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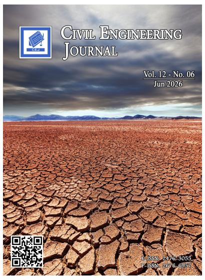
Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 12, No. 06, June, 2026



Performance Evaluation of Infiltration Wells Through Integration of Field Testing and GeoStudio SEEP/W Simulation

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Received 29 December 2025; Revised 19 May 2026; Accepted 23 May 2026; Published 01 June 2026

Abstract

This study aimed to evaluate the accuracy of GeoStudio SEEP/W simulations in representing field conditions and to determine the optimal configuration of infiltration wells. A hybrid method combining field measurements and simulation was applied to three infiltration wells, with field tests conducted under two scenarios full filling of well A and simultaneous filling of all three wells. The analysis included soil permeability data, controlled inflow rates from the reservoir, and measured seepage flow rates. The results showed that the initial seepage flow rate in Well C was higher than the simulation data, with parallel interaction producing the highest initial flow rate, indicating the influence of local geotechnical conditions. Model calibration using site-specific hydraulic conductivity and saturation parameters improved simulation accuracy. Parallel well interaction was found to increase infiltration capacity by approximately 30% compared to a single well, and the optimal distance between wells was recommended to be at least 1.5-2 times the well diameter to avoid overlap of saturated zones. This study makes theoretical contributions by establishing a framework that integrates field measurements and simulations, particularly for calibrating early-stage seepage behavior across multiple scenarios. The validated model offers practical guidelines for optimal infiltration well planning, advancing effective urban flood mitigation.

Keywords: Infiltration Wells; Field Testing; GeoStudio SEEP/W; Induced Wells Response; Parallel Interaction.

1. Introduction

Climate change triggers shifts in rainfall patterns in urban areas [1]. Increase in high-intensity rainfall with short duration. This condition increases surface runoff and reduces natural infiltration [2]. This condition increases the frequency and severity of urban flooding [3]. The impact is exacerbated by urbanization. Urbanization increases impervious surfaces and soil compaction [4]. This significantly reduces the soil's infiltration capacity [5]. Many existing conventional drainage systems are unable to accommodate increased peak discharge and runoff volumes [6].

In recent decades, green infrastructure approaches have included the use of infiltration wells [7]. Infiltration wells have been developed as an alternative to reduce runoff and delay peak flows [8]. Various studies show that infiltration wells can help reduce runoff [9]. The depth of flooding decreased, especially during moderate rainfall events [10]. However, the performance of infiltration wells is highly dependent on the local soil conditions. Soil permeability, heterogeneity, and rainfall characteristics all play a role [11]. Field application of infiltration wells to increase infiltration capacity and expand the hydraulic zone of influence [12].

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https://doi.org/10.28991/CEJ-2026-012-06-05

Along with the development of numerical modeling, subsurface seepage flow-based software such as GeoStudio SEEP/W has been widely used to analyze infiltration processes and groundwater movement [13]. Enabling the evaluation of infiltration well performance [14]. More systematic and efficient performance compared to field testing alone. However, most studies remain limited to a single operational scenario [15]. Hydraulic interactions between infiltration wells and the effects of varying conditions have not been studied in depth [16]. Additionally, differences between simulation results and field measurements in the early stages are still frequently reported.

The development of 2D subsurface flow models enables a more detailed evaluation of infiltration infrastructure performance [17]. Even though grouped infiltration well systems are essentially three-dimensional. These limitations are addressed using an equivalent-parameter approach [18]. The hydraulic behavior of grouped wells is represented by equivalent infiltration wells, and the interaction between wells and the total system contribution is modeled in a 2D model. Research gaps indicate the need for studies that integrate multi-scenario field testing with calibrated numerical modeling [11]. The equivalent approach, which presents a grouped infiltration well system, is important for evaluating the model's ability to represent complex field conditions as well as identifying model limitations in the early phase and seepage transition.

Based on this background, the study aims to evaluate seepage flow rates in infiltration wells through field tests and simulations with GeoStudio SEEP/W under several operational scenarios. The model's accuracy in representing field conditions is assessed by examining the interaction between wells using an equivalent approach, and the main contribution addresses the gap between urban infiltration studies at the system scale. The focus is on surface runoff and local seepage studies, which are generally limited to a single scenario. The expected results support better infiltration and well planning. The government is assisted in technical planning to develop flood control systems. This study reinforces the role of numerical modeling in adaptive urban drainage planning. Modeling does not require extensive physical prototypes.

2. Methodology

2.1. The Study Area

This study was conducted at Sebelas Maret University, Surakarta City, Indonesia. The location has highly permeable soil, making it suitable for seepage analysis. This location covers land with relatively high hydraulic conductivity. Surakarta represents a subgroup of flood-prone cities that still have natural infiltration capacity. However, there is intense rainfall accumulation, increased impervious cover, and limited drainage. These conditions differ from flood-prone cities that have developed on low-permeability land [19]. The infiltration well performance values obtained cannot be directly generalized to cities with less permeable soil [20]. This study is considered an upper bound on the effectiveness of infiltration-based solutions. Identified mechanisms for runoff reduction and peak discharge delay. Reduction through distributed infiltration. Consistent with recent findings from urban contexts implementing green infrastructure. Measurements were taken at three infiltration wells, and all data used were obtained directly from the field test. Soil parameters are shown in Table 1.

