ACAE

SCIENTIFIC PAPER
Published: June 17, 2026
https://doi.org/10.13167/2026.32.12

Analysis of combination test of infiltration box and absorption well to reduce road flooding

Awliya Tribhuwana[1]✉, Slamet Imam Wahyudi[2] and Mohammad Faiqun Niam[2]

[1] Swadaya Gunung Jati University, Faculty of Engineering, Department of Civil Engineering, Jl. Pemuda No. 32, 45132, Cirebon, Indonesia

[2] Sultan Agung Islamic University, Faculty of Engineering, Department of Civil Engineering, Jl. Raya Kaligawe Km 4, 50112, Semarang, Indonesia

Corresponding author:
Awliya Tribhuwana

Received:
June 11, 2025

Revised:
April 14, 2026

Accepted:
May 6, 2026

Published:
June 17, 2026

Citation:
Tribhuwana, A.; Wahyudi, S. I.; Niam, M. F.
Analysis of combination test of infiltration box and absorption well to reduce road flooding.
Advances in Civil and Architectural Engineering, 2026, 17 (32), pp. 205-223.
https://doi.org/10.13167/2026.32.12

ADVANCES IN CIVIL AND ARCHITECTURAL ENGINEERING (ISSN 2975-3848)

Faculty of Civil Engineering and Architecture Osijek
Josip Juraj Strossmayer University of Osijek
Vladimira Preloga 3
31000 Osijek
CROATIA

Abstract:
Urbanisation increases impervious surfaces, leading to increased runoff and flood risk, particularly in tropical urban areas. This study examines the effectiveness of a combination of infiltration boxes and wells installed in road medians as a decentralized stormwater management strategy. Experiments were conducted using a laboratory-scale flume model to compare hydrological responses with and without an infiltration system. The analysed parameters included runoff volume, peak discharge, peak time, and infiltration efficiency. The results indicated that the system performance varied depending on configuration, with runoff reductions ranging from 30,34 to 59,37 %. Under optimal conditions, the system was able to reduce peak discharge by up to 85,17 % and delay peak flow time by approximately 35 min, indicating significant improvements in retention capacity and flow control. The infiltration efficiency ranged from 50,74 to 68,47 %, indicating the system ability to increase water absorption and reduce surface runoff. However, under extreme rainfall conditions (> 100 mm/h), the system capacity reached its maximum limit, necessitating integration with conventional drainage. In conclusion, these findings confirm that infiltration boxes are an effective low impact development solution and can be integrated to improve urban hydrological resilience.

Keywords:
infiltration box; surface runoff; peak discharge; flume channel; green infrastructure

1 Introduction

Urbanisation increases the proportion of impermeable surfaces such as roads, rooftops, and sidewalks, which reduces infiltration and increases surface runoff and flood risk [1]. In urban areas, approximately 50 % of the surfaces are impermeable, resulting in 29 % of the rainfall flowing over sandstone and 17 % over limestone [2]. During heavy rainfall events, runoff volumes increase significantly, particularly on impermeable surfaces [3]. Although permeable surfaces still contribute to surface runoff, their contribution increases particularly during heavy rainfall and extreme events. Therefore, the design of adaptive urban drainage systems must consider rainfall characteristics, as well as the distribution of impermeable and permeable surfaces [4].

This research focuses on the increasing impervious surface area due to urbanisation, which significantly increases surface runoff and flood risk in urban areas. Various blue-green infrastructure (BGI) approaches such as rain gardens, biofiltration channels, green roofs, and permeable pavements have emerged as effective strategies for reducing runoff and improving water quality [5],[6]. BGI elements use biophysical mechanisms to store, filter, and infiltrate rainwater. Bioretention ponds in Italy have been able to reduce runoff volume by approximately 50 % [7]. BGI also provides additional benefits such as reduced eutrophication, improved urban ecosystems, and cost efficiency [8; 9]. However, BGI implementation faces challenges such as climate uncertainty, conflicts among stakeholders, and socioeconomic and cultural barriers [10].

The success of BGI integration depends heavily on public awareness, technical capacity, and collaborative cross-sectoral approach [11]. Several countries have successfully integrated conventional drainage systems into nature-based solutions. China's "Sponge City" program successfully captured up to 91 % of annual runoff [12], far above the national target of 80%. In addition to flood control, the program improved water quality, supported groundwater recharge, and enhanced the aesthetics of urban areas [13]. Specific methods that have proven effective included permeable pavements, green roofs, and vegetated ditches; each of them has demonstrated significant runoff reduction depending on the design and local conditions [5; 14]. However, a research gap remains regarding the application of modular infiltration systems in limited spaces, particularly in road media.

Most previous studies have focused on large-scale systems such as rain gardens or retention ponds, resulting in limited experimental research demonstrating the effectiveness of infiltration boxes in limited spaces. This approach aligns with the principles of low impact development (LID) and best management practices (BMP), which emphasise managing runoff near its source by utilising natural processes such as infiltration and filtration [15]. Previous research has shown that vegetated infiltration systems could significantly increase the infiltration rates [16]. However, only a few studies have quantitatively evaluated the effectiveness of infiltration boxes in road media using experimental approaches.

Therefore, this study aimed to evaluate the performance of a combined hydrological system of infiltration boxes and wells through laboratory simulations using a flume model. The analysis was conducted by integrating historical rainfall data for the period 2014-2024, which had undergone a quality control process, homogeneity test (RAPS), and innovative trend analysis (ITA), thus producing representative hydrological inputs. The main contribution of this study is the experimental evidence regarding the effectiveness of a modular infiltration system in reducing runoff, reducing peak discharge, and increasing infiltration at the laboratory scale, which is hydraulically scaled using the Froude similarity principle. This study is one of the first to experimentally evaluate a modular infiltration system installed in a median road space using controlled channel modelling.

2 Methodology

2.1 Research design

This study used an experimental laboratory approach to document a road drainage system under two conditions: without intervention (conventional) and with intervention in the form of infiltration boxes and wells. This approach aimed to modify hydrological parameters, such as runoff volume, peak discharge, peak time, and infiltration efficiency.
The rainfall data were obtained from the Cimanuk-Cisanggarung River Basin Management Agency (BBWS), Cirebon, Indonesia, for the observation period of 2014-2024 (Figure 1). These data were processed into annual maximum time series (AMS) as the basis for the hydrological analysis.

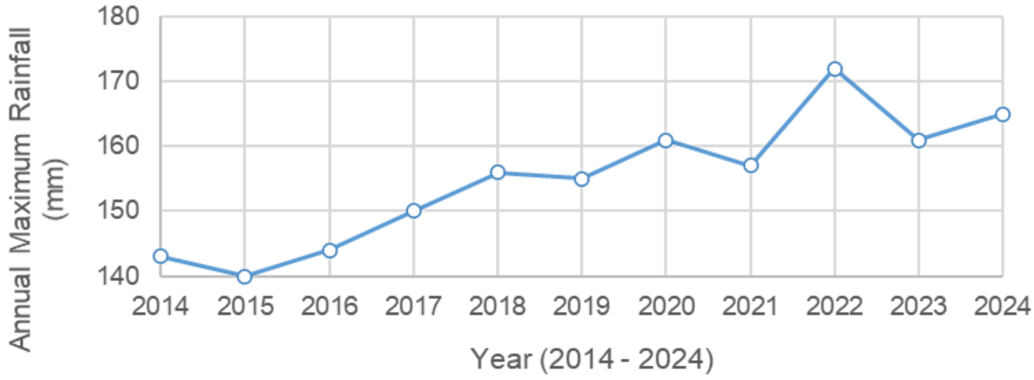

Figure 1. Annual maximum rainfall time series (2014-2024)

Furthermore, the rainfall data used in this study underwent quality control (QC) steps, including checking for missing data, outlier detection, consistency testing using the double mass curve (DMC) method, homogeneity testing using rescaled adjusted partial sums (RAPS) and ITA methods to evaluate homogeneity and trends. The rainfall data were then analysed using frequency analysis with the Weibull approach to obtain the P80 and P90 rainfall values. These values were then converted to rainfall intensity using the Mononobe formula [17] to obtain the rainfall intensity for a 1-hour duration. This rainfall intensity was then converted to laboratory scale using the Froude similarity principle. This approach ensured a good match between the field conditions and physical model (flume) used in the experiment. The analysed data included the runoff volume, flow response time, and infiltration volume. The artificial rainfall volume (input) was measured to determine the total amount of water entering the system during the simulation.
The runoff volume (output) was calculated from the amount of water leaving the system after passing through the road surface and drainage channels. The difference between the inflow and outflow volumes was used to calculate the infiltration volume that was successfully absorbed by the infiltration box and well. The flow response time was measured by recording the time elapsed from the start of the artificial rainfall to the maximum runoff discharge. This parameter is useful for assessing the system response to rainfall, which has implications for flooding potential in real-world environments. To analyse the effectiveness of the intervention, the runoff reduction efficiency was calculated by comparing the runoff volume under conditions with and without the intervention. The runoff coefficient was calculated to describe the characteristics of the road surface with respect to runoff. This coefficient was obtained by comparing the runoff and incoming rainwater volumes. The lower the runoff coefficient, the greater the ability of the system to absorb rainwater will be.

