# Development of a low frost-point generator operating at sub-atmospheric pressure



(Article begins on next page)

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# Green gutter as a Nature-based Solution for mitigation and adaptation strategy in urban environments



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Abstract:

The overarching goal in addressing climate change is to understand how humans can act within urban environments to mitigate its impacts, given the profound effect it has on daily life. The primary focus is on reducing its causes and introducing adaptation measurements to promote environmental well-being. Implementing Natural-based Solution (NbS can enhance urban resilience while addressing key environmental challenges. In this context, the main goal of this paper was to conduct an experimental study to evaluate the efficiency of an innovative green infrastructure named green gutter made of mineral wool as a prospective green wall, that can be used to delay stormwater. The experimental tests were carried out at the DTU, dept of Engineering Technology, Ballerup, Denmark. The key targets assessed include the system's capacity to reduce peak flow, delay the arrival time of peak flow, and retain water. Additionally, the duration required for the system to completely empty and fully recover its operational functionality will be examined to estimate when it would be ready to manage the subsequent rainfall events. The system's performance shows a consistent capacity to delay peak flows, especially during shorter, high-intensity rainfall events, such as those lasting 10 minutes, where it reduced peak flow by approximately 50%, and postpone it completely at the end of the precipitation. Key finding is the ability to manage the shorter rainfall, so the most intense precipitation events. This could be a significant contribution to enhanced resilience against flooding and inundation, supporting sustainable urban development and climate change adaptation efforts. By effectively delaying peak flow and managing runoff, this system can contribute to establishing a comprehensive framework for water management within a larger project. This may involve incorporating multiple gutters within a catchment area, strategically distributed at key points.

## Highlights

- An innovative green wall filled with mineral wool for stormwater management was tested
- Experimental tests of the unplanted system were performed for hydraulic characterization
- Results show a peak flow reduction of 50% for a 5-year rain with 10 min duration
- Peak flow delay was on average 15 min among the rain events tested

# Green gutter as a Nature-based Solution for mitigation and adaptation strategy in urban environments


## ABSTRACT

The overarching goal in addressing climate change is to understand how humans can act within urban environments to mitigate its impacts, given the profound effect it has on daily life. The primary focus is on reducing its causes and introducing adaptation measurements to promote environmental well-being. Implementing Natural-based Solution (NbS) can enhance urban resilience while addressing key environmental challenges. In this context, the main goal of this paper was to conduct an experimental study to evaluate the efficiency of an innovative green infrastructure named green gutter made of mineral wool as a prospective green wall, that can be used to delay stormwater. The experimental tests were carried out at the DTU, dept of Engineering Technology, Ballerup, Denmark. The key targets assessed include the system's capacity to reduce peak flow, delay the arrival time of peak flow, and retain water. Additionally, the duration required for the system to completely empty and fully recover its operational functionality will be examined to estimate when it would be ready to manage the subsequent rainfall events. The system's performance shows a consistent capacity to delay peak flows, especially during shorter, high-intensity rainfall events, such as those lasting 10 minutes, where it reduced peak flow by approximately 50%, and postpone it completely at the end of the precipitation. Key finding is the ability to manage the shorter rainfall, so the most intense precipitation events. This could be a significant contribution to enhanced resilience against flooding and inundation, supporting sustainable urban development and climate change adaptation efforts. By effectively delaying peak flow and managing runoff, this system can contribute to establishing a comprehensive framework for water management within a larger project. This may involve incorporating multiple gutters within a catchment area, strategically distributed at key points.


**Keywords:** Nature-based solutions, climate adaptation, stormwater management, green infrastructure

## INTRODUCTION

In recent decades, the predominant discussion has revolved around the issue of climate change and how human can act to tackle this problem in the urban environment (Kyprianou et al., 2023), aiming to reduce the causes and sources of climate change in order to promote the human well-being and environment protection (Frumkin et al., 2017). It is important to highlight that humans settlements represent focal points where the impacts of climate change will be intensely felt, as they are the heart of the problem, being both the victims and responsible for this phenomenon (Živković, 2019, United Nations, 2024). Stormwater runoff is an increasing problem in urban areas, as urbanization processes normally lead to an increase in impermeable surfaces, reducing the share in water balance related to rainwater infiltration in soil (Maria Manso, 2021). Numerous sources of pollution and their consequential impacts stem from human activity (Omri & Boubaker, 2024). Cities must enact integrated policies to achieve greater sustainability, resource efficiency, energy conservation, pollutant reduction, and adequate water management (Pörtner et al., 2022). Traditional stormwater management is based on drainage systems leading to the sewage network, but intense rainfall events may overload the sewage system, causing overflow and flooding (Li et al., 2024). Alternatively, it is possible to adopt local infrastructure aiming at reducing runoff by temporary storage or infiltration, using different types of so-called green infrastructure such as Nature-Based Solutions - NbS (European Commission, 2024).