Table 1. Soil parameters

Parameter	Unit	Well A	Well B	Well C
Water content	%	45.13	40.13	52.61
Void ratio	–	0.98	0.88	1.24
Hydraulic conductivity	cm/s	8.82×10^{-3}	7.11×10^{-3}	1.17×10^{-2}
Gravel	%	1.83	2.98	0.00
Sand	%	50.79	54.44	57.00
Silt	%	47.39	42.58	43.00
Clay	%	0.00	0.00	0.00

Table 1 shows physical and hydraulic properties of soil around wells A, B, and C. Soil water content (w, %) represents gravimetric water content obtained from laboratory testing. Pore ratio (e, -) is the ratio between pore volume and solid particle volume. Soil porosity and compressibility. Conductivity (K, cm/second) indicates the saturated permeability of the soil. Input parameter in the SEEP/W simulation to represent seepage. Grain size composition of gravel, sand, silt, and clay fractions. The soil is dominated by coarse to medium-grained material. Consistent with relatively high hydraulic conductivity values. Shows that soil in all infiltration wells is dominated by sand and silt fractions. Based on test parameters, permeability is relatively high, and well C shows the largest hydraulic conductivity. Furthermore, infiltration potential is faster, and well B has the lowest void ratio, which can slow down the seepage rate.

2.2. Field Test Scenario

A combination of field testing and numerical simulation using GeoStudio SEEP/W was applied to develop hybrid models for analyzing seepage and the interactions between infiltration wells. Subsequently, water load tests were conducted on three locations, as presented in Figure 1.

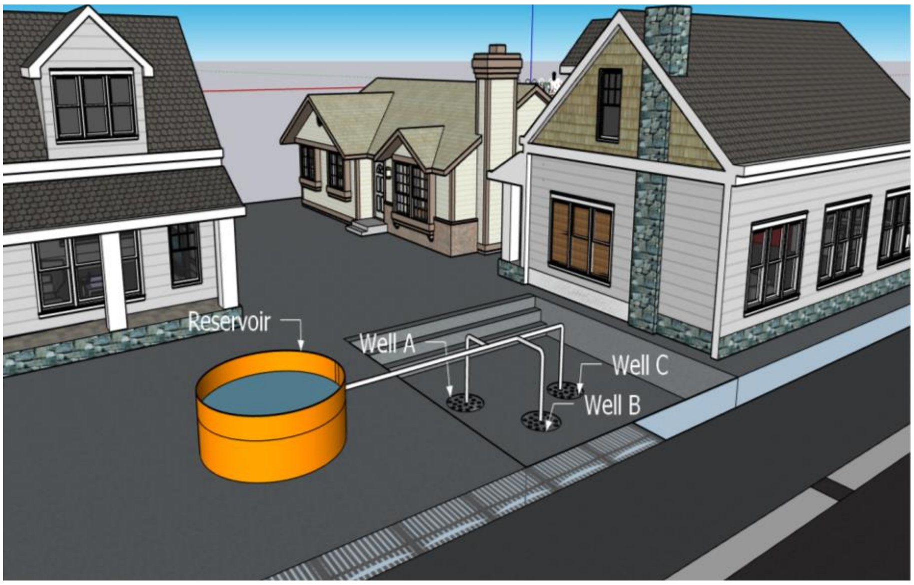

Figure 1. Parallel Well Interaction

Figure 1 shows field testing for surface flow was simulated using a water reservoir, with infiltration conducted through two scenarios. The selection of two scenarios in this study is based on infiltration well engineering practices. It presents the two most critical and informative operational conditions. Scenario one involves filling one well and monitoring the response in the surrounding wells. This test is equivalent to an injection test used to understand the local hydraulic response [21]. The relationship between discharge and water level. The single-well scenario was designed to isolate and characterize the behavior of the base seepage. The dynamics of initial soil saturation were an important aspect of the identified early-phase seepage gap. The second scenario involves operating infiltration wells in groups. Scenario two explicitly investigates interactions between wells. The system's overall capacity directly addresses the imbalance in multi-well, multi-operational conditions. This filling represents systemic conditions at the regional level. The interaction between wells, overlapping saturated zones, and total infiltration capacity is the dominant factor. This scenario is relevant for evaluating system performance during short-duration heavy rainfall events. This study focuses on two boundary conditions, namely maximum local response and maximum system performance.

In the first scenario, a single full recharge was applied to well A to monitor its impact on wells B and C. Meanwhile, wells A, B, and C were simultaneously recharged in the second scenario to assess system interaction and capacity. Infiltration wells were measured using a pipe device to monitor water fluctuations. The objective of the first scenario was to determine the reservoir's maximum performance under extreme conditions. Infiltration wells were also filled to measure the response of well A and observe the influence of others in the vicinity. Seepage patterns were observed to represent conditions of high rainfall intensity. The second scenario involved filling all three wells to assess the effectiveness of the group-based system in enhancing infiltration capacity. The main objective was to simulate an integrated drainage system at an urban scale. Therefore, an analysis was conducted based on seepage time and flow rate.

