

Comparative hydraulic performance of infiltration wells and injection wells: Implications for urban flood mitigation in Medan City, Indonesia

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ABSTRACT

Urban flooding has become an increasingly serious challenge in many tropical cities due to rapid urbanization, increasing impervious surfaces, and the limited capacity of conventional drainage systems. Infiltration wells and injection wells have emerged as decentralized stormwater management measures to enhance infiltration and reduce surface runoff; however, comparative field evaluations of their hydraulic performance under tropical urban conditions remain limited. This study compares the hydraulic performance of infiltration wells and injection wells through field investigations conducted at four sites in Medan City, Indonesia, comprising two infiltration wells and two injection wells. Following natural rainfall events, water-level recession was monitored after rainfall had ceased and the water level had reached approximately ground level. Repeated short-term measurements (1-minute intervals over 30 minutes) and long-term measurements (1-hour intervals over 6 hours) were conducted to characterize the hydraulic response of the wells. Representative infiltration rates were determined by linear regression, while an exponential recession model was employed to characterize the long-term hydraulic behavior of the injection wells and estimate surrounding subsurface transmissivity. The results indicate that the investigated injection wells exhibited higher average specific infiltration rates, ranging from 1.37 to 1.58 cm/min, compared with 0.37 to 0.92 cm/min for the infiltration wells. In contrast, the investigated infiltration wells, which had larger diameters and cross-sectional areas, exhibited substantially greater observed volumetric recharge rates, reaching 4599 cm³/min compared with approximately 250–290 cm³/min for the injection wells during the 30-minute experiments. The exponential recession model captures the observed long-term water-level recession behavior and provides a practical approach to evaluating injection-well performance. The findings suggest that both systems may have complementary roles in urban stormwater management. Injection wells may be advantageous where land availability is limited and rapid infiltration is required, whereas infiltration wells may be preferable where greater volumetric recharge capacity is needed, owing to the larger dimensions of the investigated wells. The findings further emphasize the importance of regular maintenance, particularly for injection wells, to control sediment accumulation, while stormwater pretreatment should be considered to minimize potential groundwater contamination. These results provide practical guidance for selecting infiltration technologies that complement conventional urban drainage systems in tropical cities.

Keywords: infiltration well, injection well, hydraulic performance, urban flood mitigation, stormwater management, Medan City.

INTRODUCTION

Urban flooding has become one of the most pressing environmental and engineering challenges in rapidly developing cities worldwide. Population growth, urban expansion, and the increasing conversion of permeable land into impervious surfaces have significantly altered the natural hydrological cycle, resulting in higher surface runoff, reduced groundwater recharge, and more frequent flood events (Przestrzelska et al., 2024). In many tropical cities, including Medan, Indonesia, conventional drainage systems are increasingly unable to accommodate the growing volume of stormwater, particularly during high-intensity rainfall events. Medan, the capital of North Sumatra Province and one of the major urban centers in Indonesia, is characterized by extensive built-up areas, rapid urban development, and a tropical climate with rainfall occurring throughout the year. Consequently, sustainable stormwater management strategies that promote local infiltration have received increasing attention as complementary approaches to conventional drainage infrastructure.

Among decentralized stormwater management measures, infiltration wells and injection wells are widely recognized as practical methods for reducing surface runoff while simultaneously enhancing groundwater recharge (Netzer et al., 2024; Zeydilinejad et al., 2024; Fiori et al., 2025). Both systems have been implemented in various urban environments to reduce runoff volumes and improve local water balance. However, their hydraulic behavior differs substantially because of differences in geometry, infiltration mechanisms, and interactions with subsurface geological conditions.

Previous studies have investigated the hydraulic performance of infiltration facilities under various geological and climatic conditions, focusing on infiltration rates, groundwater recharge, water quality, and stormwater management (Dillon et al., 2019). Nevertheless, most published studies evaluate individual systems independently or rely primarily on laboratory experiments and numerical simulations. Direct field-based comparisons between infiltration wells and injection wells under identical urban conditions remain limited, particularly in tropical cities where rainfall characteristics, soil properties, and urban development differ considerably from those in temperate regions. As a result, engineers and urban planners have

limited field evidence to support the selection of the most appropriate infiltration technology for specific site conditions.

Unlike many previous studies that evaluate stormwater infiltration systems using either short-term infiltration tests or numerical simulations alone, the present study integrates short-term field measurements, long-term recession analysis, recharge-capacity calculations, and estimation of subsurface transmissivity within a unified field-based framework. This integrated approach enables a comprehensive comparison of infiltration wells and injection wells under tropical urban conditions and provides practical engineering information for the design and selection of stormwater recharge systems.

Therefore, this study aims to compare the hydraulic performance of infiltration wells and injection wells based on field investigations conducted at four locations in Medan City, Indonesia. The comparison considers infiltration rates, infiltration discharge, and long-term hydraulic behavior to evaluate the relative performance of both systems under actual operating conditions. Beyond comparing hydraulic characteristics, this study discusses the practical implications of the findings for urban flood mitigation, stormwater management, maintenance requirements, and groundwater protection. The results are expected to provide practical engineering guidance for selecting appropriate infiltration technologies that complement conventional drainage systems in tropical urban environments.

BACKGROUND

Urban stormwater infiltration

Rapid urbanization has significantly altered the natural hydrological cycle by replacing permeable land surfaces with impervious infrastructure such as roads, buildings, and pavements. Consequently, infiltration decreases while surface runoff and peak discharge increase, leading to more frequent urban flooding and reduced groundwater recharge. Conventional drainage systems alone are often insufficient to accommodate increasing runoff volumes, particularly during high-intensity rainfall events. Therefore, decentralized stormwater management measures that promote local infiltration have become increasingly important as complementary

solutions for improving urban water resilience (Fletcher et al., 2015; Przestrzelska et al., 2024). Recent studies have emphasized that infiltration-based systems not only reduce runoff but also enhance groundwater recharge and improve the sustainability of urban water resources (Fletcher et al., 2015; Ashley et al., 2013).

Among decentralized stormwater management practices, infiltration wells and injection wells are recognized as practical methods for restoring part of the natural hydrological balance. These systems reduce the volume of stormwater entering drainage networks while simultaneously increasing groundwater recharge. Consequently, they have become important components of sustainable urban drainage systems (SuDS), low impact development (LID), and managed aquifer recharge (MAR) strategies adopted in many urban areas.