Nature-based Solutions (NbS) consist in technologies and practices used to protect, and restore natural or modified ecosystems, supporting the mitigation of social challenges using natural or inspired in nature processes, providing benefits to both human well-being and biodiversity (Naumann et al., 2023). NbS were developed aiming, at the same time mitigate the impacts of urbanization on the hydrological response of watersheds and to promote approaches that minimize natural resources usage and support environmental and biodiversity preservation (Lafortezza et al., 2018; Sowińska-Świerkosz et al., 2022). The use of NbS offers multiple benefits, including environmental positive effects, such as: thermal comfort and carbon sequestration (Getter et al., 2009), air pollution filtering (Tomson et al., 2021), water retention (Almaaitah et al., 2022) and biodiversity enhancement (Hoeben et al., 2021); social cohesion and contribution to well-being (Roggero et al., 2020), as well as economic advantages. As pointed out by Beceiro et al. (2020), the aforementioned features of NbS highly contribute to urban resilience and adaptation to the issues related to climate change.

Indeed, a closer look at the built environment shows that opportunities lie in transforming buildings with NbS to support climate adaptation through the widespread use of green infrastructures, like green roofs and green walls (Kandel et al., 2024).

Green infrastructure including green walls and green roofs are among the most environmentally friendly technologies for cleaning water and air in urban areas (Biswall et al., 2022). According to Addo Bankas et al. (2024), Green infrastructure (GI) fundamentals focus on the integration of natural elements and ecological processes to promote environmental resource protection in a sustainable way. They are the most desired form of architecture in recent times with the aim of harnessing sustainable benefits and compensating some environmental issues caused by urban development (Besir & Cuce, 2018). Supporting stormwater management, attenuating heat island effect, extending roof life, reducing greenhouse gases emissions, improving air quality, creating recreational areas and providing sound insulation, are just some of the potential benefits of the green infrastructure to the built environment (Chen et al., 2024; Heshmat et al., 2022).

Green roofs consist of roofs coated with green vegetation and growing medium (Shafique et al., 2018), whereas green walls can be defined as a greenery system envelop on vertical layer and are also often referred to as vertical greenery system (VGS), vertical garden, vertical green, vertical landscaping, and bio walls (Manso & Castro-Gomes, 2015). Among NbSs, green walls are the most appropriate approach in urban areas, due to the lack of horizontal space (Costamagna et al., 2022). When compared with green roofs, green walls really present an advantage in terms of available space for installation in dense urban areas, as high-rising buildings have a much larger vertical area than roof space (Pérez et al., 2014, Ragheb et al., 2016). The application of green walls has recently broadened from solely offering aesthetic values to solving urban environmental challenges (Addo-Bankas et al., 2021). In addition to the aesthetical benefits, VGS can act as a decentralized solution for climate adaptation and flood mitigation (Oral et al., 2020), since it can contribute to reduce stormwater runoff flow and rate, acting as a break for water flow (Galvão et al., 2024). Indeed, as presented above, green walls are multifunctional and can be used not only as a filtration media to remove pollution from greywater, but also delaying storm water, enabling reducing peaks in the urban drainage systems and therefore supporting flood prevention urban infrastructure (Essuman-Quainoo et al., 2023).

While previous research indicated the benefits of NbS on urban climate adaptation, the extent of their impact remains insufficiently studied (Ferrario et al., 2024). Manso et al. (2021) also highlighted that existing research is mainly focused on the quantification of green roofs performance and recommends that further studies should address green walls related effects. Similarly, according to Palermo et al. (2023), there is still a gap on studies addressing green walls efficiency in managing stormwater, despite these systems present similar hydrological processes as other NbS. In this context, the main goal of this paper was to conduct an experimental study to evaluate the efficiency of an innovative green infrastructure named green gutter made of mineral wool as a prospective green wall, that can be used to delay stormwater.

## MATERIAL AND METHODS

### *Description of the experimental apparatus*

The experimental tests were carried out at the DTU, dept of Engineering Technology, Ballerup, Denmark. The experimental apparatus consists in a gutter filled with Rockflow by Rockwool's company a special type of mineral wool designed to be used in water delay systems, capable of dealing with heavy rain phenomena. This structure, hereinafter called green gutter, is conceived as the basis of a prospective VGS. The current experiments focused on the hydraulic performance of the system in the absence of vegetation, hence excluding the further beneficial effect of evapotranspiration that will be assessed in future studies. Table 1 provides an overview of the main physical properties of the mineral wool used in this study (Rockwool, 2025).