Measurement of seepage flow rate was performed using a pipe and periodic water-level recordings. Water is pumped from a well into a reservoir. The inflow rate can be controlled steadily. The drop in water level due to infiltration is observed directly through a measuring pipe. Scale readings are in centimeters. Practical measurement resolution. Accuracy of pipe scale and visual readability in the field. Potential for major errors due to surface fluctuations caused by initial conditions and visual limitations due to lighting [22]. The seepage rate is calculated from the change in water level over the observation interval. Uncertainty in water level readings directly affects the accuracy of the seepage rate. To minimize the effect of errors, the analysis focuses on the decline time interval. The measuring pipe provides a representative estimate of the seepage rate, particularly for the transition phase approaching stability.

The testing equipment is shown in Figures 2 and 3. As shown in Figures 3 and 4, each test was equipped with a filling pipe and a measuring pipe to record the water level drop at periodic intervals. The data obtained were processed to determine the actual seepage discharge. This method allows direct field analysis of infiltration performance, which is compared with results from numerical simulation using GeoStudio SEEP/W.

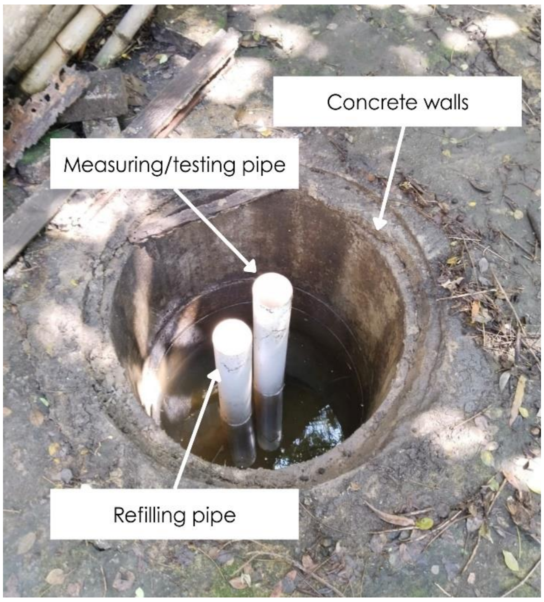

Figure 2. Field installation of the infiltration well and measurement pipes used for seepage testing

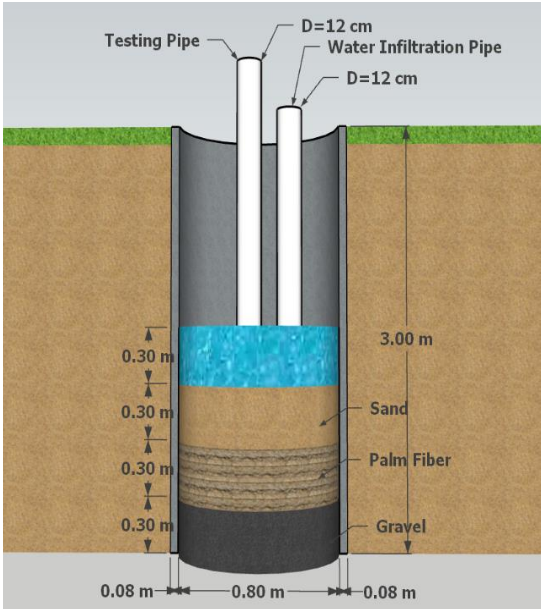

Figure 3. Conceptual design and material configuration of the infiltration are well used in this study

Figures 2 and 3 show infiltration wells had a diameter of 0.8 m, a depth of 2 m, and a pipe diameter of 12 cm. Figure 2 shows the actual condition of the infiltration wells in the field. Concrete walls, water level measurement pipes. This figure explains the field-testing method used to confirm water-level decline measurements. Direct decline through the measuring pipe. Measurements are used to calculate the seepage rate from changes in water height over time. Figure 3 shows a conceptual diagram of the infiltration wells used in the study. Geometric dimensions, pipe configuration, and arrangement of filling material layers. The filling material consists of sand, coconut fiber, and gravel. This diagram is used for two-dimensional numerical modeling using GeoStudio SEEP/W. Referring to Figures 2 and 3, the integration between conceptual design and field implementation is discussed. This approach reinforces the transparency of the methodology analyzed in the study.

2.3. Theoretical Approach to Modeling

The research is based on the theory of seepage flow in saturated and unsaturated porous media. The theory follows Darcy's law and the mass continuity equation [23]. Fluid flow is controlled by hydraulic gradients and soil conductivity. [24]. Temporal variations are represented through unsteady flow formulations. Numerical modeling uses GeoStudio SEEP/W, which implements two-dimensional finite element method formulations. Approach to seepage analysis in infiltration wells. Theoretically, unsaturated flow behavior is controlled by the relationship between pore water pressure, flow rate, and hydraulic conductivity [23, 24]. Behavior described by the soil water retention curve [25]. This study does not explicitly include unsaturated parameters due to limitations in field data. The analysis focuses on transient responses towards saturated conditions. Medium to long-term seepage behavior for evaluating infiltration well performance.

The three-dimensional infiltration well system is represented as an asymmetrical 2D cross-section [26]. The grouped-well configuration applied the equivalent well approach [27]. Several wells were modeled as a single entity with effective hydraulic parameters. This approach enabled consistent representation of the system's hydraulic response in 2D modeling.

2.4. Analysis of GeoStudio SEEP/W Software

The SEEP/W simulation model, developed by GeoStudio [28], is a numerical tool for subsurface flow analysis based on Darcy's law. This model simulates water flow networks and soil infiltration to analyze groundwater level rise and infiltration volume. Subsequently, simulation results are compared with field data to evaluate the performance of infiltration wells, as shown in Figure 4.