2.2 Infiltration box design

The infiltration box system applied in this study was designed for installation within road medians as a decentralized unit for rainwater harvesting and stormwater management. The design considered several factors, including hydraulic performance, temporary storage volume, and the infiltration capability of the surrounding soil. In addition, the system consisted of supporting elements such as connecting pipes and inlet channels to convey runoff into the infiltration unit. These components were arranged to promote a more uniform flow pattern and improve the overall infiltration performance. The design model of the infiltration system used in this study is presented in Figure 2.

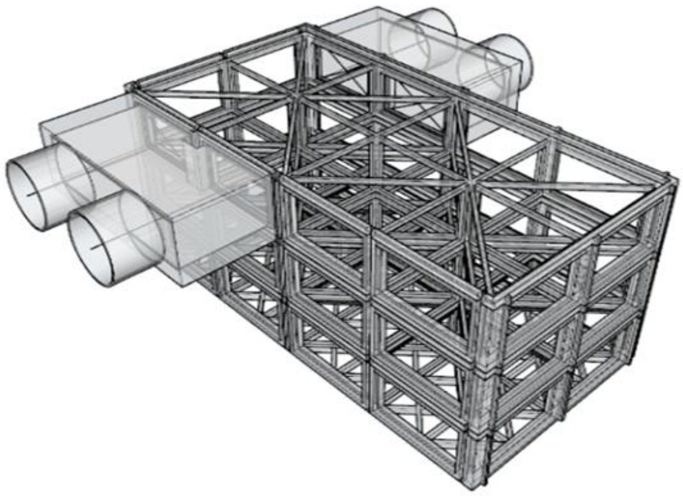

Figure 2. Design model of infiltration box, pipe and inflow connector

The infiltration box was specifically designed for installation in road media and served as a decentralised rainwater-harvesting unit. The box structure consisted of cavities on each side to collect the surface runoff formed by the intersection of rectangular diagonals inward. The cavities were interconnected to form a large box. Each box was made of plastic with dimensions adapted to a laboratory testing channel system: 20 cm long, 10 cm wide, and 9 cm high. All perforated walls allowed excess water to infiltrate the surrounding medium or drain. The infiltration media were empty, and a geotextile fabric was used to wrap all walls to prevent external material from entering the infiltration box. This design prioritises the modularity and ease of maintenance, making it suitable for retrofitting in limited urban environments. The hydraulic capacity of the box was determined based on the rainfall intensity and catchment area, ensuring adequate retention time and infiltration rate under varying flow conditions.

2.3 Flume setup

The experiment was conducted using a flume model consisting of three main components: the median as the location of the infiltration box, Flume 1 as the main drainage channel functioning as an outlet system, and Flume 2 as a secondary drainage channel functioning as a lateral flow distribution. The median channel measured 35 × 50 × 250 cm; the drainage channel measured 24 cm × 40 cm × 250 cm; and the infiltration well channel measured 24 × 80 × 250 cm. All channels were made of 5 mm thick glass reinforced with an L-shaped steel frame with a soil storage capacity of 0,44 m³.

The dimensions of the laboratory model were determined using a geometric similarity approach with a scale ratio of 1:5 for the field conditions. This ratio was obtained by comparing the characteristic lengths between the model (2,5 m) and field prototype (12,5 m) such that all length, width, and height dimensions were scaled proportionally by a factor of 1/5. This approach ensures that the geometric representation of the model maintains a shape appropriate for actual field conditions.

To illustrate the experimental system configuration used in this study, a three-dimensional (3D) model was developed to represent the channel layout, median position, infiltration box placement, as well as the implementation and measurement stages during testing. The model was intended to describe the overall relationship among the system components, including the geometric configuration, placement of the infiltration unit, installation process, and measurement of hydraulic parameters. The series of models and the experimental procedures used in this study are presented in Figure 3.

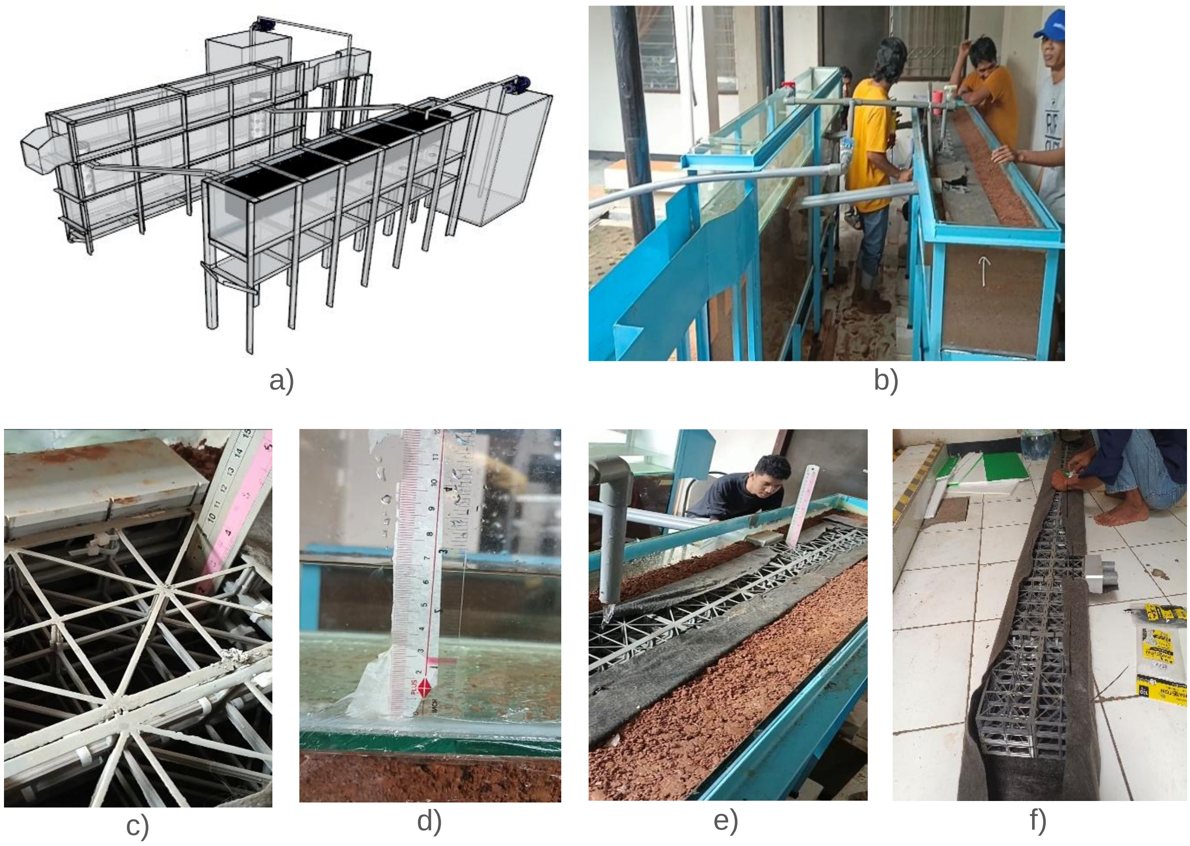

Figure 3. Drainage flume and median flume models: a) three dimensions of flume; b) laboratory flume; c) measurement of water level in infiltration box; d) measurement of water level in drainage flume; e) placement of infiltration box in median flume; and f) assembling the infiltration box into one unit and installing geotextiles

A three dimensional (3D) model of the flume and median flume drainage system (Figure 3) was designed to simulate the runoff flow and infiltration processes under laboratory conditions. This model shows the geometric configuration, elevation differences, and arrangement of the main components of the system, such as channels, catch basins, and infiltration units. The physical implementation of the flume model in the laboratory was used to represent the surface runoff conditions in a controlled manner by regulating the flow in the median and drainage channels.