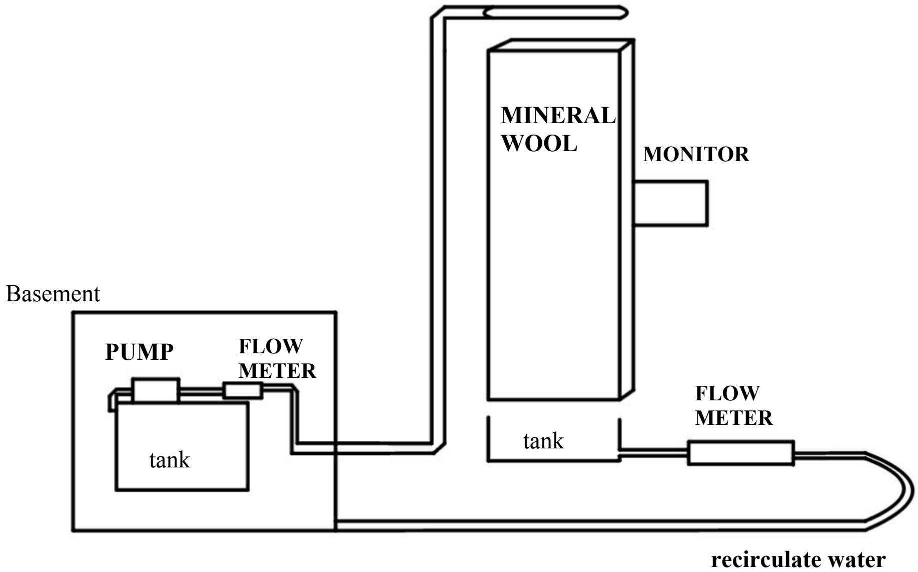
*Table 1. Physical characteristics of the mineral wool used in the experimental setup*

| **Property** | Value |
|---|---|
| material | 97% raw material basalt and recycled stone wool. |
| density | 5% |
| porosity | 95% |
| k-value (permeability/hydraulic conductivity) | 50 to 200 meters per 24 hours |
| lifespan | 50 years |

Figure 1a shows a schematic representation of the system and Figure 1b provides a photo the experimental apparatus. The downspout comprises a metal box filled with mineral wool. Water enters at the top of the mineral wool and flows downward through the system. Moisture sensors embedded at various levels within the porous material facilitate monitoring of the filling and emptying process based on water content.

The structure measures 4 meters in height, width 0,6 m, and depth 0,15 m. Along its elevation, 8 moisture sensors (DFRobot®) divided in 2 lines of 4 are embedded within the filling material to assess saturation levels and water content. This facilitates the estimation of drainage processes and the system's water retention capacity. Real-time monitoring data (MONITOR) was accessible through a web-based open platform (ThingSpeak®).

Behind the gutter, a Digital Temperature Humidity Sensor (Fafeicy FS400-SHT3X) is positioned to monitor humidity and temperature fluctuations. The outflows are monitored using a GE AquaTrans™ AT600 ultrasonic flowmeter. The system presents a pump and valves used to control the flow rate according to the values desired.




*(a)*

*(b)*

*Figure 1.(a) Schematic diagram of the experimental apparatus; (b) Experimental apparatus: 4 m metal casing filled with mineral wool gutter and position of the 8-moisture sensor numerated show in red.*

***Design of experiments***

The initial phase of experimentation pertains to preliminary tests conducted to understand the system's functionality, its response to initial input, and the performance of the different sensors, focusing on their data collection capabilities. The gutter was tested with two distinct flow rates, 200 and 400 litres per hour, both for a duration of 1 hour, representing respectively a precipitation event of intensity 12mm/h and 25mm/h. Trials were conducted iteratively, with intervals of 48 hours between runs, ensuring adequate time for the system to return to its driest state. It was determined that the system required approximately 4 hours as time interval to recover its functional operations, as indicated by the moisture sensors too. The second preliminary phase aimed to discern its principal purpose finds out the maximum capacity of the system of 1200 litres per hour which corresponds to an intensity of 74 mm/h. This indicates that gutter will experience overflow when rainfall is larger than 74 mm, since the buffering capacity is exceeded, and the gutter cannot retain more water. This approach proved that water was not effectively retained within the gutter for subsequent use, whereas the main goal of the gutter will be in the attenuation of peak flow. In addition to these preliminary findings, attention was directed towards addressing very high-intensity rainfall events, with the primary focus on exploring the potential and efficacy of the gutter system in mitigating the adverse impacts of intense precipitation events as an adaptation strategy within the context of climate change-induced scenarios.

The primary objective is to comprehend how the system works as the two most influential parameters (i.e., flow rate and duration of the event) vary. Thus, the influence of these two parameters has to be assessed.

Adhering to engineering and statistical methodologies, it was decided to analyse these parameters through Intensity-Duration-Frequency (IDF) curves and choose among them two different return periods for subsequent comparison. The IDF curves were obtained in Winther et al. (2011). Based on the obtained data, an assessment was conducted to determine which values would be compatible with the system. Given that the maximum capacity of the gutter is assessed on 1200 l/h and the delay interval is nearly always 10 minutes, the highest return period was set at 5 years. A return period of half a year, shorter than the previous one, was selected to evaluate the system response to more frequent but less intense events. Regarding duration, it was chosen to advance 10 minutes by 10 minutes, and to double the 30 minutes by 1 hour. To correlate the volume per hour of rain (l/h) and the intensity of rain (mm/h), it is considered the roof of DTU laboratory, approximately 16 $m^2$. Therefore, the experiments were carried out with the pre-determined constant rain intensity for the corresponding durations, as shown in Table 2.