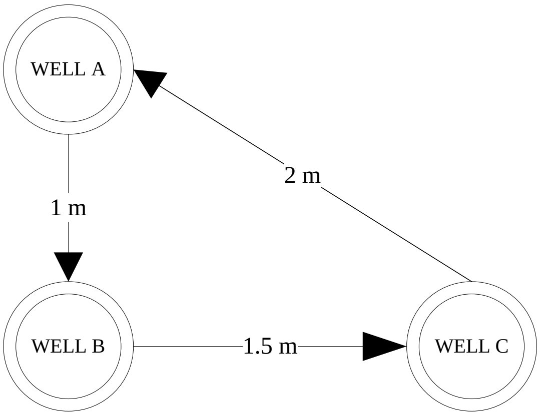

Figure 4. Infiltration wells model in the field

Figure 4 shows the 2D model visualizes the configuration of wells A, B, and C as well as distances from actual field conditions, which influence the direction and distribution of seepage. The layout of wells also affects the hydraulic interactions among scenarios, as spacing influences the distribution of saturated pressure zones. Moreover, a proper configuration promotes uniform infiltration and accelerates percolation into deeper soil layers. In the model, soil parameters are incorporated, with saturated conditions and hydraulic conductivity calibrated to match field data. The equivalent well approach in SEEP/W 2D modeling. The hydraulic interaction of grouped infiltration wells is presented in equivalent form. This approach is used to accommodate the limitations of the SEEP/W 2D model. Limitations in capturing three-dimensional flow around wells operating simultaneously. Several infiltration wells are represented as one equivalent well. Parameters include diameter, discharge, and hydraulic conductivity. Parameters are based on infiltration capacity equivalence. This approach can evaluate the average hydraulic performance of the system and the interaction of field-scale wells.

Model calibration is carried out in stages by adjusting the parameters that most influence seepage response. Hydraulic conductivity values, initial soil saturation conditions, and flow boundary conditions. These parameters are adjusted to represent soil conditions prior to well charging. Adjustments are made to approximate field conditions [29]. Model suitability using evaluation criteria [30]. The coefficient of determination (R^2) from simulation and field testing, with a value ≥ 0.85, is considered indicative of good suitability. The suitability of the seepage reduction curve in the transition phase towards stability. Calibration focused on improving accuracy in the transition and stability phases [31]. The calibrated model can present field seepage behavior more consistently for planning purposes. An illustration of the research method can be seen in Figure 5.

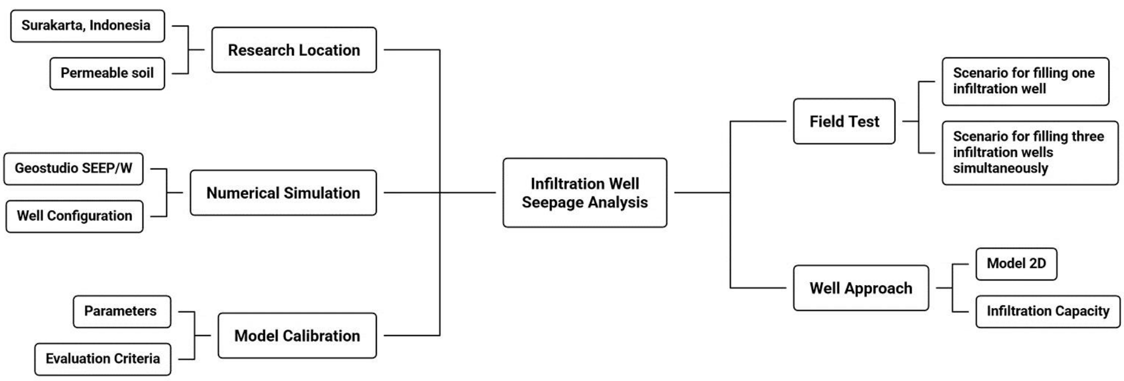

Figure 5. Flowchart of the research methodology

3. Results and Discussion

Field testing of one full-scale variant of infiltration wells was conducted during the rainy season with a water level of 1.5 m from the bottom. Modeling was performed using GeoStudio SEEP/W 2D software to compare the performance of infiltration wells. Based on the results, water movement from well A to B occurs through underground flow pathways. Meanwhile, Well C shows a higher water level rise compared to B.

The observed differences are related to soil characteristics and the distance from well A. After 100 minutes, the infiltration rate stabilizes, showing that groundwater recharge and geotechnical factors can significantly influence neighboring wells. For grouped infiltration wells, proper spacing and orientation are critical to optimize load distribution and prevent saturated pressure zones that reduce system efficiency. A comparison of field test data and GeoStudio simulation results for well A is presented in Figure 6.