Hydraulic characteristics of infiltration wells and injection wells

Although both infiltration wells and injection wells aim to increase groundwater recharge, their hydraulic mechanisms differ considerably (Bouwer, 2002; Netzer et al., 2024; Netzer et al., 2025). An infiltration well temporarily stores stormwater and allows water to infiltrate through its bottom and side walls into the surrounding soil. Its hydraulic performance depends primarily on soil permeability, well diameter, storage volume, groundwater level, and the extent of the wetted surface area. Because of their relatively large diameter, infiltration wells generally provide substantial storage capacity and can infiltrate large water volumes despite moderate infiltration rates.

In contrast, an injection well conveys water into deeper subsurface formations through a relatively narrow borehole. Its hydraulic performance therefore depends strongly on the hydraulic properties of the receiving formation. Deeper injection wells may exhibit higher infiltration rates where they intersect subsurface formations with favorable hydraulic properties (Bouwer, 2002).

The hydraulic performance of both systems is influenced by several factors, including subsurface hydraulic properties, groundwater table depth, well geometry, and maintenance conditions. Sediment accumulation and clogging may progressively reduce infiltration capacity, emphasizing

the importance of periodic maintenance to sustain long-term performance (Dillon et al., 2019).

Factors affecting hydraulic performance

The hydraulic performance of infiltration wells and injection wells is governed by the interaction between well characteristics and site-specific hydrogeological conditions. Soil permeability is generally the most influential factor because it controls the rate at which water infiltrates into the surrounding ground (Bouwer, 2002). In addition, geological formations, groundwater table depth, and aquifer properties influence the movement and storage of infiltrated water, particularly for injection wells that discharge directly into deeper permeable layers.

The geometry of the well, including its diameter, depth, and storage volume, also affects hydraulic performance. Larger-diameter wells generally provide greater storage capacity and infiltration discharge, whereas deeper injection wells may achieve higher infiltration rates by accessing more permeable strata (Bouwer, 2002). In practice, long-term performance is further influenced by sediment accumulation and clogging, which reduce hydraulic conductivity and infiltration capacity over time (Dillon et al., 2019; Suprayogi et al., 2019). Consequently, regular maintenance and appropriate pretreatment of stormwater are essential to sustain the effectiveness of infiltration systems and to minimize the risk of groundwater contamination (Netzer et al., 2024).

Previous studies and research gap

Previous studies have extensively investigated infiltration facilities from the perspectives of groundwater recharge, infiltration capacity, water quality, and stormwater management (Dillon et al., 2019; Netzer et al., 2024). Recent research has also examined the hydraulic performance of dry and wet infiltration wells for urban rainwater harvesting and managed aquifer recharge, demonstrating their potential to reduce urban runoff while enhancing groundwater resources (Netzer et al., 2024; Netzer et al., 2025).

Despite these advances, most published studies focus on individual infiltration technologies, numerical simulations, or laboratory-scale experiments. Direct field-based comparisons between conventional infiltration wells and injection wells under identical tropical urban

conditions remain limited. Furthermore, relatively few studies evaluate these systems not only in terms of infiltration rate but also with respect to infiltration discharge, long-term hydraulic behavior, maintenance requirements, and their practical implications for urban flood mitigation (Fletcher et al., 2015).

Therefore, this study compares the hydraulic performance of infiltration wells and injection wells based on field measurements conducted in Medan City, Indonesia. By integrating short-term infiltration tests with long-term hydraulic observations, the study provides practical engineering guidance for selecting appropriate infiltration technologies according to site characteristics, hydraulic performance, maintenance considerations, and sustainable urban stormwater management.

MATERIALS AND METHODS

Study area

This study was conducted in Medan City, North Sumatra, Indonesia, where rapid urbanization has increased impervious land cover and consequently reduced natural infiltration while increasing stormwater runoff. These conditions have contributed to more frequent urban flooding and have highlighted the need for sustainable stormwater management strategies that enhance groundwater recharge.

Four artificial groundwater recharge facilities were selected as representative study sites, consisting of two conventional infiltration wells and two injection wells located in different urban districts of Medan. The selected wells represent commonly adopted infiltration technologies constructed under varying hydrogeological conditions. Their locations were chosen to provide a practical comparison of the hydraulic

performance of the two systems under actual field conditions. Table 1 summarizes the principal characteristics of each investigated well; Figure S1 shows photographic documentation of the investigated recharge wells and representative field measurements; Figure S2 shows the locations of four investigated recharge wells.

Regional geological and hydrogeological information indicates that the study area is characterized by heterogeneous Quaternary deposits. The regional geological setting includes the Medan Formation, alluvial deposits, and volcanic deposits associated with the surrounding volcanic systems (Figure S3). The hydrogeological map further indicates spatial variability in aquifer conditions across the investigated area (Figure S4). The aquifer materials are generally associated with unconsolidated deposits comprising coarse- to medium-grained gravel and sand with clay interbeds, with groundwater moving through intergranular pore spaces and, locally, through fractures or openings. These regional characteristics provide geological context for interpreting the hydraulic behavior of the investigated recharge wells; however, site-specific borehole logs, grain-size distributions, and hydraulic conductivity measurements were not available.

Field measurements

The hydraulic performance of the investigated wells was evaluated through field monitoring conducted following natural rainfall events. Measurements were initiated after rainfall had ceased and the water level in the well had reached approximately ground level. Consequently, no additional rainfall-derived inflow occurred during the monitoring period, and the subsequent water-level recession was attributed primarily to infiltration from the well into the surrounding subsurface formation.

Table 1. Characteristics of the investigated wells

Well code	Type	Geographic location	Diameter (cm)	Depth (m)	Effective depth (m)	Static water level (cm)	Material	Test program
IW-1	Infiltration well	3°35'57.4" N 98°43'18.7" E	55.0	1.25	1.25	20	Concrete ring	Short-term
IW-2	Infiltration well	3°28'49.7" N 98°37'40.6" E	80.0	1.00	1.00	Not detected*	Concrete ring	Short-term
JW-1	Injection well	3°34'45.6" N 98°42'09.2" E	15.2	12.0	4.2	130	PVC pipe	Short-term Long-term
JW-2	Injection well	3°34'15.5" N 98°43'47.2" E	15.2	12.0	9.0	190	PVC pipe	Short-term Long-term

Note: *Groundwater was not detected within the measurable depth of the well during dry-weather field observation.

Two observation schemes were employed. The first consisted of short-term recession measurements, during which water levels were recorded at one-minute intervals for approximately 30 minutes. These measurements characterized the initial infiltration process and determined representative infiltration rates through linear regression analysis. The second consisted of long-term recession measurements, in which water levels were recorded at one-hour intervals for at least 6 hours. These observations were used to investigate the long-term hydraulic response of the injection wells and to estimate surrounding subsurface transmissivity using an exponential recession model.