During testing, the water levels were measured in the infiltration box and flume drainage channel using a measuring ruler to evaluate the hydraulic response, infiltration capacity, and changes in the discharge and water level of the system during the simulation. An infiltration box was placed in the median flume as part of the infiltration system to reduce surface runoff through infiltration.

The infiltration box assembly process involved assembling the infiltration units into a unified system equipped with a geotextile layer. The geotextile served as a filtering medium to prevent the entry of fine particles into the infiltration structure, thus maintaining the hydraulic performance and system stability throughout the test.

To ensure conformity of the flow behaviour between the model and prototype, the Froude similarity principle was used, which was commonly applied in open-channel flow modelling [18-20]. In this approach, the Froude number between the model and prototype was equalised such that the discharge relationship followed the scale $Q_m = Q_p \cdot (1/5)^{2,5}$. Based on the results of the hydrological analysis, the field discharge was 1,27 L/s.

As an illustration, the relationship between the field scale and laboratory model is shown in the conceptual scheme in Figure 2, which shows a comparison of the geometric dimensions (length, width, and height) and discharge relationship between the field system and model. This scheme confirms that the physical model used fulfills the principles of geometric and dynamic similarity such that the experimental results can be scientifically represented back to field conditions. Scaling was performed using the Froude similarity principle with a length ratio of 1:5. The velocity scale was obtained as $\sqrt{1/5}$ = 0,45, while the discharge scale followed the relationship $Q_m = Q_p/55{,}9$. Based on the field discharge of 1,27 L/s, the model discharge was 0,0378 L/s.

2.4 Soil media and flume preparation

The channel was prepared by lining the base with geotextile to prevent erosion and media mixing, and then filled with sandy soil with a dominant grain size distribution of fine to medium sand (D50 ± 0,3-0,5 mm). The soil was loaded and compacted into layers, with each layer having a thickness of 10 cm, and compacted using three compactions. Backfilling was continued until the base of the infiltration box was reached. For the initial soil conditions, two scenarios were tested, saturated and unsaturated soil, to observe the differences in system performance under different moisture conditions.

In addition, the physical properties of the soil were characterised to ensure the suitability of the medium for the infiltration process. The parameters described included soil porosity and permeability. Porosity was calculated based on the ratio of the pore volume to the total soil volume, while permeability was determined using a laboratory infiltration test approach (falling head test). The test results showed that the soil used had a porosity of 0,42-0,45, which indicated a fairly good air storage capacity, and a permeability coefficient value ranging from 10^{-4} to 10^{-5} m/s. This value indicates that the soil has a moderate-to-high infiltration capacity, making it suitable for replicating the infiltration process in urban drainage systems. The soil conditions were tested under two scenarios, saturated and unsaturated, to determine the effect of moisture conditions on the infiltration rate.

2.5 Tested variables and their measurement process

This study examined five key variables used to evaluate the effectiveness of infiltration boxes and wells in reducing surface runoff in road drainage scenarios. Each variable was measured quantitatively using standard procedures to ensure reliability and replicability of the results. The observed variables were the runoff volume, infiltration volume, time to runoff onset, flow rate, runoff duration, and infiltration.

The input water volume was measured as the total water flowing into the system during simulated rainfall. The output runoff volume was calculated based on the amount of water flowing through the drainage channels during the test period.

The runoff volume was obtained by integrating the discharge over time during the test, while the infiltration volume was calculated as the difference between the inflow water volume and runoff volume.

The runoff reduction efficiency was calculated using the following equation:

$$n_r = \frac{V_{in} - V_{out}}{V_{in}} \cdot 100\ \% \tag{1}$$

The infiltration efficiency was calculated using the equation:

$$n_i = \frac{V_{inf}}{V_{in}} \cdot 100\ \% \tag{2}$$

In this study, water-level measurements were conducted using a manual ruler gauge installed vertically at three key points: the infiltration box, median flume, and drainage flume. A ruler was used to record changes in the water level throughout the experiment at 1-minute intervals. This method was chosen because it provided stable, direct measurements, and was easy to control on a laboratory scale. To ensure accuracy, each ruler was calibrated before testing by comparing its readings with the actual water level using static reference measurements.

Furthermore, a ruler was installed perpendicular to the base of the flume to minimise reading errors due to the viewing angle (parallax error). The measurements were made consistently by the same operator to reduce subjective variability. With a measurement resolution of up to ±1 mm, this method is considered sufficiently accurate to represent water level changes in laboratory-scale experiments. The obtained data were then used to construct hydrographs and calculate hydrological parameters such as peak discharge and peak time.

Calibration testing was conducted by comparing the ruler readings to statically known water levels. The results showed that the measurement deviations were within the range of ±1-2 mm, thus satisfying the level of accuracy required for this study.

2.6 Data analysis

The data analysis in this study was conducted quantitatively to evaluate the effectiveness of infiltration boxes and wells in reducing runoff volume, increasing infiltration, and modifying surface flow characteristics. The analytical procedure consisted of several stages ranging from primary data processing to statistical interpretation. References from previous studies, such as [21] and [22], were used to compare and validate the results. As part of the hydrological time series analysis, a homogeneity test was conducted using the RAPS method to detect changes in data structure or non-stationarity [23]. The cumulative standardised deviation was calculated using the following equation:

$$S_k^* = \frac{\sum_{i=1}^{k}(X_i - \bar{X})}{\sigma} \tag{3}$$

where X_i was the *i*-th rainfall data, $\bar{X}$ was the mean value, and σ was the standard deviation. The maximum value S_k^* was used as the test statistic (Q). Furthermore, a trend analysis was performed using the ITA method by dividing the data into two equal periods and comparing them to the 45° equilibrium line [24]. The trend slope was calculated using a linear regression approach, as follows:

$$Slope = \frac{\sum(X_i - \bar{X})(Y_i - \bar{Y})}{(X_i - \bar{X})^2} \tag{4}$$

where X_i and Y_i represented data from the initial and final periods, respectively. As discussed in [25], a hydrological analysis often requires reliable time series methods such as RAPS to detect irregularities that are not easily observed using conventional techniques. The volume balance approach used in [26] and [27] was used to estimate the hydrological parameters based on the obtained volume data.

2.7 Experimental procedure

An experimental procedure was designed to evaluate the hydraulic performance of the infiltration box under various rainfall intensities and media configurations. Prior to each test, the channel system was calibrated, and the infiltration box was filled with a specific media layer to ensure uniform compaction and consistent initial moisture conditions.

The rainfall intensity used in the simulation was obtained from the analysis of field rainfall data that had undergone a quality control process. The reliable rainfall was calculated using the Weibull method, which resulted in P80 and P90 values of 103 and 99 mm/d, respectively. These values were then converted to rainfall intensity using the Mononobe formula [28], resulting in an intensity of 35,7 mm/h (P80) and 34,4 mm/h (P90) for a rainfall duration of 1 h. Daily rainfall values were converted into hourly intensities using the Mononobe equation.

Subsequently, the rainfall intensity was converted to runoff discharge using a rational method, and then scaled into a laboratory model based on the Froude similarity principle with a geometric ratio of 1:5. This scaling resulted in a model discharge rate of 0,0378 L/s, which was used as the basis for the experiment.

This value was obtained by calibrating an artificial rainfall system that ensured stable and representative flow conditions during the experimental simulations. Thus, the discharge reliably represented field hydrological conditions and enabled the evaluation of the infiltration system performance under more critical conditions.

The simulated rainfall was applied using a nozzle system to produce a controlled rainfall intensity of 0,0378 L/s for a fixed duration of 60 min. Water was applied uniformly throughout the upstream section of the channel to mimic surface runoff from a typical impermeable road. During each test, the inflow and outflow were continuously monitored using a scale ruler at three key points: the infiltration box, median flume, and drainage flume. The outflow volume was measured every minute to determine the peak discharge, total runoff volume, and peak response time. Each test configuration was performed three times to ensure repeatability and reduce measurement uncertainty.