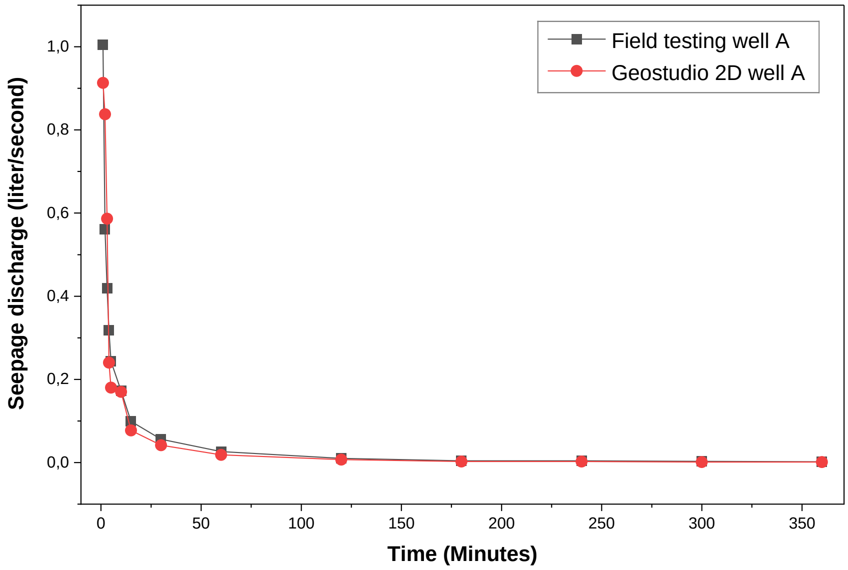

Figure 6. Comparison of seepage discharge overtime between field test and GeoStudio SEEP/W simulation in Induced wells response

Figure 6 compares field test results with the GeoStudio SEEP/W simulation for well A. The graph shows the trend of seepage flow and pattern in the infiltration well. Initial pattern analysis indicates a significant increase in seepage flow. Based on observation, the accumulation rate reached 0.9 liter/s in the first 3 minutes due to high initial hydraulic pressure. This suggested that the soil was not fully saturated during initial infiltration. The simulation shows a more conservative seepage flow pattern. The initial flow rate was lower than the field test results in the first minute. This difference was due to the initial simulation parameters not fully representing the actual field conditions. Furthermore, the high initial pressure during filling and the unsaturated soil conditions led to a flow rate that the model did not capture, suggesting the need for soil condition calibration. The model accurately captures the seepage dynamics during the initial phase and transition.

GeoStudio does not fully capture the initial conditions in the field, as early seepage reduction differs from the gradual decline modeled. This knowledge gap shows the need to consider saturated soil effects, including hydrogenation and pore closure caused by particles. GeoStudio SEEP/W provides precise estimates during the stable seepage phase, serving as a reliable tool for long-term projections. However, short-term predictions remain less accurate because sudden changes in flow under saturation are not represented. To improve this phase, the model requires careful calibration that incorporates soil saturation, pressure, and structural properties.

Meanwhile, this study shows that a well's infiltration capacity declines rapidly [32]. Insufficient potential to manage extremely high rainfall events. This conclusion was drawn from a limited sample of three wells at specific locations. Further research involving a wider range of soil types and well configurations would be useful to generalize these findings. In the second scenario, all three infiltration wells were filled. This was followed by a seepage flow assessment using field data and GeoStudio SEEP/W simulations, with the results shown in Figure 7.

Figure 7, which compares seepage discharge, shows a relatively large difference in the initial phase (0-10 minutes). The soil conditions are not yet saturated, and the initial hydraulic pressure response in the field is complex. In the transition phase (± 10-30 minutes), both curves show a downward trend in discharge and a stable phase. The field test seepage discharge decreases and approaches the simulation. In this phase, a saturated zone forms around the well. The hydraulic gradient decreases, and the flow begins to be controlled by the soil's saturated conductivity. Both curves show a more stable mechanism. The hydraulic parameters used in GeoStudio SEEP/W are representative. Over a longer period, the seepage discharge is more constant. The hydraulic equilibrium of the infiltration rate is limited by the soil's capacity. The steady state represents the long-term performance of the infiltration well. The steady state is relevant for urban drainage planning and infiltration capacity evaluation. The GeoStudio SEEP/W 2D model can provide conservative, stable estimates for design purposes.

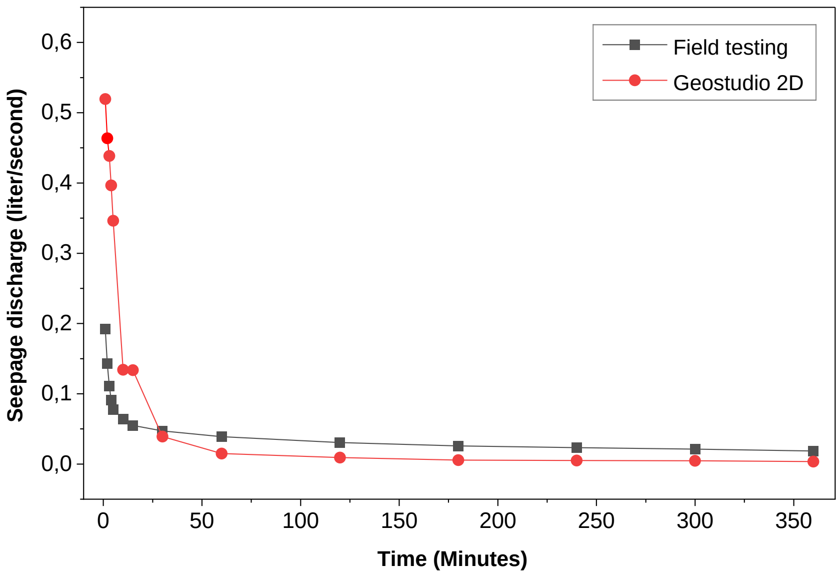

Figure 7. Comparison of field test seepage in the three wells

The convergence of curves in the transition phase confirms that the Darcy-based 2D numerical approximation effectively represents average seepage behavior. A coefficient of determination of ≥ 0.85 indicates good agreement between simulation results and field data. The model consistently represents the downward trend in seepage discharge over time. The calibrated GeoStudio SEEP/W simulation can represent medium- to long-term seepage behavior. The integration of field tests and simulations provides a more comprehensive understanding than either method alone. The differences emphasize the importance of a hybrid approach in infiltration and well research. The 2D Geostudio SEEP/W simulation is visualized in Figure 8.

