compensates air pressure fluctuations. Therefore, the sensitivity of the instrument 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 raingauge 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 event, deriving the time of start and end of rainfall, inlet and outlet discharge. For each event, the total rainfall volume (*Vp*), which represents the maximum potential inflow to the structure, is derived multiplying the cumulative sum of the raingauge measurements for the upslope drainage area (Table 1). The effective runoff volume (*Vpe*) is then calculated scaling the precipitation volume (*Vp*) according to the runoff coefficient adopted at the design stage. The inlet (V_{in}) and outlet (V_{out}) volumes of the monitored NBSs has been derived by the measurements of the water level sensors installed in the concrete pit. Moreover, the maximum rainfall intensity (considered in a time period of 5 minutes) and the mean rainfall intensity has been derived for every rainfall event. The inlet and outlet volume 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 substantial rainfall events, small rain events characterized by a total inlet volume lower than 10 m^3 were not considered. Regarding the analysis, a paired correlation matrix was performed and then the best relations 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),

$$SE = \frac{V_{in} - V_{out}}{V_{in}} 100 \tag{2}$$

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

Results

The installed instruments monitored the structure 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 is equal to 60 mm (50th percentile is 43 mm), with four events characterized 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 historical series (period 1980 – 2020, analysed with EV1-Gumbel probability distribution), we observed an event with a return period equal to 15 years and seven events characterized 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 characterized by AMC greater than one. However, regarding these events, the precedent rainfalls occurred in the interval of 2 to 5 days respect 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 total volume of the rainfall event (Vp) 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 Vp and V_{in} and the estimated linear rainfall-runoff model per structure (solid lines). Looking at the coefficients of the linear model they resulted equal to 0.761, 0.247 and 1.411 for structure 1, 2 and 3, respectively. The coefficient of the fitted linear model involving structure 3 (referred to 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 (see description of structure 3, section 2.1). 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 performance of the structure 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 resulted 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 types of rainfalls, which are characterized by different intensity-duration relations. In particular, structures 1 and 3 indicated similar rainfall conditions for their activation, while structure 2 has been 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 characterized by a duration greater than 36 hours and for a duration 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 of structure 2 since no output volumes were recorded. Among the different variables characterizing the rainfall event, the mean rain intensity and rain duration affected the outlet volume of structures 1 and 3. In particular, the two variables resulted significant ($p\text{-value} < 0.001$) in predicting the outlet volume by adopting a statistical 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. Outside this range of values the structures performed well, producing outlet volumes lower than 0.1 m^3.

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 (Bai et al., 2019; Cording et al., 2017).

The monitoring results of the three NBS structures showed overall good effectiveness in capturing and managing the water runoff through processes of infiltration and surface retention. 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 that its efficiency was always equal to 100% for the monitoring period. The good performance has not been facilitated by the lack of significant rain events. 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 to a return period of 15.0 and 16.5 years, respectively. The maximum volume of outflow measured for the three structures is equal to 0.7 m^3, highlighting the conservative approach adopted at the design stage. Indeed, NBSs usually show outflow discharges even for rainfall events of low magnitude (Davis, 2008; Géhéniau 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 to be the key factor for their successful performance. This proves, that the selection of such design variable should be scaled according to local rain aggressiveness, avoiding to consider this variable like a constant standard thickness but rather an additional to-be-sized subsurface storage volume.

Focusing on the runoff coefficient, the differences between the values adopted in the design and those values estimated from field data (linear models, Figure 3) resulted similar for structure 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 the estimation of 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 ground water fluxes as reported in Line and Hunt (2009). We suggest to derive the expected water amount by a comprehensive study of water processes, through the analysis of remote sensed 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 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 characterized by a mean intensity of 2.5 mm/h and duration of 65 hours. In agreement, the studies of Line and Hunt (2009) and Shuster et al. (2017) found out that the cumulative rainfall depth is a variable heavily affecting the 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 useful 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 characterizing the study area. Other studies analysed similar rainfall variables as reported in the review of Eckart et al. (2017). In accordance with the study of Hunt et al. (2008), we found out that the increase of precipitation height decreases the raingarden 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 raingarden performance. Our conclusion was that the design hypothesis should not only consider a rain duration maximizing the peak discharge flowing into the NBSs as suggested by several guidelines, but also an additional design rainfall scenario characterized by a mean intensity of 2.5 mm/h for the duration of 2-3 days (Figure 6). The outcome corroborates design guidelines (MNCPA, 2007; WIDNR, 2010), generally indicating that raingardens should be sized to mitigate the first peak flush of the storm. Thanks to the accurate monitoring setup, we found out 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 the monitoring of NBS structures (Nichols, 2018). Particularly in these cases, to assess the performance of the structures under extreme rainfall scenarios, the use of numerical models (i.e. HYDRUS-1D) might represent a precious integration (Nichols et al., 2021). Thanks to the installation of an ad-hoc measurement setup, data collected in this project can be used in next studies investigating the reliability of numerical models.