Water-level and well-geometry measurements were conducted using simple manual field equipment. Well depth was determined using a plumb bob and measuring tape, whereas water level was measured using a float-and-line arrangement with a measuring tape. The measuring tape had a range of 0–20 m and a resolution of 1 mm. Rainfall was collected using an ombrometer installed in accordance with ISO 23350:2021, and rainfall depth was determined using a graduated measuring cylinder with a range of 0–25 mm and a resolution of 0.5 mm. No formal calibration of the manual measuring equipment was performed, and independent instrument accuracy was therefore not quantified. Nevertheless, measurement consistency was maintained by using the same equipment, measurement procedures, and observation protocol for all replicate tests. Details of the measurement equipment are provided in Table S7, whereas the standardized initial and measurement

conditions applied to the field tests are summarized in Table S9.

Rainfall depth preceding each individual field test was recorded using the on-site ombrometer. The rainfall observations associated with all replicate tests are provided in Table S8.

To confirm measurement reliability, identical field procedures and measuring equipment were used for each test. Each measurement was repeated twice to verify the repeatability of the observed hydraulic response. Complete water-level time series for all replicate measurements are provided in the Supplementary Material: Tables S1 to S4 for the short-term experiment and Tables S5 and S6 for the long-term experiment. Both replicate tests for each well were analyzed individually, and their corresponding regression results are reported to demonstrate measurement repeatability.

Analytical procedure

Figure 1 illustrates the overall methodology adopted in this study. The investigation began with post-rainfall monitoring of water-level recession in the investigated wells. The collected data were subsequently analyzed using two complementary approaches.

The short-term observations were analyzed using linear regression to determine representative specific infiltration rates. These rates were multiplied by the horizontal cross-sectional area of each well to calculate recharge capacity, representing the volumetric rate of water-level recession within the well. The long-term observations

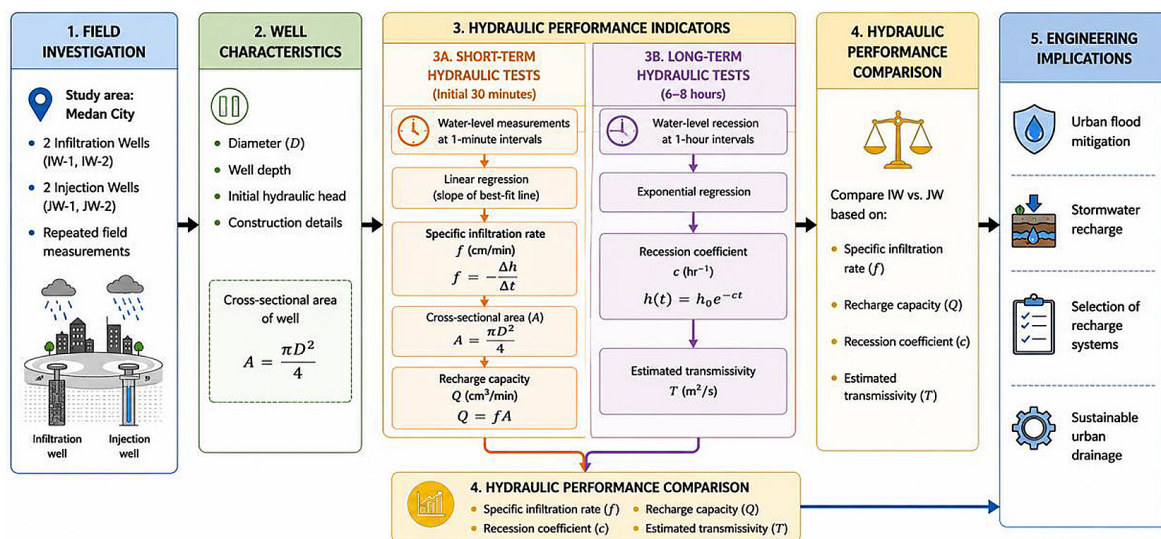


Figure 1. Field testing and analytical framework for evaluating the hydraulic performance of infiltration and injection wells

were analyzed using an exponential recession model to characterize the hydraulic response of the wells during prolonged infiltration. The resulting recession coefficient was subsequently used to estimate subsurface transmissivity and to evaluate the hydraulic characteristics of the surrounding subsurface formation.

Finally, the hydraulic performance of infiltration wells and injection wells was compared based on infiltration rate, recharge capacity, recession characteristics, and estimated transmissivity. The engineering implications of these hydraulic parameters were then interpreted with respect to urban stormwater management and artificial groundwater recharge.

Hydraulic performance indicators

Specific infiltration rate and cross-sectional area

The specific infiltration rate was determined from the measured rate of water-level decline during the infiltration tests and is expressed as

$$f = - \frac{\Delta h}{\Delta t} \quad (1)$$

where: f – specific infiltration rate (cm/min), Δh – change in water level (cm), and Δt – elapsed time (min).

For comparison, the representative specific infiltration rate was defined as the average water-level recession rate over the 30-minute monitoring period and estimated from the slope of the best-fit linear regression line through the measured water-level data. This approach uses all observations within the standardized monitoring period and reduces the influence of individual measurement fluctuations. In contrast, minimum and maximum infiltration rates were calculated from successive one-minute water-level changes.

The cross-sectional area A of each well was calculated as

$$A = \frac{\pi D^2}{4} \quad (2)$$

where: D – well diameter.

The cross-sectional area represents the horizontal area of water stored in the well. Because infiltration wells generally have larger diameters than injection wells, they possess considerably larger cross-sectional areas and consequently greater potential recharge capacities.

Recharge capacity

The volumetric infiltration discharge Q was determined from

$$Q = fA \quad (3)$$

where: Q – observed volumetric recharge rate (cm³/min), f – specific infiltration rate (cm/min), and A – horizontal cross-sectional area of the water column in the well (cm²).

The quantity represents the volumetric rate at which stored water leaves the well during the post-rainfall recession period. In this study, it is used as an operational indicator of recharge capacity under the measured field conditions and should not be interpreted as the well's maximum design capacity. Unlike the specific infiltration rate, the observed volumetric recharge rate incorporates well geometry and therefore provides an additional practical indicator for comparing the investigated systems under the measured field conditions.