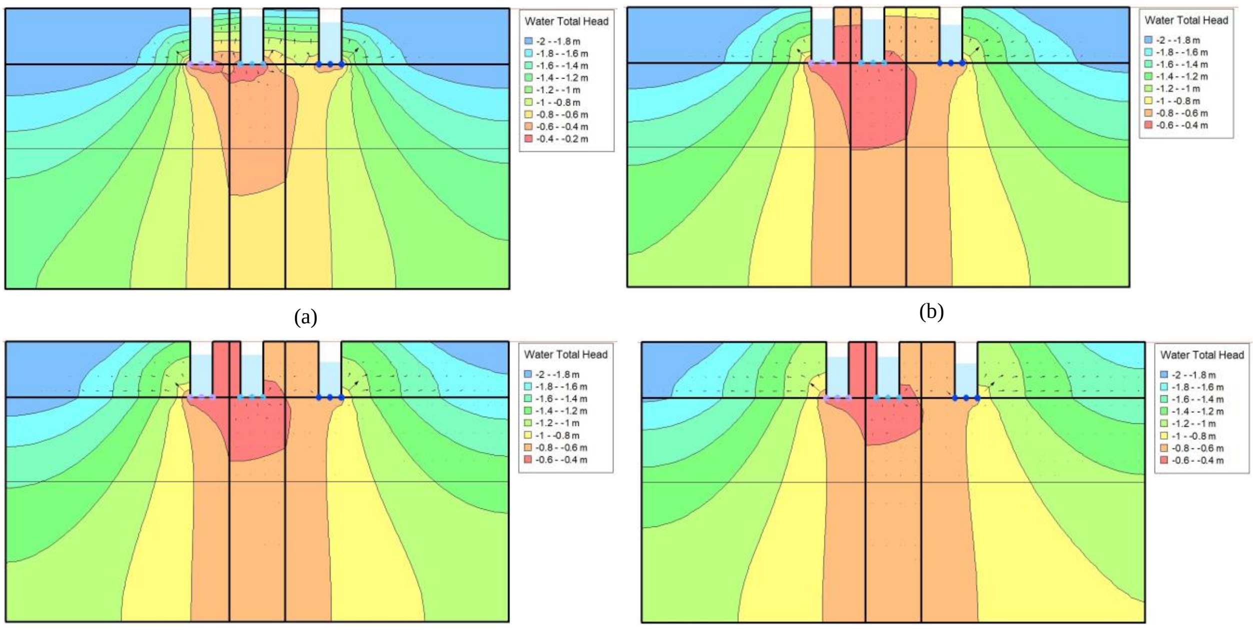

Figure 8. Simulation based on GeoStudio SEEP/W (a) stable phase with seepage time of 30 minutes (b) transition phase with seepage time of 90 minutes (c) advanced transition phase with seepage time of 160 minutes (d) stable phase with seepage time of 360 minutes.

Figure 8 shows GeoStudio SEEP/W simulation results of water seepage patterns. The red zone shows high hydraulic pressure around wells, suggesting limited seepage and unsaturated soil conditions [33]. In Figures 8c and 8d, the pressure zone begins to rise, with yellow and green colors indicating water seeping into deeper layers. This condition suggests that soil is nearing saturation, leading to declining infiltration rates as saturated pressure builds beneath the soil layer. Therefore, the saturated zone expands, and water spreads further downward. In this intermediate phase, the interactions between wells are identified, emphasizing the importance of spacing in a clustered system. Wells placed extremely close together create overlapping pressure zones that interfere with and reduce seepage efficiency. The results in Figure 8 show the stable phase reached after four hours, when hydraulic equilibrium is achieved. Green and blue colors show evenly distributed water flow, while infiltration rate declines to a low level, and pressure around wells converges [34]. Evaluation of the hydraulic response of a group of infiltration wells to equivalent infiltration.

Equivalent wells are designed to maintain the system's total infiltration capacity. The seepage area is expanded based on field flow-depth conditions. Equivalent wells with a diameter of 2.4 m and a depth of 2 m represent three individual wells without deepening the structure. The initial boundary conditions are set based on field measurement results. The recharge conditions follow the parallel filling scenario. This is consistent with the grouped well configuration. The equivalent well-test results graph is shown in Figure 9.