*Table 2. Rain intensity, duration and equivalent return period for the set of experiments tested.*

| | Rain Duration (min) | | | | Return period (Years) |
|---|---|---|---|---|---|
| | 10 | 20 | 30 | 60 | |
| Rain intensity (mm/h) | 68 | 46 | 30 | 20 | 5 |
| | 30 | 19 | 15 | 9 | 0.5 |

For each event, two experiments per day were conducted, the second taking place 4 hours after the first one was interrupted. Since the first experiment was performed on a completely empty gutter, the primary analysis focuses on it. On its side, the second experiment is taken in consideration to consolidate the first result and in case evaluate any differences or similarities in the system's response to the same event occurring after a few hours.

***Data acquisition, treatment and analysis***

Regarding the flow meter values, the primary focus lies in assessing the time taken to achieve the outflow discharge corresponding to the maximum flow rate provided as input, and the time to subsequently empty the system. This analysis aims to comprehend the system's capability to delay the arrival of peak flow and retain water during the emptying process.

In order to compute these values, data for each experiment, are arranged into separate tables, which account several columns used to create and plot the values in a time-series graph. This will be useful for analysing the flow pattern, enabling the calculation of time intervals of the outflows and peak flow.

Table 3 shows the template of the table used for data analysis, where the first columns regard the time: one is to convert hours into minutes, the next one to evaluate the minutes elapsed from the beginning of the experiment, and the next one from the stopping of it. Next to them, there is the column with the corresponding flow rate in liter per second, and next one that indicate the corresponding percentage of the flow rate relative to the inflow rate.

*Table 3. Template of data analysis table*

| Test | hours as minutes | min spent since start | min spent since the stop | flow meter (l/s) | percentage | behaviour |
|---|---|---|---|---|---|---|

The fluctuations of measurements due to instrument precision are strongly evident on Figure 2.

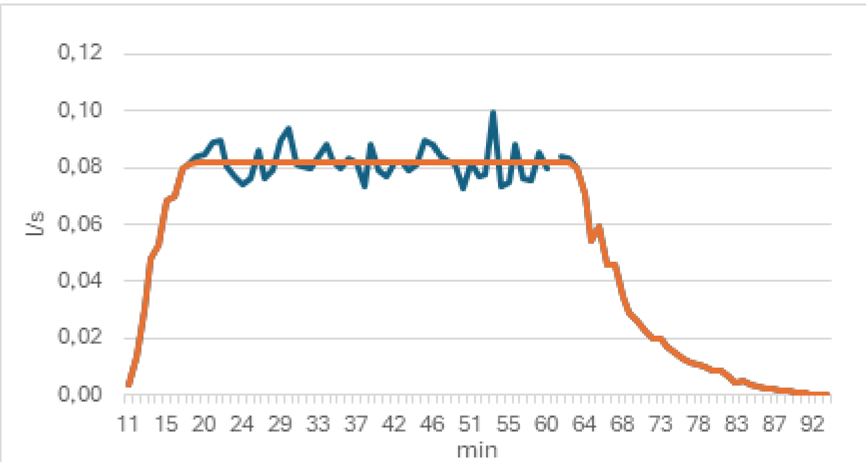



*Figure 2. Example of time-series graph with the evaluation and definition of plateau behaviour during the saturation phase*

Two main actions are computed on it. The first addresses null flow measurements due to electronic interruptions, which are easily removed manually. The second action defines a mean behaviour during the phase where noise and outliers are more present. In particular, this phase is situated after the filling process and before the emptying process, when the flow rate reaches an average value. This one will be calculated and indicated as the maximum flow rate of that experiment and, therefore the peak. When the maximum flow rate is more or less reached, the curve exhibits a plateau behaviour on the graph. This occurs because the gutter is completely full, the material inside is saturated, and the water simply passes through it. The maximum flow rate is reached, and fluctuations are attributed to water bouncing inside the tank before the flow meter, and turbulence at the flow meter. Therefore, the analysis calculates the average flow rate values within this interval, leading to a plateau-like behaviour.

This plateau value represents the maximum percentage of flow rate achieved during the event, and so the peak flow. This assumption is supported by analysing what happens with the filling process. Indeed, it can be observed that after the filling process, when the material is saturated, the function of the gutter effectively ceases. The gutter is capable of delaying the water flow until saturation is reached and can delay the release of water after the stop. This remains the case until the end of the test run, when the pump is stopped, halting the flow of water, and there is no more incoming flow. Since the rockwool is saturated, it cannot retain additional water, which simply passes through. The following analysis addresses these two main goals.