Exponential recession analysis and estimation of transmissivity

The long-term decline of the water level in the injection wells was analyzed using an exponential recession model,

$$h(t) = h_0 e^{-ct} \quad (4)$$

where: $h(t)$ – hydraulic head inside the well above the static groundwater level at time t (cm), h_0 – initial hydraulic head above the static groundwater level (cm), and c – recession coefficient (hr⁻¹).

The recession coefficient describes the temporal hydraulic response of the surrounding subsurface formation during infiltration.

The long-term infiltration behavior of the injection wells was analyzed using the exponential recession model described in Equation 4. Assuming axisymmetric radial subsurface flow from a cylindrical well into an idealized homogeneous receiving formation, the instantaneous infiltration discharge can be expressed using the conventional radial-flow formulation (Ferris and Knowles, 1954; Bouwer and Rice, 1976):

$$Q(t) = \frac{2\pi T}{\ln\left(\frac{r_e}{r_w}\right)} h(t) \quad (5)$$

where: $Q(t)$ – instantaneous recharge capacity at time t (m³ s⁻¹), T – surrounding subsurface transmissivity (m² s⁻¹), $h(t)$ – hydraulic

head at time t (m), r_e – effective radius of influence (m), and r_w – well radius (m).

An effective radius of influence $r_e = 10$ m was adopted for the transmissivity estimation. This parameter represents the approximate radial distance over which the hydraulic-head disturbance generated by the well is dissipated and should not be interpreted as the physical depth of the well. To evaluate the influence of this assumption on the estimated transmissivity, a sensitivity analysis was conducted using r_e values of 5, 10, and 20 m.

Because the hydraulic head declines exponentially with time as expressed in Equation 4, the recharge capacity also decreases exponentially,

$$Q(t) = Q_0 e^{-ct} \quad (6)$$

where the initial recharge capacity is:

$$Q_0 = \frac{2\pi T}{\ln\left(\frac{r_e}{r_w}\right)} h_0 \quad (7)$$

The recession coefficient is related to the estimated transmissivity of the surrounding subsurface formation through

$$c = \frac{2\pi T}{A \ln\left(\frac{r_e}{r_w}\right)} \quad (8)$$

where: A is the cross-sectional area of the injection well as stated in Equation 2.

Rearranging Equation 8 yields the expression used to estimate the transmissivity of the surrounding subsurface formation.

$$T = \frac{cA}{2\pi} \ln\left(\frac{r_e}{r_w}\right) \quad (9)$$

where: T – estimated transmissivity of the surrounding subsurface formation ($\text{m}^2 \text{s}^{-1}$), c – exponential recession coefficient (s^{-1}), A – cross-sectional area of the injection well (m^2), r_e – effective radius of influence (m), and r_w – well radius (m).

The regression-derived recession coefficient was converted to SI units before calculating transmissivity. The resulting values of T should therefore be interpreted as model-based estimates of the effective transmissive response of the surrounding subsurface formation under the assumed radial-flow conditions, rather than as independently measured aquifer transmissivity.

Recharge capacity was adopted as the principal engineering performance indicator because it directly represents the volumetric stormwater

infiltration capacity of the recharge system. In contrast, transmissivity characterizes the hydraulic behavior of the surrounding subsurface formation and therefore serves as a supporting hydrogeological parameter that helps interpret differences in recharge performance and subsurface hydraulic behavior among the investigated wells.

Nevertheless, the four hydraulic performance indicators adopted in this study represent complementary aspects of stormwater recharge performance. The specific infiltration rate characterizes the rate of water-level decline; recharge capacity quantifies the volumetric stormwater infiltration capability of the well; the recession coefficient describes the temporal hydraulic response during long-term infiltration; and the estimated transmissivity reflects the hydraulic characteristics of the surrounding subsurface formation. Together, these indicators provide a comprehensive framework for evaluating and comparing the hydraulic performance of infiltration wells and injection wells.

For interpretation of the results, it should be noted that the field measurements were recorded as the downward displacement of the water surface from its initial position. Consequently, the plotted water-level variable increases toward an equilibrium value, particularly during the long-term tests, whereas the corresponding hydraulic head decreases exponentially according to Equation 4.

RESULTS AND DISCUSSION

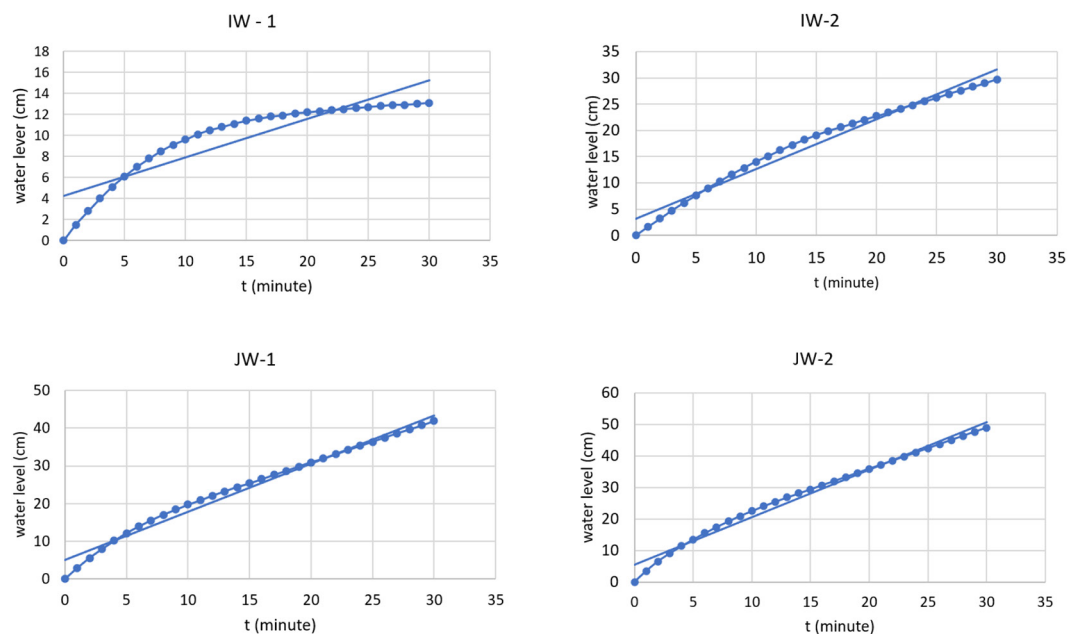
Short-term hydraulic characteristics of the investigated wells

The short-term infiltration tests were conducted to evaluate the initial hydraulic performance of the investigated infiltration wells and injection wells under field conditions. Water-level measurements were recorded at one-minute intervals over a 30-minute period, and the corresponding infiltration rates were determined using the analytical procedure described in Section 3. The hydraulic characteristics obtained from these measurements, including the infiltration rate, cross-sectional surface area, and recharge capacity, are summarized in Table 2, while the temporal variations in water level are presented in Figure 2.