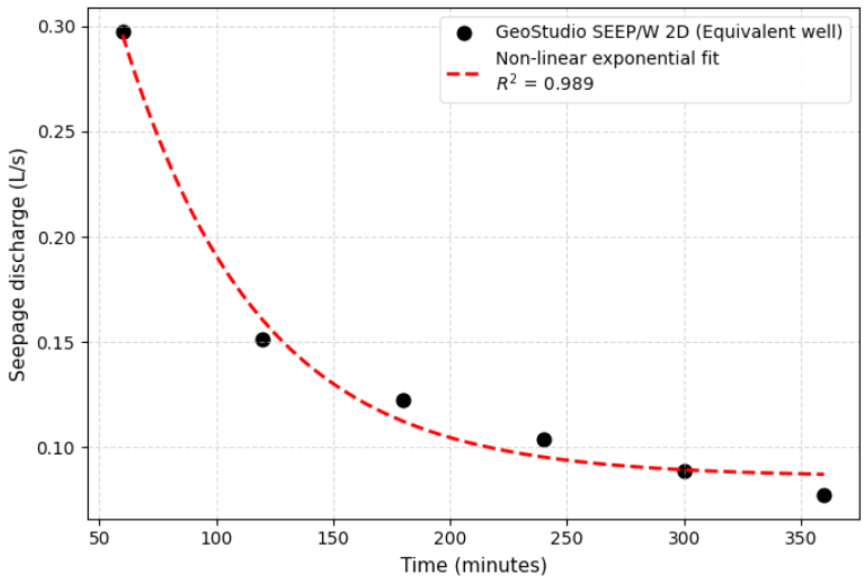

Figure 9. Equivalent infiltration well seepage discharge

Figure 9 shows the infiltration time (minutes) and seepage discharge (liters/second) in the equivalent infiltration well. The discharge decreases progressively and almost linearly over time. The initial value is 0.29 liter/second and approaches 0.07 liter/second at 360 minutes. The initial phase of seepage discharge is relatively high due to the large hydraulic gradient. This condition reflects the intensive infiltration phase. The soil is still predominantly unsaturated, so it can accept large amounts of water. Over time, a saturated zone develops around the well. The seepage discharge decreased gradually. Seepage discharge decreases non-linearly over time. The exponential model can accurately represent seepage. A well's ability to absorb water decreases as the soil becomes saturated. The R^2 value was 0.98, meaning that 98% of the seepage discharge was explained by changes in infiltration time. A coefficient of determination of ≥ 0.85 indicates good agreement between simulation results. The response system was stable and controlled in the equivalent well configuration. The equivalent well approach effectively smoothed out interference between wells. Equivalent infiltration wells can be effectively represented by a 2D model. The equivalent approach is effective for system scale analysis and preliminary design evaluation. Compared to grouped well graphs, equivalent well responses represent the system's average behavior. Transition phase towards stable conditions. This approach captures total capacity without modeling each well individually.

GeoStudio SEEP/W simulations can consistently present the evolution of saturated zones and the distribution of pore water pressure. Other times were analyzed but not displayed to maintain visual clarity. These results confirm that the calibrated simulation model accurately represents seepage behavior. The decline phase is stable, with the first scenario showing sharp seepage patterns in both tests and simulation. The capacity of a single well is constrained by soil saturation [35] and uneven water distribution. The second scenario performs better, achieving higher capacity and faster drawdown, as indicated by a 20% infiltration rate. In this study, hydraulic loads are balanced, and well C provides the highest initial capacity, while others support residual flow. The parallel configuration enhances efficiency by accelerating water level decline.

Soil parameters are represented by a single effective value for each well. Field test results on alluvial soil with relatively high conductivity. An approach is used to present the average hydraulic response around the well [36]. The approach is also used to assess interactions between wells. Hydraulic connections between wells are primarily controlled by horizontal conductivity and hydraulic gradient [37]. Determination of seepage discharge distribution between wells [38]. Spatial and vertical soil variations are not explicitly modeled. Soil heterogeneity can affect flow paths and seepage discharge rates. Simulation results present the average behavior of the system. The results of this study are mainly applicable to areas with high-conductivity subsoil. Generalization to cities with clay soil or shallow water levels requires parameter adjustment. Selection of two scenarios: full filling of one well and simultaneous filling of several wells as extreme boundary conditions [39, 40]. Scenario capturing maximum response. The use of a single soil parameter value is an approach with representative values. This behavior is related to the limitations of the early seepage phase.

The difference between field test results and simulations during the early seepage phase is influenced by the model's simplification of soil flow physics [41]. Unsaturated soil flow parameters were not explicitly included due to limitations in the retention curve data. Complex field conditions and initial saturation dynamics made it difficult to represent seepage response without adequate unsaturated data [42]. The SEEP/W model used has implemented transient flow analysis with time-varying boundary conditions. Seepage dynamics during the transition phase towards stable conditions are represented realistically [43]. The simulation results show good compliance. The main focus is on medium to long-term capacity and performance planning for infiltration wells [42]. The research approach is a rational methodology focused on predicting system performance. The approach understands the main mechanisms of seepage and interactions between wells [44]. While maintaining the limitations of the model and the data. Partial filling and non-constant inflow are recommended as further developments. Long-term operational simulations and adaptive evaluations of more complex rainfall patterns. This modeling uses the two-dimensional (2D) GeoStudio SEEP/W model. This analysis does not fully represent the three-dimensional (3D) flow process.