2.8 Hydrological performance evaluation

The data analysis focused on evaluating the hydrological performance of the infiltration and infiltration well systems based on the results of the flume experiment. Unlike the previous stage, which focused on processing rainfall data, this analysis aimed to interpret the response of the system to simulated rainfall conditions. The data obtained from the experimental results were analysed to compare the system performance between conditions without intervention (conventional) and conditions with intervention (infiltration system). The parameters analysed included the runoff volume, peak discharge, flow response time, and infiltration efficiency. The reduction in runoff volume was calculated based on the difference between the runoff volume under the uninterrupted and intervention conditions. The peak discharge was analysed by comparing the maximum discharge values recorded in each scenario. The flow response time was evaluated based on the difference in the time required to reach the peak discharge. This research was also supported by previous studies, such as a comparison of runoff in areas with and without infiltration boxes [29] and a laboratory evaluation of bioretention [30]. This experimental design combined laboratory simulations and predictive modelling to provide a comprehensive overview of the effectiveness of the system.

2.8.1 Runoff volume reduction

During the evaluation stage, the performance of the infiltration system was assessed by comparing runoff and infiltration values under two conditions: without the infiltration system and with the application of a combined infiltration box and infiltration well system. The comparison was conducted to identify changes in hydrological characteristics resulting from the implementation of the infiltration system, particularly in reducing surface runoff discharge and improving water infiltration into the soil. A summary of the runoff and infiltration measurement results for both test conditions is presented in Table 1. The runoff discharge measurements showed a decrease in runoff volume after implementation of the infiltration box.

Table 1. Runoff and infiltration without and with infiltration boxes and wells

Location	Without box and infiltration well		With infiltration box and well	
	Runoff (L/s)	**Infiltration** (L/s)	**Runoff** (L/s)	**Infiltration** (L/s)
Median flume	0,02870	0,00904	0,01166	0,02598
Flume drainage	0,02709	0,01045	0,01314	0,02355

Before treatment, the runoff volumes in the middle channel were 0,02870 and 0,02709 L/s, respectively. After using the infiltration box and well, this figure decreased to 0,01166 L/s in the middle channel (or decreased by 0,01704 L/s). In the drainage channel, after the use of the infiltration box and well, this figure decreased to 0,01314 L/s (or decreased by 0,01395 L/s).

This reduction reflected the increased capacity of the land to retain and absorb rainwater, which had previously become surface runoff. Thus, the infiltration box functioned as an effective water conservation structure to reduce surface runoff loads, particularly during moderate to high intensity rainfall. In percentage terms, the runoff volume decreased by 59,37 % in the median channel, while in the drainage channel, it decreased by 51,50 %, as calculated by dividing the runoff difference by the initial runoff. This reduction significantly contributed to controlling flooding and restoring the soil absorption capacity, as well as supporting the principles of sustainable water management in urban areas.

2.8.2 Peak flow reduction

A comparison of the runoff hydrographs in the drainage and median flume with and without the use of infiltration boxes and wells is shown in Figure 4. In the drainage flume, the system without infiltration produced a higher peak discharge than that with infiltration, indicating that the application of the infiltration unit reduced the surface runoff and extended the flow response time. In the median flume, the use of the infiltration box affected the hydrograph characteristics and runoff duration during the testing process. Overall, the infiltration system reduced the peak discharge and flow characteristics in both flume models.

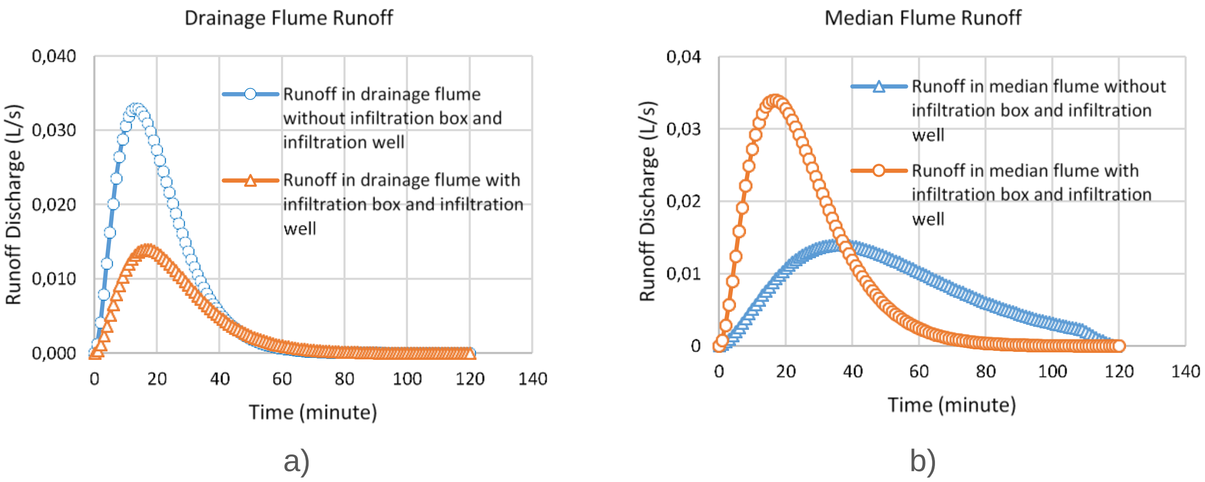

Figure 4. Peak flow reduction: a) drainage flume runoff; and b) median flume runoff

The ability of a stormwater management system to reduce the maximum runoff rate (peak flow) during rainfall is critical for evaluating the hydraulic performance of LID strategies, as excessive peak flow can cause flooding and overload the urban drainage infrastructure. In this study, infiltration boxes installed in drainage channels were designed to reduce peak flow by temporarily storing surface runoff and increasing infiltration within the boxes and underlying media. Peak flow reduction indicates the capacity of the system to absorb and retain stormwater, thus levelling the hydrograph and reducing the flood risk.

The peak flow reduction was calculated by comparing the highest observed discharge rate during rainfall under two conditions: without an infiltration box (control) and with the existing infiltration system. The drainage experiment results showed that the infiltration box effectively reduced the peak flow by 5,90-61,66 % for the drainage channels, while the median channel reduced the peak flow by 16,92-85,17 %.

2.8.3 Peak time

Time-to-peak (TTP) is the time interval between the start of runoff and peak flow rate achieved during a rainfall event. This parameter provides an overview of the response of a drainage or surface system to rainfall and is essential for the effectiveness of an infiltration system. The test results showed significant differences in the hydrological response between conditions with and without infiltration boxes. In the scenario without infiltration boxes (control), the peak flow was reached at 21 min with a discharge of 0,0326 L/s. Conversely, in the condition with infiltration boxes, the peak flow occurred later, at 31 min, with a lower peak discharge value of 0,0138 L/s.

Table 2. Peak flow reduction and time delay flume median

Condition	**Peak time** (min)	**Peak discharge** (L/s)	**Decrease in discharge** (L/s)	**Decrease** (%)	**Time delay** (min)
Without infiltration box	21	0,0326	---	---	---
With infiltration box	31	0,0138	0,0188	57,67	10

The peak discharge reduction was 62,06 %, while the TTP varied between 15 and 35 min, depending on the system configuration and test conditions. The actual delay reached 15 min, which was a significant limit, indicating that the system effectively slowed the runoff flow, thereby reducing the peak pressure on the drainage channel and risk of local flooding.

Table 3. Peak flow reduction and time delay flume drainage

Condition	**Peak time** (min)	**Peak discharge** (L/s)	**Decrease in discharge** (L/s)	**Decrease** (%)	**Time delay** (min)
Without infiltration box	22	0,0340	---	---	---
With infiltration box	57	0,0129	0,0211	62,06	35

2.8.4 Infiltration efficiency

Based on the calculations for the median channel, the infiltration efficiency without an infiltration box was 23,90 %, while that with the infiltration box increased to 68,47 %. This indicated that approximately 1/3 of the rainwater infiltrated into the soil without intervention. However, after the infiltration box technology was implemented, more than half of the rainwater infiltrated into the soil.