Conclusions

The study investigated the monitoring data collected of three NBSs created 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, concluding also that adoption of a drainage layer of at the least of 0.8 m demonstrate 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 m^3) even if precipitation events were of medium-high magnitude. Thanks to rainfall data and inflow and outflow measurements, we further identified the most critical rainfall characteristics in terms of unmanaged volume. Results showed that 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 comprehensive analysis, since in urban areas runoff can also derive from areas outside than the identified drainage area that could lead to an inappropriate functionality of the NBS. The precise evaluation of the NBSs through the ad-hoc measurement setup associated with the rainfall pattern collected for two years and the performed analysis 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 the North Italy. Moreover, the experimental setup is still acquiring data in order to detect the NBS performance over time and evaluate the mitigation function with more severe events. In addition, further research can benefit from the presented data in order to validate numerical models and support the assessment of the hydrological effects of NBS at a catchment level.

References

Alpert, P., Ben-Gai, T., Baharad, A., Benjamini, Y., Yekutieli, D., Colacino, M., Diodato, L., Ramis, C., Homar, V., Romero, R., Michaelides, S., Manes, A., 2002. The paradoxical increase of Mediterranean extreme daily rainfall in spite of decrease in total values. Geophys. Res. Lett. 29, 31-1-31–4. https://doi.org/10.1029/2001GL013554

Apollonio, C., Petroselli, A., Tauro, F., Cecconi, M., Biscarini, C., Zarotti, C., Grimaldi, S., 2021. Hillslope erosion mitigation: An experimental proof of a nature-based solution. Sustain. 13. https://doi.org/10.3390/su13116058

Bai, Y., Li, Y., Zhang, R., Zhao, N., Zeng, X., 2019. Comprehensive performance evaluation system based on environmental and economic benefits for optimal allocation of LID facilities. Water

(Switzerland) 11. https://doi.org/10.3390/w11020341

Bettella, F., D’Agostino, V., Bortolini, L., 2018. Drainage flux simulation of green roofs under wet conditions. J. Agric. Eng. 49, 242–252. https://doi.org/10.4081/jae.2018.838

Biddoccu, M., Opsi, F., Cavallo, E., 2014. Relationship between runoff and soil losses with rainfall characteristics and long-term soil management practices in a hilly vineyard (Piedmont, NW Italy). Soil Sci. Plant Nutr. 60, 92–99. https://doi.org/10.1080/00380768.2013.862488

Bortolini, L., Zanin, G., 2018. Hydrological behaviour of rain gardens and plant suitability: A study in the Veneto plain (north-eastern Italy) conditions. Urban For. Urban Green. 34, 121–133. https://doi.org/10.1016/j.ufug.2018.06.007

Braca, G., Bussettini, M., Mariani, S., Lastoria, B., 2021. Il Bilancio Idrologico Gis BAsed a scala Nazionale su Griglia regolare – BIGBANG: metodologia e stime. Rapporto sulla disponibilità naturale della risorsa idrica. Istituto Superiore per la Protezione e la Ricerca Ambientale, Roma.