The measured infiltration rates varied noticeably among the four investigated wells, reflecting differences in site conditions and well

Table 2. Hydraulic characteristics of the investigated wells during the initial 30-minute infiltration period

Well	Cross-sectional area, (cm ²)	Test 1 f (cm/min)	R^2	Test 2 f (cm/min)	R^2	Mean $f \pm SD$ (cm/min)	Mean observed volumetric recharge rate, Q (cm ³ /min)
IW-1	2,375.83	0.37	0.8083	0.36	0.8055	0.37 ± 0.01	867
IW-2	5,026.55	0.88	0.9500	0.95	0.9748	0.92 ± 0.05	4599
JW-1	181.46	1.28	0.9812	1.46	0.9965	1.37 ± 0.13	249
JW-2	181.46	1.50	0.9846	1.66	0.9877	1.58 ± 0.11	287

**Figure 2.** Water-level variation during the initial 30-minute infiltration period. Dotted lines represent the measured water-level data, whereas solid lines represent the linear regression used to determine the average specific infiltration rate f

configurations. Overall, the injection wells exhibited higher average specific infiltration rates than the infiltration wells, indicating that water could be transmitted more rapidly into the surrounding subsurface during the initial infiltration period. However, the results also demonstrate that infiltration rate alone does not adequately represent the hydraulic effectiveness of an artificial recharge system.

Recharge capacity, expressed as the volume of water leaving the well per unit time, depends on the specific infiltration rate and the horizontal cross-sectional area of the well. Although the injection wells generally exhibited higher specific infiltration rates, the infiltration wells exhibited substantially greater observed volumetric recharge rates because their larger diameters resulted in much greater horizontal cross-sectional areas. Consequently, a given water-level decline in an infiltration well corresponds to a substantially

larger volume of water leaving the well. In other words, the geometric advantage of the infiltration wells compensated for their lower specific infiltration rates.

The relatively low volumetric recharge rates of the investigated injection wells are partly associated with their small cross-sectional areas. According to the relationship $Q = fA$, well diameter directly influences the calculated volumetric recharge rate through its effect on cross-sectional area. However, the present study did not experimentally evaluate injection wells of different diameters; therefore, the effect of increasing injection-well diameter on actual field performance cannot be determined from the present results. Further field investigations involving injection wells with different diameters under comparable hydrogeological conditions are needed to evaluate this effect.

These observations highlight the different hydraulic characteristics of the two recharge

systems. Injection wells are hydraulically efficient in transmitting water into deeper subsurface layers, making them suitable where rapid localized infiltration is desired and land availability is limited. In contrast, the investigated infiltration wells exhibited greater observed volumetric recharge rates because their larger diameters provided substantially greater water-storage cross-sectional areas, making them potentially suitable for managing larger stormwater volumes where sufficient land is available.

Differences in infiltration performance within each well type may partly reflect the local groundwater conditions observed during field measurements. During dry weather, groundwater was not detected within the measurable depth of IW-2 (Table 1), whereas a shallower water level was observed at IW-1. Consistent with this difference, IW-2 exhibited a higher infiltration rate than IW-1. A similar pattern was observed for the injection wells: JW-2 had a deeper static water level than JW-1 during dry-weather conditions and also exhibited a higher infiltration rate. A deeper water table provides greater available unsaturated storage and may therefore contribute to more favorable infiltration conditions. However, because groundwater levels were observed during the field investigation rather than monitored continuously, this relationship should be interpreted as a plausible contributing mechanism rather than a demonstrated causal relationship.

The present study demonstrates that evaluating artificial recharge systems solely on the basis of specific infiltration rate may lead to misleading engineering conclusions. A comprehensive assessment should therefore consider both the specific infiltration rate, which characterizes the rate of water-level recession, and the observed volumetric recharge rate, which represents the rate of water-volume loss from the well under the

measured field conditions. This dual-parameter evaluation provides a more practical framework for designing and selecting artificial recharge systems in urban environments.

The replicate measurements shown in Table 2 indicate relatively small within-well variability, with standard deviations SD of 0.01, 0.05, 0.13, and 0.11 cm/min for IW-1, IW-2, JW-1, and JW-2, respectively. Because only two replicate tests were available for each well, these values are reported descriptively to quantify measurement spread and were not used for inferential significance testing.

Long-term hydraulic behavior of the investigated injection wells

Following the short-term hydraulic evaluation, long-term monitoring was conducted exclusively on the two injection wells to evaluate their hydraulic response and the characteristics of the surrounding subsurface formation. Water levels were measured at hourly intervals for approximately 6–8 hours and analyzed using the exponential recession model. The resulting hydraulic parameters are summarized in Table 3, while the corresponding water-level recession curves are presented in Figure 3. The recession coefficients reported in Table 3 represent the mean values obtained from the two repeated long-term tests for each injection well, whereas Figure 3 presents the first test as a representative example.

The exponential model provided consistently strong fits for both replicate tests, with R^2 values of 0.9969 and 0.9961 for JW-1 and 0.9900 and 0.9898 for JW-2, respectively. The corresponding fitted equations and regression statistics are provided in Tables S5 and S6. The corresponding RMSE values were also small relative to the observed recession magnitudes, further supporting

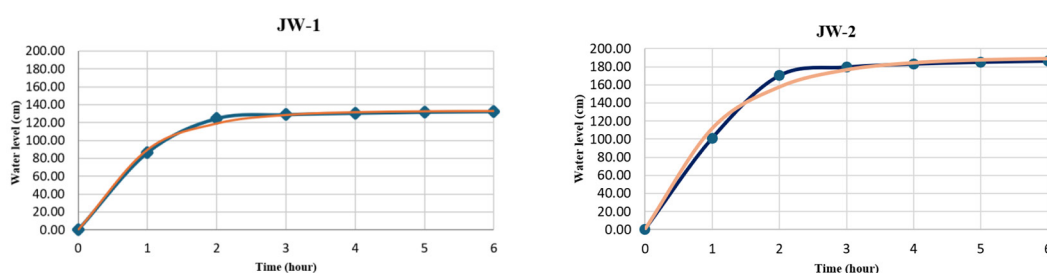


Figure 3. Water-level variation during the long-term infiltration tests for (a) JW-1 and (b) JW-2. Measured data (dotted lines) are compared with the fitted exponential regression curves (solid lines) used to determine the recession coefficient c

Table 3. Long-term hydraulic response of the investigated injection wells during the 6-hour monitoring period

Injection Well	Min. f (cm/min)	Max. f (cm/min)	Average f (cm/min)	Average Q (cm ³ /min)	Recession Coefficient, Mean $c \pm$ SD (hr ⁻¹)	Estimated Transmissivity, T (m ² /s)
JW-1	0.007	1.48	0.26	47.43	1.158 ± 0.054	$(4.53 \pm 0.21) \times 10^{-6}$
JW-2	0.010	1.69	0.37	67.49	0.882 ± 0.006	$(3.45 \pm 0.02) \times 10^{-6}$

the adequacy of the exponential model for representing the long-term water-level response.