Table 4. Increase in infiltration

Condition	**Without infiltration box and well infiltration** (L/s)	**With infiltration box and well infiltration** (L/s)
Median flume	0,00904	0,02598
Flume drainage	0,01045	0,02355

This indicated that the infiltration box significantly reduced the volume of surface runoff and increased the amount of water absorbed by the soil. A higher infiltration efficiency is essential for replenishing groundwater reserves, reducing the risk of local flooding, and supporting plant growth in vegetated areas or gardens.

2.8.5 Increased infiltration

The calculations also showed that the infiltration flow rate increased from 0,00904 L/s without the box to 0,02598 L/s after the installation of the infiltration box. This represents a significant 68,47 % increase in the infiltration performance after the implementation of the infiltration system. This indicates that the infiltration box significantly improves the ability of the soil to absorb water. This increase was due to the increased water absorption area, presence of empty space within the box that facilitated faster absorption, and reduction in surface runoff, allowing more water to be absorbed.

Overall, the implementation of the infiltration box proved effective in increasing the efficiency and volume of rainwater infiltration into the soil. This supports sustainable water management strategies, especially in urban areas or areas at high risk of flooding. With a nearly three-fold increase in efficiency from 23,90-68,47 %, this technology can be recommended as a simple yet impactful solution for water conservation and runoff control.

3 Results

3.1 Rainfall data validation

The rainfall data used in this study were subjected to a series of validation tests to ensure their reliability and suitability for hydrological analyses. The validation process included consistency testing using the DMC, homogeneity testing using the RAPS method, and trend analysis using the ITA method.

3.1.1 Double Mass Curve (DMC)

To evaluate the consistency of the rainfall data used in this study, an analysis was carried out using the Double Mass Curve (DMC) method. This method was applied to identify possible changes in rainfall patterns or inconsistencies during the observation period by comparing the cumulative relationship between data from the observation station and the reference data. A stable linear trend in the relationship indicates that the data are consistent and suitable for further hydrological analysis. The results of the DMC analysis for rainfall data from 2014 to 2024 are presented in Figure 5. The consistency of the rainfall data was evaluated using the DMC method by comparing the cumulative rainfall from the observation stations with that from the reference stations (Harjamukti and Kertajati).

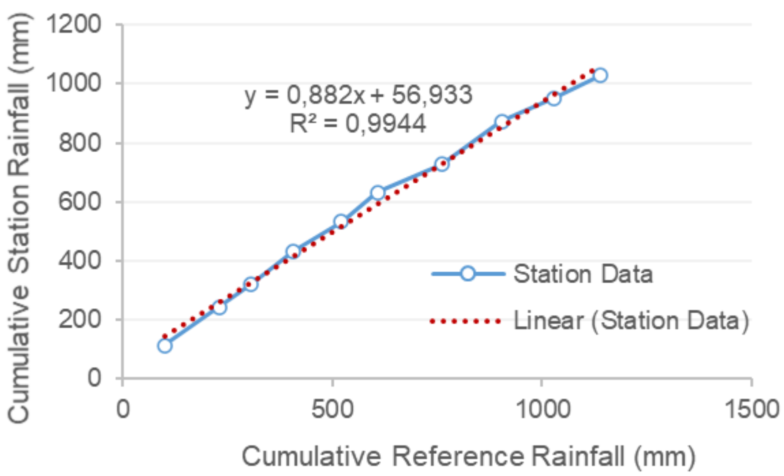

Figure 5. DMC of rainfall data (2014-2024)

As shown in Figure 5, the cumulative rainfall relationship exhibits a strong linear pattern with a coefficient of determination equal to R^2 = 0,9944. The absence of slope deviation indicated that the rainfall data were consistent and reliable for further hydrological analysis.

3.1.2 Rescaled Adjusted Partial Sums (RAPS)

To ensure the homogeneity of the rainfall data throughout the observation period, an analysis was performed using the Rescaled Adjusted Partial Sums (RAPS) method. This method was applied to detect changes in the data structure, non-uniformity, or possible deviations within the rainfall time series. By examining the cumulative deviation from the mean value, the RAPS method can indicate the stability of rainfall patterns during the observation period. The results of the homogeneity analysis using the RAPS method for rainfall data from 2014 to 2024 are presented in Figure 6.

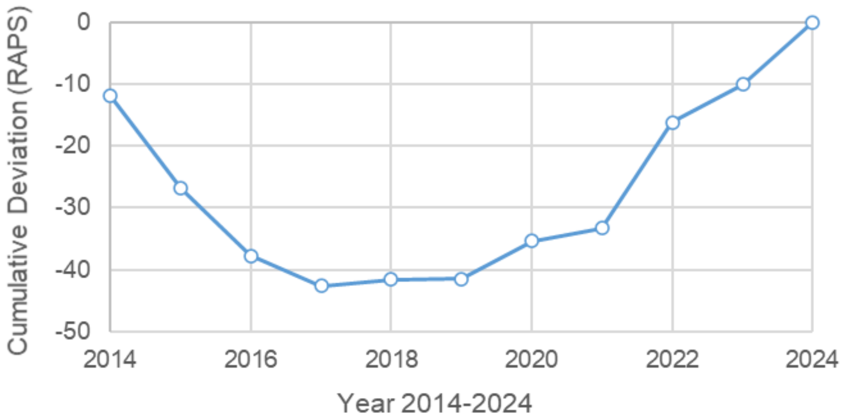

Figure 6. RAPS analysis of rainfall data (2014-2024)

The results showed that the cumulative deviation fluctuated around a stable pattern without significant abrupt changes. This indicated that the rainfall data were homogeneous and did not exhibit structural inconsistencies during the observation period.

The homogeneity of the rainfall data was evaluated using the RAPS method. The calculated test statistic yielded Q=1,12, which was lower than the critical value of Q=1,14 at the 5 % significance level. The cumulative deviation pattern gradually returned to zero, indicating stable fluctuations without any abrupt changes (Figure 6). Therefore, the rainfall data were considered homogeneous and suitable for further hydrological analyses.

3.1.3 Innovative Trend Analysis (ITA)

The ITA method was applied to evaluate the presence of trends in the rainfall data. The ITA graph (Figure 7) shows that most data points are distributed near the 1:1 reference line, with a few points slightly above the line, indicating a weak increasing trend. However, the overall distribution indicated that the trend was not significant, and the rainfall data could be considered relatively stable over the observation period.

The blue line represents the rainfall data in the second subset of the observation time series, while the orange line shows the ITA reference line (1:1 line) used to identify trends. Based on the graph, most of the data are above the 1:1 reference line, indicating an increasing rainfall trend during the 2014-2024 observation period. This pattern shows that rainfall values in the final observation period tend to be higher than those in the initial period, indicating an increasing trend in the rainfall data.

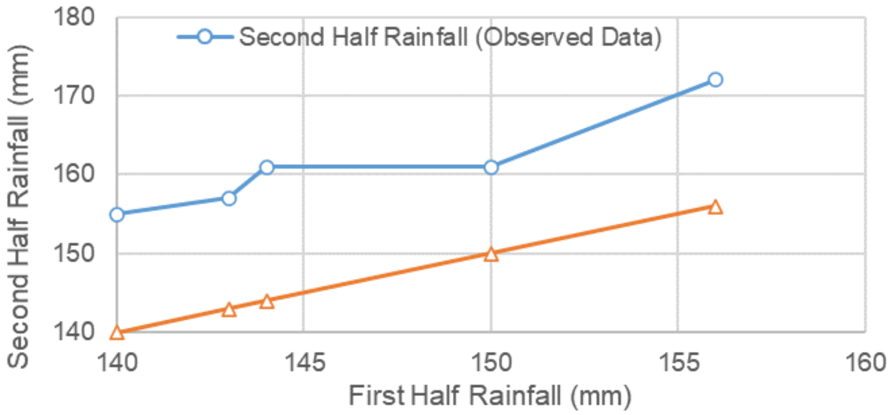

Figure 7. ITA of rainfall data (2014-2024)

3.2 Reduction of runoff volume

The differences in the overflow and infiltration responses in the median channel owing to the implementation of infiltration boxes and wells compared to the system without an additional infiltration system are shown in Figure 8. The system without infiltration boxes and wells resulted in a higher runoff discharge and reached its peak earlier than the system with infiltration. Conversely, the implementation of infiltration boxes and wells enhanced the infiltration process and gradually reduced the surface runoff discharge.