Brunetti, M., Lentini, G., Maugeri, M., Nanni, T., Auer, I., Böhm, R., Schöner, W., 2009. Climate variability and change in the Greater Alpine Region over the last two centuries based on multi-variable analysis. Int. J. Climatol. 29, 2197–2225. https://doi.org/10.1002/joc.1857

Chan, F.K.S., Griffiths, J.A., Higgitt, D., Xu, S., Zhu, F., Tang, Y.T., Xu, Y., Thorne, C.R., 2018. “Sponge City” in China—A breakthrough of planning and flood risk management in the urban context. Land use policy 76, 772–778. https://doi.org/10.1016/j.landusepol.2018.03.005

Church, S.P., 2015. Exploring Green Streets and rain gardens as instances of small scale nature and environmental learning tools. Landsc. Urban Plan. 134, 229–240. https://doi.org/10.1016/j.landurbplan.2014.10.021

Cording, A., Hurley, S., Whitney, D., 2017. Monitoring methods and designs for evaluating bioretention performance. J. Environ. Eng. 143, 05017006. https://doi.org/10.1061/(ASCE)EE.1943-7870.0001276

Davis, A.P., 2008. Field Performance of Bioretention: Hydrology Impacts. J. Hydrol. Eng. 13, 90–95. https://doi.org/10.1061/(ASCE)1084-0699(2008)13:2(90)

Eckart, K., McPhee, Z., Bolisetti, T., 2017. Performance and implementation of low impact development – A review. Sci. Total Environ. 607–608, 413–432. https://doi.org/10.1016/j.scitotenv.2017.06.254

European Commission, 2015. Towards an EU research and innovation policy agenda for nature-based solutions & re-naturing cities.

Faivre, N., Fritz, M., Freitas, T., de Boissezon, B., Vandewoestijne, S., 2017. Nature-Based Solutions in the EU: Innovating with nature to address social, economic and environmental challenges. Environ. Res. 159, 509–518. https://doi.org/10.1016/j.envres.2017.08.032

Ferro, V., 2011. Una nuova teoria per lo studio dei processi di efflusso dagli stramazzi. L'Italia For. e Mont. 66, 127–139. https://doi.org/10.4129/ifm.2011.2.03

Géhéniau, N., Fuamba, M., Mahaut, V., Gendron, M.R., Dugué, M., 2015. Monitoring of a rain garden in cold climate: case study of a parking lot near Montréal. J. Irrig. Drain. Eng. 141, 04014073. https://doi.org/10.1061/(asce)ir.1943-4774.0000836

Gülbaz, S., Kazezyılmaz-Alhan, C.M., 2017. Experimental investigation on hydrologic performance of LID with rainfall-watershed-bioretention system. J. Hydrol. Eng. 22, 1–10. https://doi.org/10.1061/(asce)he.1943-5584.0001450

Hirabayashi, Y., Mahendran, R., Koirala, S., Konoshima, L., Yamazaki, D., Watanabe, S., Kim, H., Kanae, S., 2013. Global flood risk under climate change. Nat. Clim. Chang. 3, 816–821. https://doi.org/10.1038/nclimate1911

Hunt, W.F., Smith, J.T., Jadlocki, S.J., Hathaway, J.M., Eubanks, P.R., 2008. Pollutant removal and peak flow mitigation by a bioretention cell in urban Charlotte, N.C. J. Environ. Eng. 134, 403–408. https://doi.org/10.1061/(asce)0733-9372(2008)134:5(403)

Ishimatsu, K., Ito, K., Mitani, Y., Tanaka, Y., Sugahara, T., Naka, Y., 2017. Use of rain gardens for stormwater management in urban design and planning. Landsc. Ecol. Eng. 13, 205–212. https://doi.org/10.1007/s11355-016-0309-3

Jennings, A.A., Berger, M.A., Hale, J.D., 2015. Hydraulic and hydrologic performance of residential rain gardens. J. Environ. Eng. 141, 04015033. https://doi.org/10.1061/(asce)ee.1943-7870.0000967

Jiang, C., Li, J., Li, H., Li, Y., Zhang, Z., 2020. Low-impact development facilities for stormwater runoff treatment: Field monitoring and assessment in Xi'an area, China. J. Hydrol. 585, 124803. https://doi.org/10.1016/j.jhydrol.2020.124803

Line, D.E., Hunt, W.F., 2009. Performance of a bioretention area and a level spreader-grass filter strip at two highway sites in North Carolina. J. Irrig. Drain. Eng. 135, 217–224. https://doi.org/10.1061/(asce)0733-9437(2009)135:2(217)

Majidi, A.N., Vojinovic, Z., Alves, A., Weesakul, S., Sanchez, A., Boogaard, F., Kluck, J., 2019. Planning nature-based solutions for urban flood reduction and thermal comfort enhancement. Sustain. 11. https://doi.org/10.3390/su11226361