As an illustrative calculation, the estimated transmissivity T for JW-1 reported in Table 3 was obtained using the mean recession coefficient $c = 1.1584 \text{ hr}^{-1}$, well radius $r_w = 0.076 \text{ m}$, and effective radius of influence $r_e = 10 \text{ m}$. The recession coefficient was converted to SI units as $c = 1.1584/3600 = 3.2178 \times 10^{-4} \text{ s}^{-1}$, while the well cross-sectional area was $A = \pi (0.076)^2 = 0.01815 \text{ m}^2$. Substituting these values into Equation 9 gives $T = 4.53 \times 10^{-6} \text{ m}^2/\text{s}$.

The monitored injection wells exhibited an exponential decline in water level throughout the observation period. The rapid initial decline resulted from a large hydraulic gradient between the water stored in the well and the receiving formation. As infiltration progressed, the hydraulic gradient gradually decreased, producing a slower rate of water-level recession until hydraulic equilibrium was approached.

Differences in the recession coefficient and estimated transmissivity between the two wells suggest spatial variability in the hydraulic response of the receiving subsurface formation. Higher estimated transmissivity values indicate a more rapid dissipation of hydraulic head within the idealized analytical framework used in this study. Both injection wells approached near-equilibrium conditions after approximately two hours, after which only minor water-level changes were observed.

The sensitivity analysis showed that the assumed radius of influence had a moderate effect on the estimated transmissivity. For r_e values of 5, 10, and 20 m, the estimated transmissivity was 3.89×10^{-6} , 4.53×10^{-6} , and $5.18 \times 10^{-6} \text{ m}^2/\text{s}$ for JW-1, and 2.96×10^{-6} , 3.45×10^{-6} , and $3.94 \times 10^{-6} \text{ m}^2/\text{s}$ for JW-2, respectively. Thus, halving or doubling the assumed radius of influence changed the estimated transmissivity by approximately 14%, while JW-1 consistently exhibited a higher estimated transmissivity than JW-2. This indicates that the comparative interpretation of the two injection wells is not highly sensitive to moderate uncertainty in the assumed radius of influence.

The long-term results demonstrate that the hydraulic performance of an injection well should be evaluated using both structural performance indicators (specific infiltration rate and recharge capacity) and hydrogeological response indicators (recession coefficient and estimated transmissivity). Together, these parameters provide a more comprehensive assessment of the effectiveness of injection wells for sustainable urban groundwater recharge.

The replicate long-term tests shown in Table 3 indicate limited within-well variability, with standard deviations SD of 0.054 hr^{-1} for JW-1 and 0.006 hr^{-1} for JW-2. Because only two replicate tests were available for each well, these values are reported descriptively and were not used for inferential significance testing.

Engineering implications for urban stormwater management

The results demonstrate that infiltration wells and injection wells provide complementary functions in urban stormwater management. Infiltration wells offer greater recharge capacity because of their larger well diameter and horizontal cross-sectional area, making them suitable for locations where large stormwater volumes can be retained and sufficient land is available. In contrast, injection wells exhibit higher specific infiltration rates and require a smaller footprint, making them more appropriate for densely developed urban areas where space is limited.

The field observations indicate that hydraulic head is one of the primary factors governing the hydraulic performance of both infiltration wells and injection wells. At the beginning of each test, the larger head difference between the water stored in the well and the surrounding groundwater generated relatively high infiltration rates and recharge capacities. As the water level declined, the hydraulic gradient gradually decreased, leading to progressively lower infiltration rates until near-equilibrium conditions were reached. Consequently, the effectiveness of these stormwater infiltration systems is

expected to decrease when groundwater levels are already high before rainfall events, because the available hydraulic head driving infiltration becomes smaller.

The study further shows that the hydraulic performance of artificial recharge systems should not be evaluated solely on the basis of infiltration rate. A comprehensive assessment should also consider recharge capacity and the hydraulic characteristics of the surrounding subsurface formation. While the infiltration rate and recharge capacity describe the performance of the recharge structure, the recession coefficient and estimated transmissivity reflect the ability of the surrounding geological formation to receive and transmit infiltrated water.

From a practical perspective, the selection of an appropriate recharge system should consider site-specific conditions, including land availability, subsurface hydraulic properties, antecedent groundwater level, stormwater volume, and maintenance requirements. Proper pretreatment of stormwater and periodic maintenance are also essential to minimize clogging and protect groundwater quality, thereby ensuring sustainable long-term operation of artificial recharge systems.

Although recharge wells may complement conventional urban drainage systems, their potential contribution to flood mitigation depends strongly on how they are spatially implemented. Rather than relying on a small number of wells to accommodate large concentrated runoff volumes, recharge wells should preferably be distributed throughout the urban catchment so that stormwater can be intercepted and infiltrated close to where it is generated. This distributed approach is intended to intercept stormwater close to its source, reducing the runoff volume and rate entering the drainage network and potentially relieving local drainage loads. However, the effectiveness of individual wells remains dependent on site-specific hydraulic and hydrogeological conditions. Recharge wells should therefore be regarded as distributed source-control measures that complement, rather than replace, adequately designed urban drainage systems. Their implementation should form part of an integrated flood-management strategy incorporating surface drainage, temporary storage, safe overflow pathways, stormwater pretreatment, and regular maintenance.

Comparison with previous studies

The present study demonstrates that infiltration wells and injection wells exhibit different hydraulic characteristics associated with differences in well geometry, hydraulic head, and the hydraulic properties of the surrounding subsurface formation. The field measurements showed that the injection wells generally exhibited higher specific infiltration rates, whereas the infiltration wells provided greater recharge capacities owing to their larger diameters. These findings are consistent with previous studies reporting that recharge systems extending to deeper permeable layers generally provide higher infiltration capacities than systems infiltrating only through the unsaturated zone (Sasidharan et al., 2021; Netzer et al., 2024).