Furthermore, the infiltration curve in the system with infiltration showed greater water absorption capacity and longer flow duration. This indicates that the use of infiltration boxes and wells is effective in retaining, temporarily storing, and infiltrating water, thereby helping to reduce the concentration of surface runoff in the median channel.

The results of this study indicated that the implementation of infiltration boxes significantly reduced the volume of surface runoff. Based on the data and calculations obtained without infiltration boxes, the recorded runoff volume reached 0,0287 L/s. After installing the infiltration boxes, the runoff volume decreased to 0,0117 L/s. This represents a reduction in runoff volume of 0,0170 L/s, equivalent to 59,37 % of the initial total runoff. These results demonstrate that the infiltration system can significantly reduce surface runoff by increasing the retention and infiltration capacity of the soil medium [31], which emphasises the effectiveness of identifying subperiod deviations in discharge data using RAPS to measure system responsiveness.

However, across all measurement configurations, the runoff reduction varied between 30,34% and 59,37 %, indicating that the system effectiveness was significantly influenced by the configuration and interaction between the infiltration box and infiltration well. This reduction indicates that the infiltration box can increase the capacity of the soil to absorb rainwater, thereby reducing the amount of water flowing over the surface. This runoff reduction effectiveness was also related to the porous media used in the infiltration box, which provided space for the water to drain gradually into the soil.

Furthermore, this effect is particularly important in urban or built-up areas where impervious land is extensive and the risk of flooding increases during rainfall. By significantly reducing the runoff volume, the infiltration box system not only helps reduce the burden on the drainage system but also supports water conservation and sustainable water management efforts. These results confirm that the optimal configuration, particularly the median configuration equipped with an infiltration box, provides the best performance in reducing runoff compared to the other configurations.

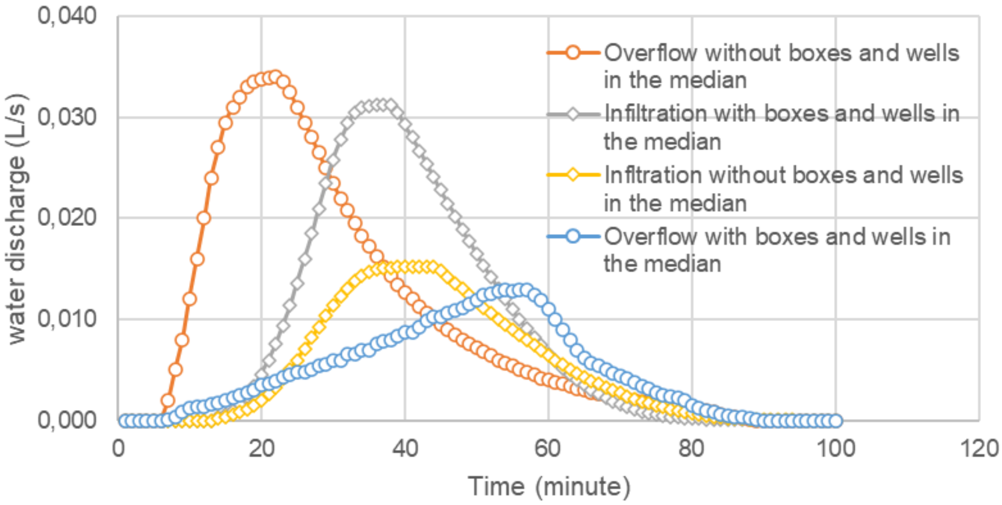

Figure 8. Comparison of median discharge without and with infiltration box and well

3.3 Peak flow reduction and time delay

The implementation of infiltration boxes has been shown to significantly reduce the peak flow and delay the peak flow times (Figure 9). Observations showed that the system without an infiltration box had a peak flow of 0,0339 L/s, which occurred 22 min after the rainfall began. In the system with the infiltration box, the peak flow decreased to 0,0129 L/s at 57 min.

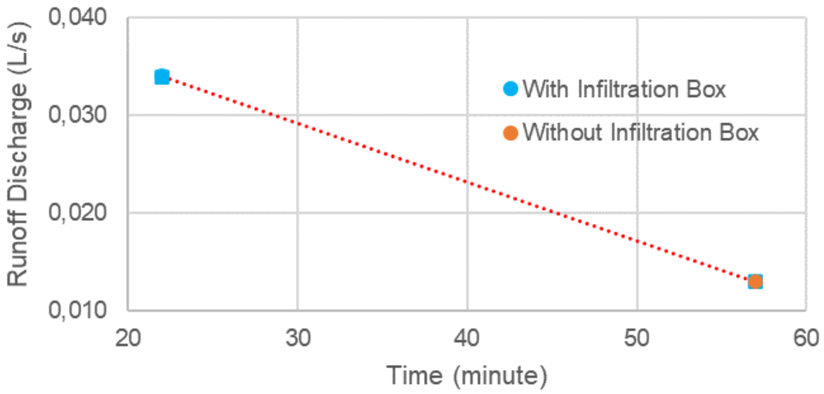

Figure 9. Peak flow reduction and time delay

This indicated a peak discharge reduction of up to 61,91 % under certain test conditions, with the maximum performance reaching 85,17 % in the optimal configuration. Overall, the peak discharge reductions ranged from 16 to 85,17 % with a median value of approximately 32,74 % in the less optimal configuration.
This represents a peak discharge reduction of 0,0210 L/s, equivalent to 61,91 % of the initial condition without infiltration. Furthermore, the peak time delay varied between 15 and 35 min depending on the system configuration and available infiltration capacity, indicating that the infiltration box system could slow surface runoff, allowing more time for water to infiltrate the soil and extend the runoff concentration period.
This peak discharge reduction indicates that the infiltration box is effective in reducing the intensity of the surface runoff, potentially reducing the risk of inundation or local flooding. Meanwhile, the peak time delay plays a role in balancing the load on the drainage system, particularly during heavy rainfall. Overall, these results reinforce the role of infiltration boxes as nature-based solutions for sustainable stormwater management strategies in urban areas.

3.4 Infiltration efficiency

A comparison of the infiltration discharge characteristics in the median channel with and without the use of infiltration boxes and wells is shown in Figure 10. The system using infiltration boxes and wells produced higher infiltration discharge than the system without the additional infiltration system. This indicates that the presence of the infiltration unit can increase the water absorption and storage capacity of the infiltration medium.
Furthermore, the infiltration discharge in the system with infiltration boxes peaked more quickly, and the infiltration process was sustained for a longer duration. Meanwhile, in the system without infiltration boxes and wells, infiltration continued through the channel bed, but with a more limited capacity. Overall, these results indicate that the use of infiltration boxes and wells is effective in increasing infiltration and reducing the potential for surface runoff in the median channel.

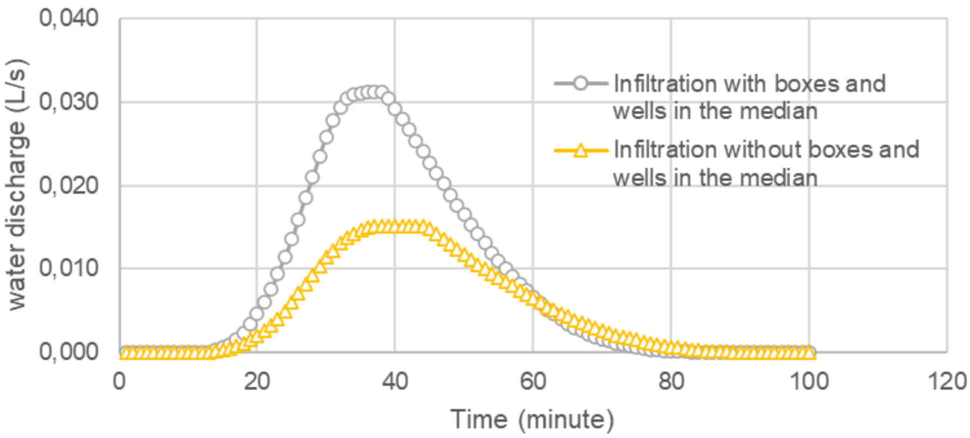

Figure 10. Infiltration discharge in median without and with infiltration box and well

Based on the data obtained, the runoff volume decreased from 0,02870 to 0,01166 L/s after the installation of the infiltration box. The difference of 0,01704 L/s indicates an increase in the infiltration volume resulting from the implementation of the infiltration system. The infiltration efficiency is defined as the ratio of the infiltration volume to the total inflow volume. The experimental results showed that the infiltration efficiency increased from 23,90 % under conventional conditions to 68,47 % after the implementation of the infiltration box. This indicated that more than 2/3 of the infiltrating water was effectively absorbed into the soil system. This value is significant for laboratory-scale testing using artificial rainfall scenarios and road surfaces that are representative of urban conditions. This efficiency is influenced by various factors such as the porosity and permeability of the media used in the infiltration box, water level in the channel, and duration of artificial rainfall.
In the context of urban stormwater management, the infiltration efficiency ranged from 50,74 to 68,47 % depending on the system configuration and test conditions, indicating that the infiltration box had significant potential to reduce runoff loads and support local infiltration. With scale-up and design optimisation, this efficiency can be further improved for field applications.