Maragno, D., Gaglio, M., Robbi, M., Appiotti, F., Fano, E.A., Gissi, E., 2018. Fine-scale analysis of urban flooding reduction from green infrastructure: An ecosystem services approach for the management of water flows. Ecol. Modell. 386, 1–10. https://doi.org/10.1016/j.ecolmodel.2018.08.002

Martínez, J., Reca, J., Morillas, M.T., López, J.G., 2005. Design and calibration of a compound sharp-crested weir. J. Hydraul. Eng. 131, 112–116. https://doi.org/10.1061/(ASCE)0733-9429(2005)131:2(112)

MNCPA, 2007. Start-to-finish rain garden design: a workbook for homeowners.

Nichols, W., 2018. Modeling Performance of an Operational Urban Rain Garden Using HYDRUS-1D. Thesis. Villanova University.

Nichols, W., Welker, A., Traver, R., Tu, M. "Peter," 2021. Modeling seasonal performance of operational urban rain garden using HYDRUS-1D. J. Sustain. Water Built Environ. 7, 04021005. https://doi.org/10.1061/JSWBAY.0000941

Pagliacci, F., Defrancesco, E., Bettella, F., D'Agostino, V., 2020. Mitigation of urban pluvial flooding: what drives residents' willingness to implement green or grey stormwater infrastructures on their property? Water 12, 3069. https://doi.org/10.3390/w12113069

Ruangpan, L., Vojinovic, Z., Di Sabatino, S., Leo, L.S., Capobianco, V., Oen, A.M.P., Mcclain, M.E., Lopez-Gunn, E., 2020. Nature-based solutions for hydro-meteorological risk reduction: a state-of-the-art review of the research area. Nat. Hazards Earth Syst. Sci. 20, 243–270. https://doi.org/10.5194/nhess-20-243-2020

Shuster, W.D., Darner, R.A., Schifman, L.A., Herrmann, D.L., 2017. Factors contributing to the hydrologic effectiveness of a rain garden network (Cincinnati Oh USA). Infrastructures 2, 1–14. https://doi.org/10.3390/infrastructures2030011

Stanchi, S., Zecca, O., Hudek, C., Pintaldi, E., Viglietti, D., D'Amico, M.E., Colombo, N., Goslino, D., Letey, M., Freppaz, M., 2021. Effect of Soil Management on Erosion in Mountain Vineyards (N-W Italy). Sustainability 13, 1991. https://doi.org/10.3390/su13041991

Stander, E.K., Borst, M., O'Connor, T.P., Rowe, A.A., 2010. The effects of rain garden size on hydrologic performance. World Environ. Water Resour. Congr. 2010 Challenges Chang. - Proc. World Environ. Water Resour. Congr. 2010 3018–3027. https://doi.org/10.1061/41114(371)309

Swain, D.L., Wing, O.E.J., Bates, P.D., Done, J.M., Johnson, K.A., Cameron, D.R., 2020. Increased flood exposure due to climate change and population growth in the United States. Earth's Futur. 8. https://doi.org/10.1029/2020EF001778

USEPA - United States Environmental Protection Agency, 2000. Low impact development (LID): A literature review. Washington, DC.

WIDNR - Wisconsin Department of Natural Resources, 2010. Bioretention for infiltration. conservation practice standard.

Wilhelm, B., Arnaud, F., Enters, D., Allignol, F., Legaz, A., Magand, O., Revillon, S., Giguet-Covex, C., Malet, E., 2012. Does global warming favour the occurrence of extreme floods in European Alps? First evidences from a NW Alps proglacial lake sediment record. Clim. Change 113, 563–581. https://doi.org/10.1007/s10584-011-0376-2

Wilson, C.E., Hunt, W.F., Winston, R.J., Smith, P., 2015. Comparison of runoff quality and quantity from a commercial low-impact and conventional development in Raleigh, North Carolina. J. Environ. Eng. 141, 05014005. https://doi.org/10.1061/(ASCE)EE.1943-7870.0000842

Zhang, L., Ye, Z., Shibata, S., 2020. Assessment of rain garden effects for the management of urban storm runoff in japan. Sustain. 12, 1–17. https://doi.org/10.3390/su12239982