The delay time is evaluated in three steps:

1. When the system attains 50% of its maximum flow rate
2. When the system reaches the 70% of its maximum flow rate
3. When the peak flow is achieved

The percentage is computed as follows: $\% = 1 - \left(\frac{peak\ flow - instantaneous\ flow}{peak\ flow}\right)$.

Conversely, the emptying process, characterized by a smoother transition, involves multiple steps, progressing through flow rates of 50%, 30%, 20%, 10% of maximum flow rate, and ultimately, null flow.

The time of null flow, due to its high sensitivity to instrument precision, it is not the most reliable parameter to consider. Hence, for the sake of consistence, the first instant where a 0% flow rate is established is chosen as time null flow. In cases of oscillation, the last recorded value by the flow meter is used as the reference point. The two variables minutes and percentage that determine the computation, were considered with decimal error, and it is considered as the unit number, accounting systematic and casual errors.

## RESULTS AND DISCUSSION

The earliest discussion of the results is carried out mainly through a statistical analysis, which encompass all outcomes of the tests, among all the experiments. For each time interval of % outflow individuated as presented in previous section, an average value, the standard deviation and medians are calculated. Additionally, the maximum and minimum values are highlighted. In that way, a general overview of the system's behaviour can be obtained understanding the expected outcome variations. Through the average value, it is researched a central tendency to individuate a typical datapoint within the dataset. The reliability of that point is evaluated through the standard deviation, which will allow to gauge the variability and dispersion, providing insights into how spread out the data points are relative to the mean. With the median, it is offered an additional perspective on central tendency, by representing the middle point of the dataset that is less affected by outliers and skewed data. After the description of the central tendency, evaluation of the maximum and minimum value, will help to understand the upper and lower boundary, identifying the highest and lowest point within the data range that can be assumed. The analysis of the main set of experiments based on a constant flow input varying the duration aims to identify differences and similarities between events with the same duration but different flow rate, or same flow rate but different duration. The results of general statistical analysis of them are presented in Table 3 and 4.

| Statistic metric | Delay 50% | Delay 70% | Peak delay % |
|---|---|---|---|
| Statistical results of filling process duration (min) | | | |
| Average | 12 | 13 | 15 |
| St. dev. | 2 | 3 | 5 |
| Median | 12 | 13 | 14 |
| Minimum | 9 | 8 | 8 |
| Maximum | 18 | 19 | 27 |

*Table 4. Statistical results for set of experiments for the filling process derived by IDF curves with different amount of constant inflow rate and the corresponding duration.*

| Statistic metric | Empty till 50% | Empty till 30% | Empty till 20% | Empty till 10% | Empty 0% |
|---|---|---|---|---|---|
| Statistical results of emptying duration (min) | | | | | |
| Average | 7 | 9 | 12 | 17 | 39 |
| St. dev. | 2 | 2 | 3 | 3 | 8 |
| Median | 7 | 10 | 12 | 17 | 39 |
| Minimum | 4 | 5 | 6 | 10 | 25 |
| Maximum | 9 | 13 | 18 | 24 | 54 |

*Table 5. Statistical results for set of experiments for the emptying process derived by IDF curves with different amount of constant inflow rate and the corresponding duration*

***Peak flow delay***

The first result obtained result is the evaluation of the delay in peak flow. A notable outcome is the delay in reaching half of the inflow rate, which consistently exceeds 10 minutes (Table 4). This finding indicates effective control of the rain event.

The reliability of these results is supported by the low observed variability, given the acceptably low values of standard deviation, and the further corroboration through the median and minimum values. It is worth noticing that the maximum value was even higher than 10 minutes in some cases.

These insights suggest paying more attention to the extreme events characterized by short duration and high rainfall intensity, i.e., the ones lasting 10 minutes.

When evaluating the delay time in reaching the peak flow rate, despite the higher mean value and increased standard deviation, the key value of interest is the minimum delay. This minimum delay, which does not fall below 8 minutes, demonstrates that even in the case of 10-minute events, the peak flow rate is generally delayed until the event has nearly or completely concluded.

Figure 4 shows the inflow and outflow for a 10 min rain events, where it can be seen that the green gutter was able to provide a significant delay in peak flow in both events analyzed.