Unlike many previous investigations that evaluated recharge systems primarily using infiltration capacity or total recharge volume, the present study simultaneously considered four complementary hydraulic indicators: specific infiltration rate (f), recharge capacity (Q), recession coefficient (c), and estimated transmissivity (T). The combined use of these parameters provides a more comprehensive evaluation of recharge system performance by distinguishing the hydraulic response of the recharge structure from that of the surrounding subsurface formation.

An important observation from the field measurements is the influence of hydraulic head on recharge performance. The infiltration rate was highest immediately after the wells were filled and gradually decreased as the water level inside the wells declined. Consequently, the recharge capacity also decreased until both investigated injection wells approached near-equilibrium conditions after approximately two hours. These observations indicate that hydraulic head is one of the primary factors controlling the temporal variation of infiltration performance. Therefore, the effectiveness of both infiltration wells and injection wells is expected to decrease when groundwater levels are already high before rainfall events, because the available hydraulic head driving infiltration becomes smaller.

The field measurements were conducted following natural rainfall events, with first-hour rainfall depths ranging from approximately 19 to 35 mm. Monitoring began after rainfall had ceased and the water level in the investigated well had reached approximately ground level.

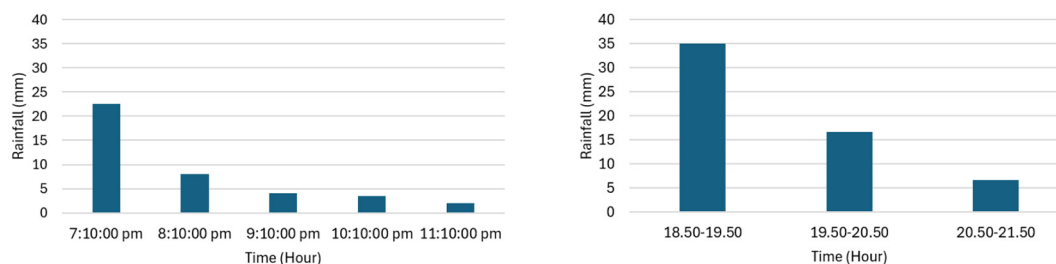


Figure 4. Typical hourly rainfall distributions preceding the post-rainfall recession measurements

Figure 4 presents two typical rainfall records preceding the post-rainfall recession measurements and shows that the largest rainfall depth occurred during the first observation interval. Rainfall observations associated with all individual field tests, including both replicate measurements, are provided in Supplementary Table S8. Following these rainfall events, both infiltration wells and injection wells exhibited measurable post-rainfall recession responses, although the recession rate gradually decreased as the available hydraulic head diminished. The results suggest that both systems can help reduce local surface runoff by promoting stormwater infiltration at its source, thereby complementing conventional drainage systems. Rather than replacing urban drainage infrastructure, infiltration and injection wells should be regarded as decentralized stormwater-management measures that can reduce runoff volume, delay peak discharge, and enhance groundwater recharge (Ksatria et al., 2022; Tiwery, 2019). However, the present study did not quantify the magnitude of flood reduction.

The repeated field measurements conducted for each well further demonstrated good measurement repeatability. The first and second trials produced similar water-level recession curves and comparable hydraulic parameters, indicating that the observed differences among wells primarily reflect variations in site conditions rather than measurement inconsistencies. Although no formal statistical analysis was performed, the close agreement between the repeated measurements provides confidence in the reliability of the adopted field-testing procedure.

Although infiltration wells and injection wells can support stormwater recharge and may contribute to urban flood mitigation, their application should be accompanied by appropriate pretreatment and regular monitoring to minimize the risk of introducing contaminants into the surrounding subsurface environment. Because injection wells

transfer stormwater directly into the subsurface through relatively narrow conduits, stormwater quality, pretreatment, and maintenance should be closely managed to reduce the risk of groundwater contamination. Studies on groundwater quality protection in urban water infrastructure and managed aquifer recharge systems have highlighted this consideration (Dillon et al., 2019; Edwards et al., 2022; Zeydalinejad et al., 2024).

From an engineering perspective, the present study suggests that the hydraulic performance of stormwater recharge systems is governed primarily by three interrelated factors: well geometry, hydraulic head, and the hydraulic properties of the surrounding subsurface formation. Together, these factors determine the specific infiltration rate, recharge capacity, and long-term hydraulic response of the recharge system. This integrated interpretation complements previous studies emphasizing the importance of recharge structure geometry and subsurface conditions in determining the effectiveness of managed recharge systems.

The findings of this study should be interpreted within the limitations of the field investigation. The analysis was based on four recharge wells located at different sites in Medan City, and the observed hydraulic responses therefore reflect the specific well geometries and subsurface conditions at the investigated locations. The estimated transmissivity values were derived from an idealized radial-flow model rather than from independent aquifer testing, while the field measurements represent post-rainfall recession responses under the observed rainfall and groundwater conditions. Consequently, the numerical differences reported between the investigated infiltration and injection wells should not be generalized to all recharge systems without consideration of site-specific hydrogeological conditions. In addition, the present study evaluates hydraulic performance at the individual-well scale and does not directly quantify catchment-scale flood reduction. Further investigations involving

more wells, detailed subsurface characterization, longer-term monitoring, and catchment-scale hydrological assessment would strengthen the broader applicability of the findings.

CONCLUSIONS

This study evaluated the hydraulic performance of infiltration wells and injection wells for urban stormwater management through field measurements conducted in Medan City, Indonesia. Short-term infiltration tests were performed on two infiltration wells and two injection wells to determine the specific infiltration rate and recharge capacity, while long-term monitoring was conducted on the injection wells to evaluate their hydraulic response using the exponential recession method.

The results indicate that the two recharge systems exhibit different but complementary hydraulic characteristics. The injection wells generally produced higher specific infiltration rates, indicating more rapid water transmission into the surrounding subsurface formation. In contrast, the investigated infiltration wells exhibited greater observed volumetric recharge rates because their larger diameters resulted in greater water-storage cross-sectional areas. These findings demonstrate that volumetric recharge rate should be evaluated alongside specific infiltration rate when assessing the hydraulic performance of artificial recharge systems.

The results further indicate that well geometry is an important consideration in volumetric recharge performance. A larger injection-well diameter would increase the cross-sectional area available for water storage; however, the present study did not experimentally evaluate injection wells of different diameters. The effect of increasing injection-well diameter on actual volumetric recharge performance should therefore be verified through dedicated field testing under comparable hydrogeological conditions.