Zölch, T., Henze, L., Keilholz, P., Pauleit, S., 2017. Regulating urban surface runoff through nature-based solutions – An assessment at the micro-scale. Environ. Res. 157, 135–144. https://doi.org/10.1016/j.envres.2017.05.023

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, S_V (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 (A*lnus glutinosa*)	Mowed lawn	Perennial herbaceous plants and evergreen shrubs

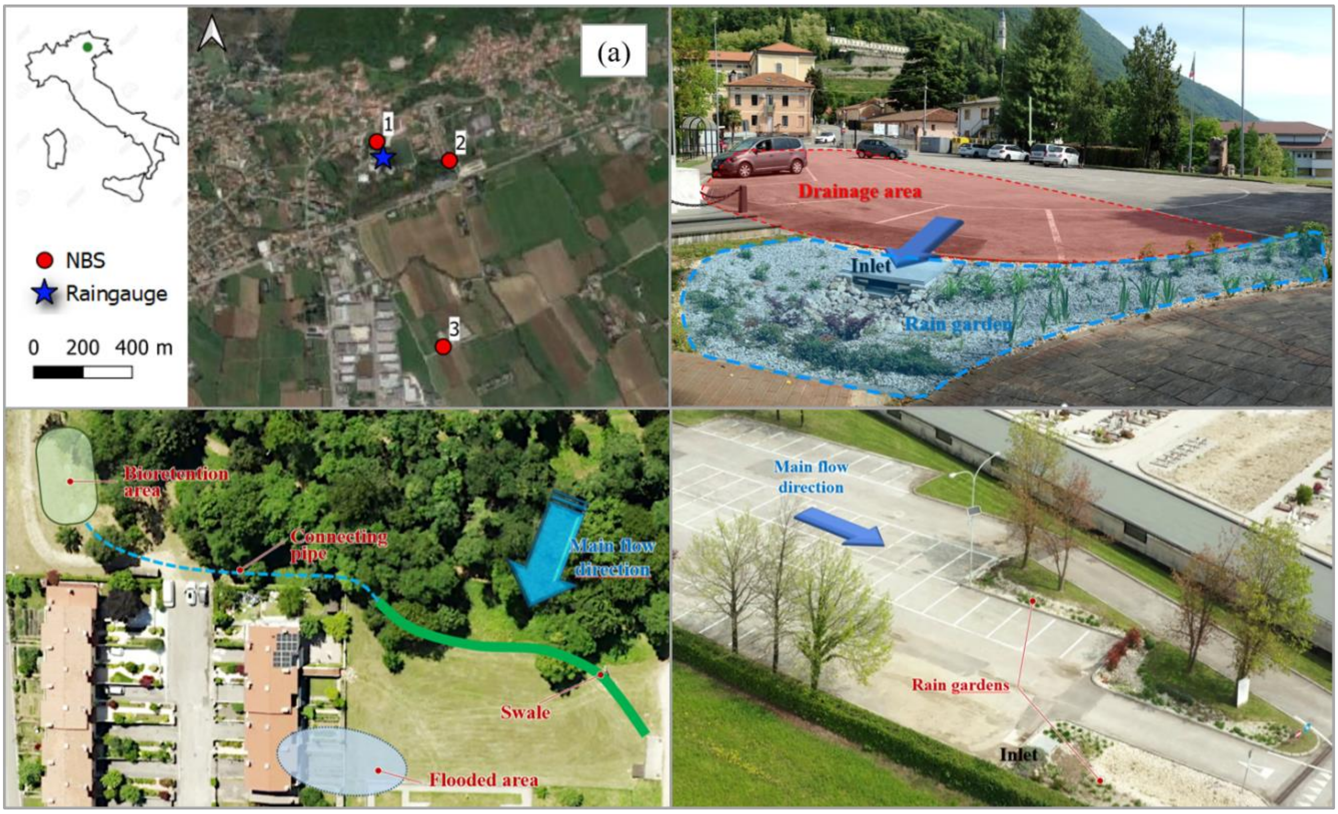

Figure 1. Aerial overview of the study area with location of the investigated NBSs (a) and photos of the investigated structures: Libertà square (b), Grumo hill (c) and Prati street (d) (Santorso, IT).