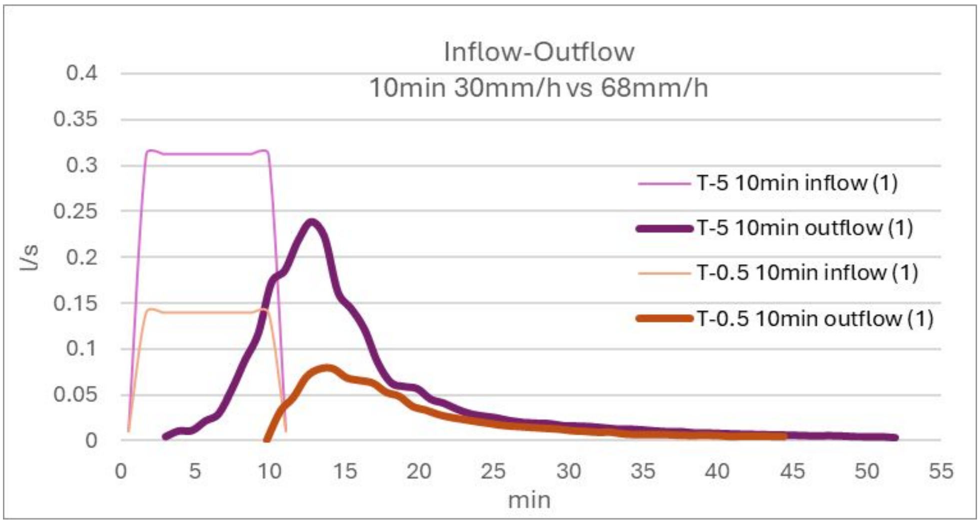



*Figure 3. Inflow-outflow graphs for the tests lasting 10min with a constant rain intensity of a) 30mm/h, corresponding to a return period T=0.5 years, and (b) 68mm/h corresponding to a return period T=5 years*

In spite of being the most impactful events characterized by the largest flow rates over short duration, these events produced the most favourable outcomes in terms of the gutter system's response. The peak flow is completely delayed until after the event has ended, and both graphical analysis and computation indicate a small yet significant reduction in peak flow, attributed to incomplete saturation.

For longer events, as one in Figure 3, once the system reaches saturation, its ability to manage water diminishes, and water passes through it without substantial retention, meaning that optimal performance occurs before saturation.

This result show that the delay time depends on the duration of the event obviously, but also on the amount of input flow rate. This assumption is properly corroborated by the statistical analysis of the preliminary test, in which for the same duration of the experiment, 60 minutes, different amount of flow rate are given as input. With a lower flow rate, the peak arrival time is longer, whereas at maximum capacity, the peak is reached much faster. Indeed, to higher flow rates correspond shorter interval of time, since the larger and the faster arriving of water produce an accountable shorter delay.

From the general statistical analysis, nevertheless, a sufficient lag interval of more than 10 minutes is estimated for all tests in order to delay 50% of the inflow. This peak flow delay provides urban drainage systems with the ability to handle water volumes for an extended period, allowing better preparation for peak flow arrivals. As a result, it reduces the risk of system overloading and mitigates the likelihood of urban flooding.

This finding holds substantial practical implications for gutter systems in urban areas, offering huge opportunities to develop water management skills. The gutter system's capacity to collect water and release it only after the most intense phase of precipitation has passed, can enhance overall water control strategies.

***Analysis of hydraulic parameters***

Some additional control parameters are computed to gain control of the analysis.

The duration of each event, modified by the presence of the gutter, is determined by evaluating the time interval referring to the time point of the first value recorded by the flow meter and the time point corresponding to the zero-flow condition. The difference, measured in minutes, represents the duration of the event, reflecting the gutter's response, including the delay and smoother release of water. This provides an initial indication of how the precipitation event is managed differently due to the gutter system, which mitigates the abrupt impact of the rainfall event. Through this time interval the damped intensity is thereby calculated.

Just for this purpose, two other control parameters are calculated such as runoff coefficient and peak reduction. In this analysis, the runoff coefficient is calculated as the ratio between the volume of water measured by the flow meter (represented by the area under the flow meter curve) and the volume of water supplied by the pump (represented by the area under the inflow curve). This parameter is critical for the design of flood control channels and delineation of potential flood hazard zones. Larger values indicate higher runoff and lower infiltration. A high runoff coefficient suggests areas susceptible to flash flooding during storms, as water moves rapidly over the surface. Peak reduction is defined as the complement of the ratio between the maximum outflow rate and the inflow rate.

The results obtained by the analysis of the experiments indicate a peak reduction consistently ranging between 10-15%, that is more likely to be due to a measurement sensitivity variation between the pump and the flow meter.

Notably, the 10-minute tests demonstrated a higher peak reduction, suggesting a possible actual physical reduction in peak flow since it is assessed around 50% with an analogue damp intensity value.

Due to this slight variation in instrument sensitivity or overflow at inlet, the runoff coefficient cannot be considered entirely reliable as a parameter, too. However, the observed range of results is not highly significant, as the primary function of the gutter system is to delay and smooth the water release rather than retain a portion of the water. This opens up a potential area of research about the vegetative gutter covers to enhance performance.