The long-term observations further showed that the hydraulic response of the injection wells followed an exponential recession pattern, with both wells approaching near-equilibrium conditions after approximately two hours. The recession coefficients and model-derived transmissivity estimates reflected differences in the hydraulic response of the surrounding subsurface formation, providing additional information on long-term

recharge behavior beyond what the short-term recession measurements provided.

An important finding of this study is the apparent influence of hydraulic head on recharge performance. Our field measurements showed that infiltration rates and recharge capacities gradually decreased as the water level inside the wells declined, indicating that the available hydraulic head is one of the principal factors controlling infiltration. Consequently, the effectiveness of stormwater recharge systems is expected to decrease when groundwater levels are already elevated before rainfall events because the hydraulic gradient driving infiltration becomes smaller.

From an engineering perspective, the present study suggests that the hydraulic performance of infiltration systems is governed primarily by three interrelated factors: well geometry, hydraulic head, and the hydraulic properties of the surrounding subsurface formation. These factors jointly determine the specific infiltration rate, recharge capacity, and long-term hydraulic response of the recharge system. The findings demonstrate that well geometry, hydraulic head, and the hydraulic properties of the surrounding subsurface formation should be considered jointly when evaluating urban stormwater recharge performance, rather than relying solely on infiltration rate.

The repeated field measurements demonstrated good repeatability of the proposed testing procedure, providing confidence in the reliability of the measured hydraulic parameters.

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REFERENCES

1. Ashley, R. M., Lundy, L., Ward, S., Shaffer, P., Walker, L., Morgan, C., Saul, A., Wong, T., Moore, S. (2013). Water-sensitive urban design: Opportunities for the UK. *Proceedings of the Institution of Civil Engineers – Municipal Engineer*, 166(2), 65–76. <https://doi.org/10.1680/muen.12.00046>

2. Bouwer, H. (2002). Artificial recharge of groundwater: Hydrogeology and engineering. *Hydrogeology Journal*, 10(1), 121–142. <https://doi.org/10.1007/s10040-001-0182-4>
3. Bouwer, H., Rice, R. C. (1976). A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells. *Water Resources Research*, 12(3), 423–428. <https://doi.org/10.1029/WR012i003p00423>
4. Dillon, P., Stuyfzand, P., Grischek, T., Lloria, M., Pyne, R. D. G., Jain, R. C., Bear, J., Schwarz, W., Wang, W., Fernandez, E., et al. (2019). Sixty years of global progress in managed aquifer recharge. *Hydrogeology Journal*, 27, 1–30. <https://doi.org/10.1007/s10040-018-1841-z>
5. Edwards, E. C., Nelson, C., Harter, T., Bowles, C., Li, X., Lock, B., Washburn, B. S., Fogg, G. E. (2022). Potential effects on groundwater quality associated with infiltrating stormwater through dry wells for aquifer recharge. *Journal of Contaminant Hydrology*, 246, 103964. <https://doi.org/10.1016/j.jconhyd.2022.103964>
6. Ferris, J. G., Knowles, D. B. (1954). *The “slug test” for estimating transmissibility*. U.S. Geological Survey Open-File Report 54–80. U.S. Geological Survey.
7. Fiori, A., de Barros, F. P. J., Bellin, A. (2025). An analytical framework for risk evaluation and design of infiltration basins for managed aquifer recharge. *Water Resources Research*, 61(1), e2024WR038516. <https://doi.org/10.1029/2024WR038516>
8. Fletcher, T. D., Shuster, W., Hunt, W. F., Ashley, R., Butler, D., Arthur, S., Trowsdale, S., Barraud, S., Semadeni-Davies, A., Bertrand-Krajewski, J. L., et al. (2015). SUDS, LID, BMPs, WSUD and more – The evolution and application of terminology surrounding urban drainage. *Urban Water Journal*, 12(7), 525–542. <https://doi.org/10.1080/1573062X.2014.916314>
9. Ksatria, N. J., Hidayatullah, T., Hasan, F., Darfia, N. E., Syarvina, Kumaryadi, M. R. (2022). Infiltration well efficacy in Ciliwung Basin based on rainfall-runoff volumetric analysis. *Jurnal Saintis*, 22(1). [https://doi.org/10.25299/saintis.2022.vol22\(01\).8693](https://doi.org/10.25299/saintis.2022.vol22(01).8693)
10. Netzer, L., Kurtzman, D., Ben-Hur, M., Livshitz, Y., Katzir, R., Nachshon, U. (2024). Novel approach to roof rainwater harvesting and aquifer recharge in an urban environment: Dry and wet infiltration wells comparison. *Water Research*, 252, 121183. <https://doi.org/10.1016/j.watres.2024.121183>
11. Netzer, L., Russo, D., Nachshon, U., Moreno, Z., Ben-Hur, M., Katzir, R., Livshitz, Y., Kurtzman, D. (2025). Drywell infiltration performance: Tests, monitoring, simple, and detailed models. *Water Resources Research*, 61(2), e2024WR037524. <https://doi.org/10.1029/2024WR037524>
12. Przestrzelska, K., Wartalska, K., Rosińska, W., Jurasz, J., Kaźmierczak, B. (2024). Climate resilient cities: A review of blue-green solutions worldwide. *Water Resources Management*, 38(15), 5885–5910. <https://doi.org/10.1007/s11269-024-03950-5>
13. Sasidharan, S., Bradford, S. A., Šimůnek, J., Kraemer, S. R. (2021). Comparison of recharge from drywells and infiltration basins: A modeling study. *Journal of Hydrology*, 594, 125720. <https://doi.org/10.1016/j.jhydrol.2020.125720>
14. Suprayogi, S., Sudarmadji, Malawani, M. N. (2019). Urban sediment in infiltration wells: A lesson from the northern area of Greater Yogyakarta City. *Indonesian Journal of Geography*, 51(3), 295–303. <https://doi.org/10.22146/ijg.33721>
15. Tiwery, C. J. (2019). Analysis of infiltration-well dimensions for reducing runoff discharge in an urban residential area (Case study of the Urimessing area, Ambon City) (in Indonesian). *Manumata: Jurnal Ilmu Teknik*, 6(1), 1–11.
16. Zeydalinejad, N., Javadi, A. A., Webber, J. L. (2024). Global perspectives on groundwater infiltration to sewer networks: A threat to urban sustainability. *Water Research*, 262, 122098. <https://doi.org/10.1016/j.watres.2024.122098>