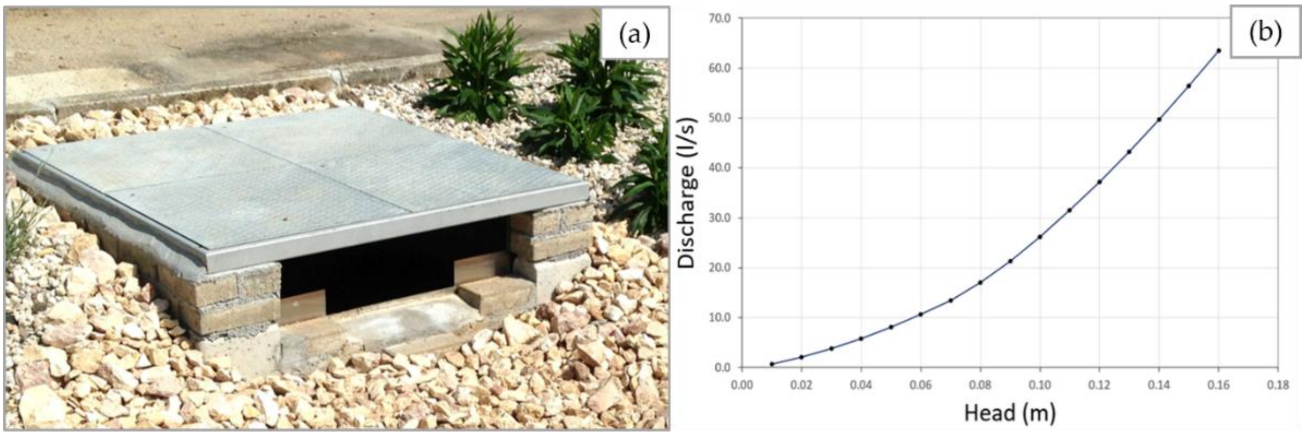

Figure 2. The compound rectangular-rectangular sharp-crested weir used to monitor the discharge of the structures (a) and plot of the relation used to derive the discharge value from the head value (b).

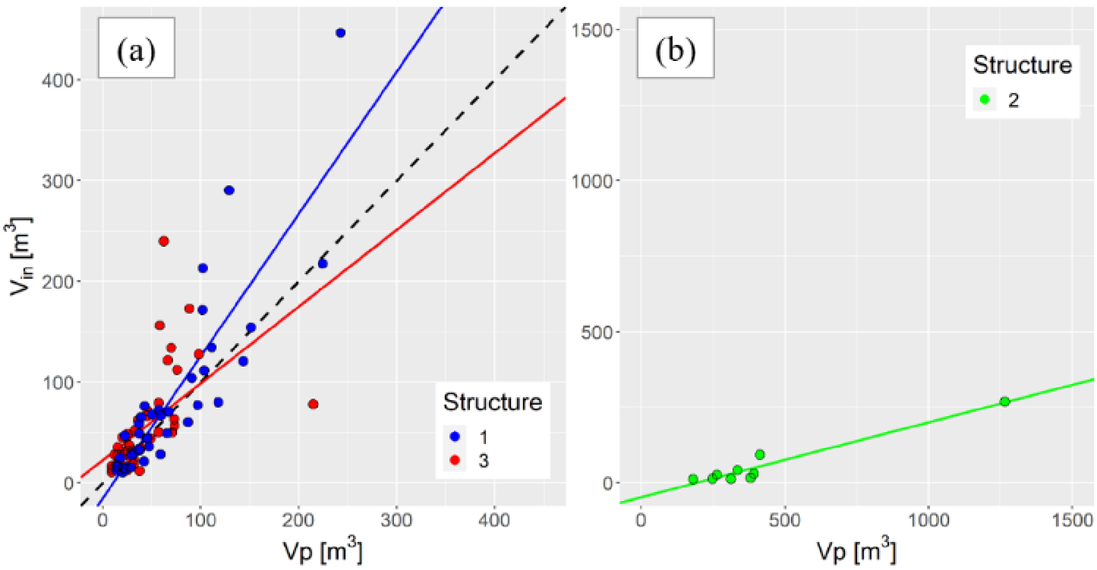

Figure 3. Scatterplot of rainfall volume event (Vp) and inlet volume for structures 1 and 3 (a) and 2 (b). Solid lines represent linear models while the dashed line the theoretical maximum admitted inlet volume (V_{in}=Vp).