4 Discussion

The results of this study provide meaningful insights into the practical relevance of integrating infiltration boxes into urban stormwater management systems. Rather than focusing on absolute performance values, the relevance lies in the ability of the system to deliver consistent hydrological benefits under varying environmental conditions and design constraints.
A key implication is that decentralised stormwater interventions such as modular infiltration boxes can be strategically integrated into underutilised urban spaces, particularly road

medians, without the need for major infrastructure upgrades. This adaptability underscores the suitability of the solution for renovation projects and resource-constrained cities.
The responsiveness of the system across a range of slope conditions also demonstrates its broad applicability to real-world urban gradients, where surface slope variability typically limits the performance of standard infiltration designs. Furthermore, by reducing peak flows and extending the time of runoff concentration, infiltration boxes can alleviate the acute stress on the downstream drainage infrastructure, thereby supporting the resilience of urban hydrological systems.
From a planning perspective, the simplicity and scalability of infiltration box design enhance its relevance for widespread adoption. The minimal footprint, coupled with ease of maintenance and modularity, aligns with the key principles of sustainable urban drainage. Nonetheless, the observed limitations under extreme rainfall intensities highlight the need for integrated solutions, in which infiltration boxes serve as part of a broader suite of adaptive drainage measures. Thus, the relevance of these findings stems from the practical flexibility of the system, its potential for widespread application in densely populated cities, and its contribution to a more distributed and climate-resilient approach to urban stormwater management.
Several studies have demonstrated significant reductions in runoff and peak discharge through the implementation of bioretention systems and other LID practices. For example, a combination of 28,4 % bioretention systems and 11,3 % vegetated ditches reduced peak runoff by 22,98-24,71 % [32]. Similarly, bioretention drainage channels (BRCs) can reduce the peak runoff by over 82 % and the maximum flow in a drainage network by up to 83 % [33]. Interestingly, several studies have highlighted additional benefits beyond runoff reduction, and nearly 50 % of the total inflowing water volume was stored or evaporated in bioretention ponds, thereby reducing the peak discharge in urban drainage systems [34]. The role of evapotranspiration in bioretention systems was emphasised, with up to 78 % of rainfall directly converted to ET in systems with internal water storage layers [35].
These results are consistent with those of previous studies on urban infiltration systems, which show similar runoff reductions and peak discharge delays in systems using permeable media and modular bioretention arrangements. However, the magnitude of the increase in the infiltration rate observed in this study exceeded some of these previous findings, likely because of the more compact and hydraulically optimised design of the infiltration box. Unlike traditional bioretention systems that typically require larger surface areas (rain gardens or gutters), the box system demonstrated here offers comparable effectiveness in spatially constrained environments such as street medians.

5 Conclusions

In this study, laboratory-scale experiments demonstrated that the application of infiltration boxes in road media significantly improved hydrological performance under controlled rainfall conditions. The installation of infiltration boxes resulted in reductions in runoff volume ranging from 30,34 to 59,37 %, peak discharge from 16,00 to 85,17 %, and delayed TTP from 15 to 35 min. Furthermore, the infiltration efficiency increased from 23,90 to 68,47 %, and the infiltration rate increased by 74,78 %, from 0,0110 to 0,0192 L/s. These findings indicate that the infiltration box system is effective in reducing the peak flow and enhancing the infiltration processes in limited urban spaces.
The performance improvements observed with the infiltration boxes were primarily owing to the increased temporary storage and percolation capacities provided by the internal media of the box. The plastic construction with customised dimensions allowed rapid surface water absorption and facilitated lateral and vertical percolation into the underlying media. The delayed onset of peak flow and lower peak discharge highlighted the box role as an infiltration and detention mechanism, reducing immediate surface runoff and distributing flow over a longer period. These results confirm the hypothesis that even small-scale modular infiltration structures can significantly modulate hydrological responses during simulated rainfall events.

From a practical perspective, this study highlights the potential of a scalable modular infiltration system to be integrated into existing urban infrastructure, particularly within underutilized road median areas. The system can support conventional drainage networks by reducing peak runoff loads and enhancing urban water resilience. The main contribution of this study lies in the development and experimental evaluation of compact yet effective modular infiltration boxes designed for installation in road medians, an area that has received limited attention in surface runoff management studies. The findings provide quantitative evidence that small-scale decentralized infrastructure can significantly reduce runoff while increasing infiltration capacity. From a scientific standpoint, the results support the application of small-footprint infiltration technologies as part of nature based solutions (NBS) for sustainable stormwater management. In addition, this experimental study contributes to the growing body of literature on low-impact development (LID) strategies for densely populated urban areas.
Although the results are promising, this study has several limitations. The experiments were conducted under laboratory conditions with a uniform rainfall intensity and controlled boundary settings, which might not capture the variability present in real-world environments, such as fluctuations in rainfall intensity, sedimentation, or surface contamination. The infiltration media used in the boxes were not systematically varied, thus limiting the analysis of the media-specific impacts. Furthermore, the long-term performance, maintenance requirements, and clogging effects, which are critical for real-world applications, are not addressed.
Future research should focus on the field-scale validation of infiltration box systems in various urban environments and climatic conditions. The investigation of different media compositions, system geometries, and integration with urban drainage networks will provide insights into the optimal design parameters. Longitudinal studies are also needed to evaluate the durability, maintenance frequency, and long-term hydrological behaviour, including seasonal variability. Combining cost-benefit analysis and life cycle assessment will further support decision-making for broader implementation in stormwater infrastructure planning.

Acknowledgments

The authors would like to express his deepest gratitude to Sultan Agung Islamic University, Semarang, and Swadaya Gunung Jati University, Cirebon, for providing the laboratory facilities and technical support needed to conduct this research.

References

[1] Gwenzi, W.; Nyamadzawo, G. Hydrological Impacts of Urbanization and Urban Roof Water Harvesting in Water-Limited Catchments: A Review. *Environmental Processes*, 2014, 1, pp. 573-593. https://doi.org/10.1007/s40710-014-0037-3
[2] Ferreira, C. S. S.; Walsh, R. P. D.; Steenhuis, T. S.; Ferreira, A. J. D. Effect of Peri-Urban Development and Lithology on Streamflow in a Mediterranean Catchment. *Land Degradation & Development*, 2018, 29 (4), pp. 1141-1153. https://doi.org/10.1002/ldr.2810
[3] Guan, M.; Sillanpää, N.; Koivusalo, H. Storm Runoff Response to Rainfall Pattern, Magnitude and Urbanization in a Developing Urban Catchment. *Hydrological Processes*, 2015, 30 (4), pp. 543-557. https://doi.org/10.1002/hyp.10624
[4] Jović, S.; Konstantinović, D.; Peško, I. Urbanisation as a Tool for Economic Growth – Novi Sad the Developmental City. *Advances in Civil and Architectural Engineering*, 2022, 13 (25), pp. 1-13. https://doi.org/10.13167/2022.25.1
[5] Li, X. et al. Green Roofs: Effects of Plant Species Used on Runoff. *Land Degradation & Development*, 2018, 29 (10), pp. 3628-3638. https://doi.org/10.1002/ldr.3102
[6] Pochodyła, E.; Glińska-Lewczuk, K.; Jaszczak, A. Blue-Green Infrastructure as a New Trend and an Effective Tool for Water Management in Urban Areas. *Landscape Online*, 2021, 92. https://doi.org/10.3097/LO.202192