***Filling and emptying duration***

Evaluating the filling process, it is possible to describe an initial slower filling of the gutter until 50% of the maximum flow rate, then the passage between 50% and 70% is the fastest one for all the experiments, with an abrupt increase of dynamic of filling. The concluding phase to reach 100% is smoothly reached, but less respect the initial phase. The last phase of the filling process is strongly influenced by the rainfall intensity, with a time to reach the peak flow that is inversely proportional to rainfall intensity.

For the same intensity of precipitation, the dependence on the duration is considered since the total amount of precipitation changes. This is traduced in faster peak reaching for the shorter events since the same intensity in shorter time results in a lower amount of precipitation, and thus to a higher capacity of the gutter to attenuate the event.

Regarding the emptying process, the main feature is that it is strongly linked to the properties of the material while it is independent on the characteristics of the event. What emerges is that the release is gradual, decreasing monotonically, however first faster drainage phase and then a second final lower one can be individuated. The former occurs in the first 30 minutes after the event have been stopped, then in twice of the time only 10% is emptied. This slower drainage, which might suggest the occurrence of retention, could support the presence of a plant layer that can use the remaining water.

Furthermore, the quick partial emptying of the gutter ensures that it will be ready again for the next event. This finding, also reflected by the moisture sensor results too, indicates a rapid and efficient recovery capacity of the system, as the completely dry condition is almost always restored within four hours. Comparing the time-series resulting by the values of the flow meter and the moisture sensor during the emptying phase, it could be noted that both measurements show a similar pattern.

Figure 4 shows the graphs corresponding to the flow meter and the moisture sensor during the emptying phase. For the moisture sensor, only the data from Field 7 (see Figure 1b) are presented to facilitate visualization and explanation. Field 7 was selected as it is one of the most representative and sensitive to all aspects of the trial process. It could be noted that both sensors show a similar pattern, but the flow meter continues to have a peak flow even before the inflow is stopped because of the delay between the inlet and outlet position where the flow meter is installed. On the other hand, the moisture sensor shows a decay in moisture values as soon as the flow stopped. In terms of response times, the flow meter in both tests gives values around zero after around 30 to 40 min, while the moisture sensors are more sensitive, showing an additional emptying process lasting for 2,5 hours (150 min).

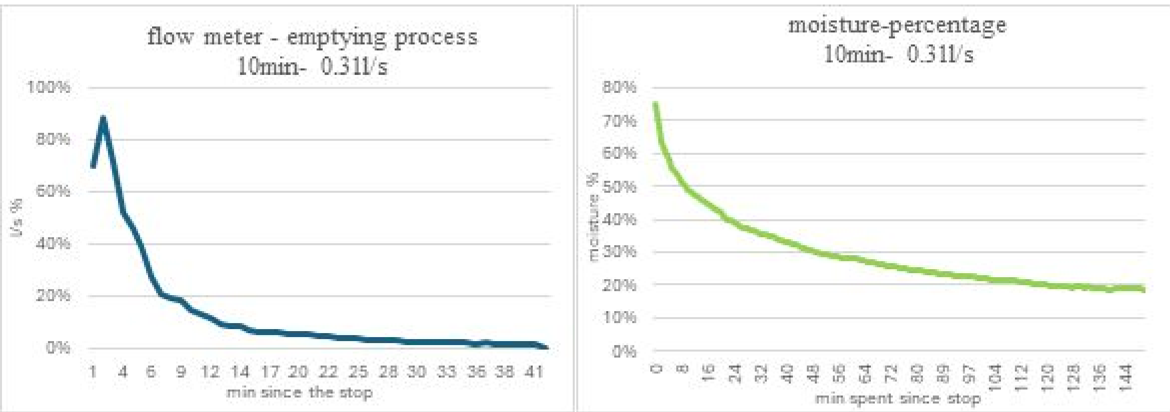



*Figure 4. Moisture and flow meter graphs for the emptying phase (a) outlet flow variation (b) moisture variation.*

This confirms the evaluation already presented on the recovery of functionality and dry condition of the gutter after certainly 4 hours, this is also corroborated by the second run of the constant flow rate tests performed after 4 hours in the same day can be very useful.

The filling process in the second experiment occurs more quickly respect the first experiment which in comparison exhibits a slower and smoother response. Specifically, the first run maintains a consistent overall behaviour with a more gradual arrival time, whereas the second run shows a steeper increase already after the 50% mark, rapidly reaching the peak. These findings suggest that, after a 4-hour interval, the gutter remains functional, although its efficiency in delaying water flow is reduced.

Regarding the emptying process, the behaviour and values are remarkably similar, with the response curves completely overlapping. This indicates that the porous material releases water in the same manner, even after just a 4-hour interval. This lays the groundwork for future studies to identify a model for the emptying equation also using moisture analysis.

**Variation of parameters over the IDF Curves**

The analysis will now attempt to pool all the experiments respectively at the return period to understand how the parameters vary across the IDF curves as the duration of the event increases and the corresponding flow rate decreases.