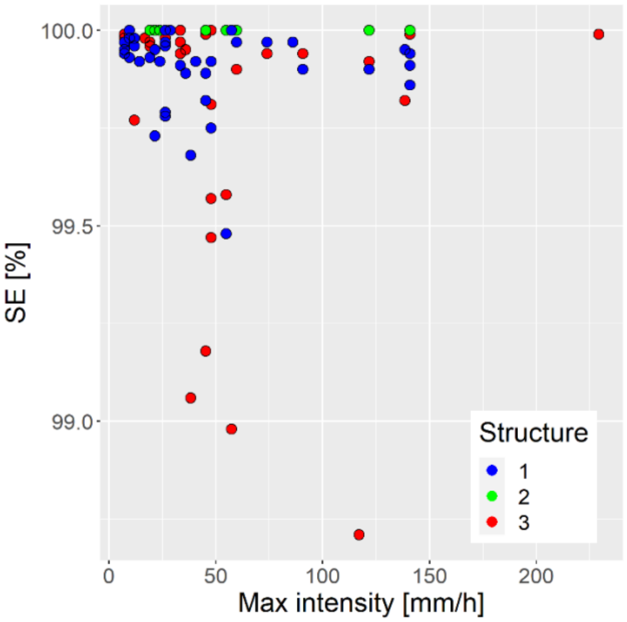

Figure 4. Scatterplot of maximum rainfall intensity and structure effectiveness (SE) for structures 1 and 3.

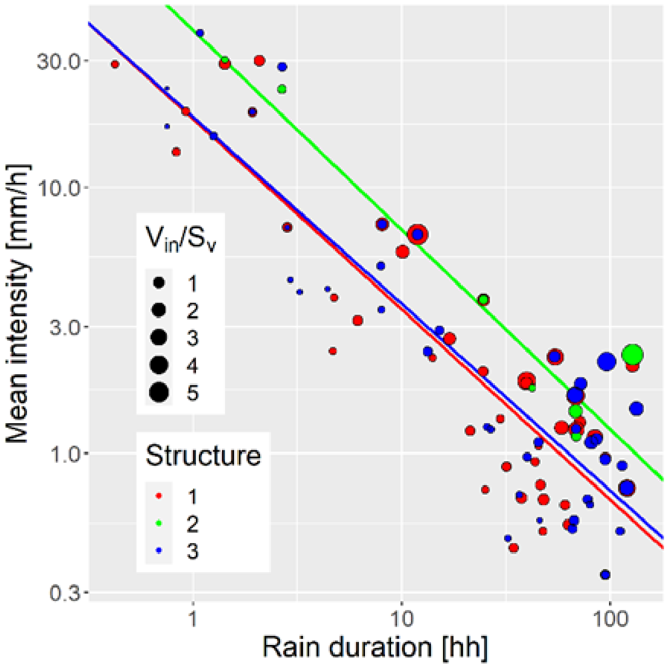

Figure 5. Scatterplot of rain duration versus mean rain intensity of the rainfall events for which the structures have been activated. The size of the dots represents the ratio between inlet volume V_{in} and storage capacity S_V of the structure. The solid lines represent the log-linear fitting between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

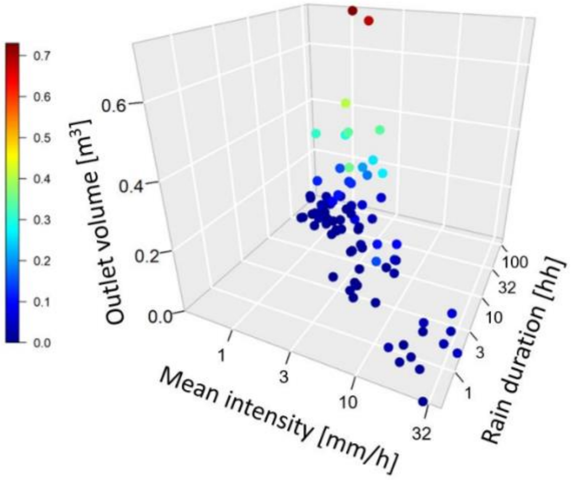

Figure 6. 3D catterplot representing the outlet volume linked to mean intensity and rainfall duration. The colour intensity represents the outlet volume. The X and Y axes are in logarithmic scale.

Appendix

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.