[7] Zanin, G.; Bortolini, L.; Borin, M. Assessing Stormwater Nutrient and Heavy Metal Plant Uptake in an Experimental Bioretention Pond. *Land*, 2018, 7 (4), 150. https://doi.org/10.3390/land7040150
[8] Wang, R.; Eckelman, M. J.; Zimmerman, J. B. Consequential Environmental and Economic Life Cycle Assessment of Green and Gray Stormwater Infrastructures for Combined Sewer Systems. *Environmental Science & Technology*, 2013, 47 (19), pp. 11189-11198. https://doi.org/10.1021/es4026547
[9] Liu, L.; Fryd, O.; Zhang, S. Blue-Green Infrastructure for Sustainable Urban Stormwater Management: Lessons from Six Municipality-Led Pilot Projects in Beijing and Copenhagen. *Water*, 2019, 11 (10), 2024. https://doi.org/10.3390/w11102024
[10] Qi, Y. et al. Addressing Challenges of Urban Water Management in Chinese Sponge Cities via Nature-Based Solutions. *Water*, 2020, 12 (10), 2788. https://doi.org/10.3390/w12102788
[11] Ariyarathna, I. S.; Abeyrathna, W. P.; Jamei, E.; Chau, H.-W. A Review of the Application of Blue–Green Infrastructure (BGI) as an Effective Urban Flood Mitigation Strategy for Livable and Healthy Cities in Australia. *Architecture*, 2023, 3 (3), pp. 461-476. https://doi.org/10.3390/architecture3030025
[12] Zhang, L.; Ye, Z.; Shibata, S. Assessment of Rain Garden Effects for the Management of Urban Storm Runoff in Japan. *Sustainability*, 2020, 12 (23), 9982. https://doi.org/10.3390/su12239982
[13] Sharma, R.; Malaviya, P. Management of Stormwater Pollution Using Green Infrastructure: The Role of Rain Gardens. *Wiley Interdisciplinary Reviews: Water*, 2021, 8 (2), e1507. https://doi.org/10.1002/wat2.1507
[14] Winston, R. J.; Arend, K.; Dorsey, J. D.; Hunt, W. F. Water quality performance of a permeable pavement and stormwater harvesting treatment train stormwater control measure. *Blue-Green Systems*, 2020, 2 (1), pp. 91-111. https://doi.org/10.2166/bgs.2020.914
[15] Damodaram, C. et al. Simulation of Combined Best Management Practices and Low Impact Development for Sustainable Stormwater Management. *Journal of the American Water Resources Association*, 2010, 46 (5), pp. 907-918. https://doi.org/10.1111/j.1752-1688.2010.00462.x
[16] Bartens, J. et al. Can Urban Tree Roots Improve Infiltration through Compacted Subsoils for Stormwater Management? *Journal of Environmental Quality*, 2008, 37 (6), pp. 2048-2057. https://doi.org/10.2134/jeq2008.0117
[17] Kim, S.; Shin, H.; Joo, K.; Heo, J. H. Development of Plotting Position for the General Extreme Value Distribution. *Journal of Hydrology*, 2012, 475, pp. 259-269. https://doi.org/10.1016/j.jhydrol.2012.09.055
[18] Pfister, M.; Chanson, H. Two-Phase Air-Water Flows: Scale Effects in Physical Modeling. *Journal of Hydrodynamics*, 2014, 26, pp. 291-298. https://doi.org/10.1016/S1001-6058(14)60032-9
[19] Leopardi, M. On Roughness Similarity of Hydraulic Models. *Journal of Hydraulic Research*, 2004, 42 (3), pp. 239-245. https://doi.org/10.1080/00221686.2004.9728389
[20] Feng, D.; Jiang, S. L.; Liu, S. Experimental Study on Filtration Performance of Geotextile Filter Used in Emergency Rescue of Dike Piping. *Journal of Industrial Textiles*, 2024, 54, 15280837241256608. https://doi.org/10.1177/15280837241256608
[21] Bedan, E. S.; Clausen, J. C. Stormwater Runoff Quality and Quantity from Traditional and Low Impact Development Watersheds. *Journal of the American Water Resources Association*, 2009, 45 (4), pp. 998-1008. https://doi.org/10.1111/j.1752-1688.2009.00342.x
[22] Hsieh, C.-h.; Davis, A. P.; Needelman, B. A. Bioretention Column Studies of Phosphorus Removal from Urban Stormwater Runoff. *Water Environment Research*, 2007, 79 (2), pp. 177-184. https://doi.org/10.2175/106143006X111745

[23] Đurin, B. et al. Application of Rescaled Adjusted Partial Sums (RAPS) Method in Hydrology – an Overview. *Advances in Civil and Architectural Engineering*, 2022, 13 (25), pp. 58-72. https://doi.org/10.13167/2022.25.6

[24] Şen, Z. Hydrological Trend Analysis with Innovative and Over-Whitening Procedures. *Hydrological Sciences Journal*, 2017, 62 (2), pp. 294-305. https://doi.org/10.1080/02626667.2016.1222533

[25] Güçlü, Y. S. Multiple Şen-Innovative Trend Analyses and Partial Mann-Kendall Test. *Journal of Hydrology*, 2018, 566, pp. 685-704. https://doi.org/10.1016/j.jhydrol.2018.09.034

[26] Stone, J. J.; Nichols, M. H.; Goodrich, D. C.; Buono, J. Long-Term Runoff Database, Walnut Gulch Experimental Watershed, Arizona, United States. *Water Resources Research*, 2008, 44 (5), pp. 1-5. https://doi.org/10.1029/2006WR005733

[27] Gillies, M. H.; Smith, R. J. Infiltration Parameters from Surface Irrigation Advance and Run-Off Data. *Irrigation Science*, 2005, 24, pp. 25-35. https://doi.org/10.1007/s00271-005-0004-x

[28] In-na, N.; Nguyen, V.-T.-V. An Unbiased Plotting Position Formula for the General Extreme Value Distribution. *Journal of Hydrology*, 1989, 106 (3–4), pp. 193-209. https://doi.org/10.1016/0022-1694(89)90072-3

[29] Winston, R. J.; Dorsey, J. D.; Hunt, W. F. Quantifying Volume Reduction and Peak Flow Mitigation for Three Bioretention Cells in Clay Soils in Northeast Ohio. *Science of the Total Environment*, 2016, 553, pp. 83-95. https://doi.org/10.1016/j.scitotenv.2016.02.081

[30] Lopes Bezerra, P. H. et al. Water Dynamics in an Infiltration Trench in an Urban Centre in Brazil: Monitoring and Modelling. *Water*, 2022, 14 (4), 513. https://doi.org/10.3390/w14040513

[31] Wang, J.; Guo, Y. Dynamic Water Balance of Infiltration-Based Stormwater Best Management Practices. *Journal of Hydrology*, 2020, 589, 125174. https://doi.org/10.1016/j.jhydrol.2020.125174

[32] Kuok, K. K. et al. Effectiveness of Bioretention System and Vegetated Swale for Reducing Urban Flood Risk in Equatorial Region: A Case Study in Kuching, Malaysia. *Sustainable Water Resources Management*, 2024, 10. https://doi.org/10.1007/s40899-024-01081-8

[33] Stec, A.; Słyś, D. New Bioretention Drainage Channel as One of the Low-Impact Development Solutions: A Case Study from Poland. *Resources*, 2023, 12 (7), 82. https://doi.org/10.3390/resources12070082

[34] Nazarpour, S.; Gnecco, I.; Palla, A. Evaluating the Effectiveness of Bioretention Cells for Urban Stormwater Management: A Systematic Review. *Water*, 2023, 15 (5), 913. https://doi.org/10.3390/w15050913

[35] Wadzuk, B. M.; Hunt, J. M.; Traver, R. G. Understanding the Role of Evapotranspiration in Bioretention: Mesocosm Study. *Journal of Sustainable Water in the Built Environment*, 2015, 1 (2), 04014002. https://doi.org/10.1061/JSWBAY.0000794