As presented in Figure 5, for the filling process, all the parameters vary in a similar way among the IDF curves. As it is anticipated, the average interval time will increase across all values, indicating a longer process for extended events and a much faster one for shorter events. This observation aligns with expectations of a longer filling process with lower flow rates. The 10-minutes event is the fastest one, but above the line of 10, remarking the complete delay of the effect after the end of the event itself. As already demonstrated by the general statistics graphs, the passage between 50% delay and 70% delay is the fastest one for all the experiments. The peak is reached slowly moving towards the longer event, which confirms the strong dependence on the amount of flow rate in the last phase of filling, as found in the general statistical analysis.


*Figure 4. Variation of parameters for filling process over the IDF curves for 2 return periods a) T:0.5 year b) T:5 year.*

Regarding the emptying process, Figure 6 exhibits similar results for almost all scenarios. This indicates that the emptying process is less dependent of the rain event that the filling process, which is notably visible in the 10, 20- and 30-minute tests, which share almost the same variation of values. The emptying process is characterized by a faster draining that occurs in the first 10 minutes having an emptying rate of 80%, after remaining 20% is emptied. This slower drainage, which might seem almost like accumulation, could be coupled with the function of a plant layer that can use the remaining water.

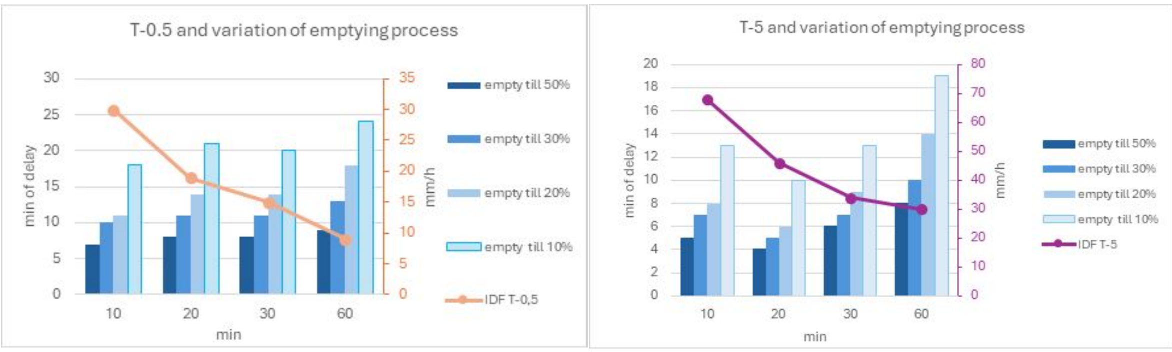



*Figure 5. Variation of parameters for emptying process over the IDF curves for 2 return periods a) T:0.5 year b) T:5 year.*

## CONCLUSION

The experimental study on the green gutter highlights its significant potential as an effective water management system, offering substantial benefits in reducing the stress on urban drainage infrastructure. Tested under various rainfall scenarios, the system demonstrated its ability to delay and reduce peak flows, mitigate rainfall intensity, and enhance short-term water retention, making it a promising addition to sustainable urban water management. The system's performance shows a consistent capacity to delay peak flows, especially during shorter, high-intensity rainfall events, such as those lasting 10 minutes, where it reduced peak flow by approximately 50%, and postpone it completely at the end of the precipitation.

The system's key advantages, thanks to mineral wool hydraulic properties, lie in its ability to delay, partially absorb and gradually release the water, ensured a manageable flow into the drainage network. The green gutter showcases itself as a sustainable solution in real-world application minimizing flash flood risks in urban areas vulnerable to extreme weather events with impermeable surfaces.

Despite its efficacy, the study identifies areas for future research and further development. Furthermore, it could be necessary to test the robustness of the system in terms of its ability to handle successive rainfall events and using more realistic rainfall events as well as to investigate the synergistic effects of a more comprehensive stormwater management network combining the green gutter with other urban green infrastructures, such as green roofs or permeable pavements. Moreover, another important aspect of this project is its scalability. While this study focused on a single green gutter, scaling up this approach could involve deploying multiple systems across urban environments. By placing these systems at strategic locations in areas prone to flooding, it can create a network that significantly reduces the risk of inundation during extreme rainfall events. Additionally, further exploration of the system's long-term performance is necessary, focusing on the durability of mineral wool under continuous exposure to urban pollutants and varying weather condition, with the possibility of obstructing the functionality.

Next steps will focus on testing the system with incorporation of plants in order to check the impact of those in the hydraulic performance as well as evaluate other benefits of the green gutter in terms of biodiversity and building aesthetics. Indeed, beyond its hydraulic advantages, the green gutter system has potential to provides broader environmental and ecological benefits as a Nature Based Solution. The proposed enhancement with a vegetative layer, transforming the gutter into a prospective green wall, will improve air quality, mitigate the urban heat island effect, reduce building energy requirement and foster biodiversity in otherwise concrete-heavy environments.

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