Date	Cumulated rainfall [mm]	Maximum intensity [mm/h]	Mean intensity [mm/h]	Duration [hours]	Duration [days]	Return period [years]
14/08/2020	41.3	140.9	38.2	1.0	0.04	2.2
23-25/08/2020	75.8	121.8	28.4	2.6	0.1	6.5
04-10/06/2020	196.2	38.2	1.5	133.7	5.5	3.2
02-09/12/2020	301.3	23.9	2.4	128.1	5.3	15
11-13/04/2021	125.4	26.3	2.3	54.0	2.2	1.9
08/07/2021	36.8	138.5	19.2	1.9	0.1	2.0
13/07/2021	79.4	140.9	6.7	11.9	0.5	2.4
01-04/11/2021	132.1	45.4	1.8	72.1	3.0	1.6

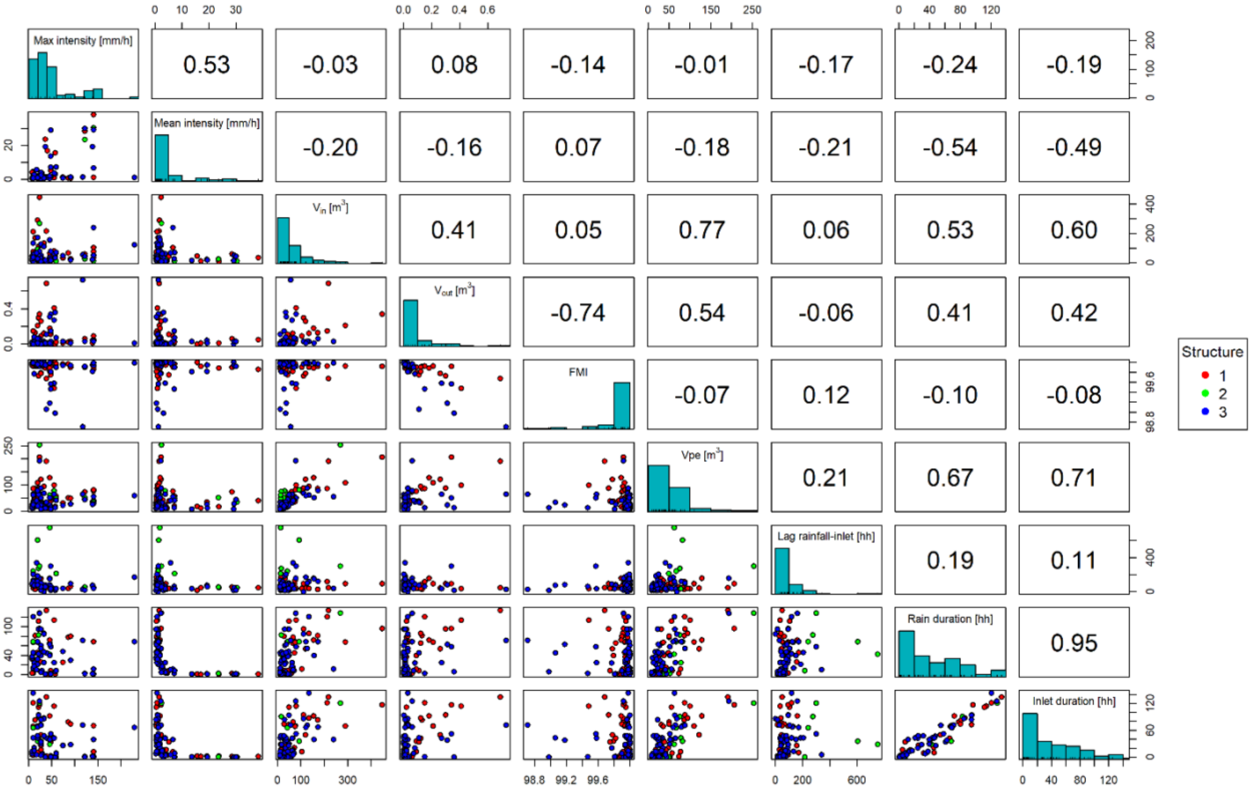

Figure 1A. Scatter plot of matrices, with bivariate scatter plots below the diagonal, histograms on the diagonal, and the Pearson correlation above the diagonal of the variables analysed involving the three structures.