2D modeling of hydraulic conditions is assumed to be uniform perpendicular to the cross-section [40]. The field conditions of interaction mean that overlapping zones cannot be resolved explicitly [39]. The configuration of grouped wells in 3D alters the effective hydraulic gradient around them [45]. This mechanism has been well documented in multi-well seepage studies and reservoir-scale studies. To mitigate these limitations, the study adopted an asymmetrical 2D cross-section that approximated the most representative slice of the 3D system. Grouped infiltration wells used the equivalent well approach [46]. The combined hydraulic concept of several wells is represented by equivalent parameters [18]. The results are interpreted as a conservative representation of infiltration performance at the system scale [45, 47]. 3D transient modeling is recommended for future studies. Studies that explicitly capture well-to-well interference in complex urban conditions.

The infiltration wells system is designed to optimally infiltrate surface water within a defined time period [48]. In this study, simulation results show that wells placed extremely close together accelerate the formation of the saturated zone, leading to a 30% reduction in infiltration rate. For soil conditions, the ideal spacing between wells is 1.5-2.5 m. However, well performance was evaluated under various scenarios, with the initial seepage phase requiring calibration due to differences in field saturation conditions [33]. These results carry direct implications for urban drainage planning [49], as the calibrated model can now be applied to predict infiltration well performance without previous construction [50]. A multi-scenario, field data-based calibration procedure [28] improves predictive accuracy under varying rainfall conditions [51]. Based on the results, the full-filling scenario shows maximum capacity, while filling all three wells indicates grouping effects, inter-well interactions, and saturation dynamics [52]. In this study, integrating field data and simulation provides an overview of seepage flow, serving as a basis for planning an adaptive urban drainage system. The method provides CCG-term infiltration. Furthermore, the procedures can be adapted as technical guidelines for urban planning of infiltration wells.

4. Conclusion

In conclusion, this study shows that integrating field testing and simulation with GeoStudio SEEP/W is an effective approach for evaluating the performance of infiltration wells in urban areas. Field testing results were obtained for two scenarios: filling one well and filling three wells simultaneously. Seepage rates are strongly influenced by the soil's initial saturation conditions, the configuration of the wells, and local hydraulic conditions. In the initial seepage phase, the measured flow rate in the field was consistently higher than the simulation results. The influence of soil conditions was not fully represented in the numerical model. As the saturated zone developed and transition conditions towards stability were achieved, the SEEP/W simulation results showed a trend of seepage discharge reduction and hydraulic equilibrium. These findings confirm that the 2D SEEP/W model can evaluate infiltration well performance over the medium- to long-term. Grouped infiltration well configurations can increase total infiltration capacity by around 30% compared to single wells. The distance between wells needs to be optimally adjusted to prevent overlapping saturated zones and decreased seepage efficiency.

The infiltration well design in this study contributes both methodologically and practically. The improvement in the reliability of GeoStudio SEEP/W for predicting seepage is based on an asymmetrical cross-section. By incorporating the concept of equivalent wells, this approach can describe the hydraulic response. The average grouped well system is considered adequate for well design with empirically determined optimal spacing. Three-dimensional flow is not explicitly modeled. The simulation results represent a conservative scale of the system. This limitation requires parameter adjustments for areas with low permeability. Further research is recommended to develop three-dimensional modeling that integrates saturated-to-unsaturated flow. The findings of this study indicate that a new hybrid approach combining field data and simulation provides a reliable and efficient technical basis for infiltration well planning. This approach to efficient drainage design critically advances stormwater management infrastructure strategies.

5. Declarations

5.1. Author Contributions

Conceptualization, O.K. and R.R.H.; methodology, B.S.; software, B.S.; validation, O.K.; formal analysis, O.K.; writing—original draft preparation, O.K., R.R.H., B.S., and S.; writing—review and editing, O.K., R.R.H., B.S., and S.; visualization, B.S. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding

This study was conducted under the Postgraduate Doctoral Research Grant of Sebelas Maret University, Agreement No. 460/UN27.22/PT.01.03/2026 in the second year of 2026.

5.4. Acknowledgments

I would also like to thank my supervisor, colleagues, and family members who have accompanied me throughout this journey their kindness, encouragement, and belief in my abilities remain an of strength. This study was conducted under the Postgraduate Doctoral Research Grant of Sebelas Maret University.

5.5. Conflicts of Interest

The authors declare no conflict of interest.

6. References

[1] Trejo-Alonso, J., Quevedo, A., Fuentes, C., & Chávez, C. (2020). Evaluation and development of pedotransfer functions for predicting saturated hydraulic conductivity for mexican soils. Agronomy, 10(10). doi:10.3390/agronomy10101516.

[2] Fuentes, S., Fuentes, C., Saucedo, H., & Chávez, C. (2022). Border Irrigation Modeling with the Barré de Saint-Venant and Green and Ampt Equations. Mathematics, 10(7), 12–15. doi:10.3390/math10071039.

[3] Dharmarathne, G., Waduge, A. O., Bogahawaththa, M., Rathnayake, U., & Meddage, D. P. P. (2024). Adapting cities to the surge: A comprehensive review of climate-induced urban flooding. Results in Engineering, 22(April), 102123. doi:10.1016/j.rineng.2024.102123.

[4] Bibi, T. S., Reddythta, D., & Kebebew, A. S. (2023). Assessment of the drainage systems performance in response to future scenarios and flood mitigation measures using stormwater management model. City and Environment Interactions, 19(March), 100111. doi:10.1016/j.cacint.2023.100111.

[5] Hassan, B. T., Yassine, M., & Amin, D. (2022). Comparison of Urbanization, Climate Change, and Drainage Design Impacts on Urban Flashfloods in an Arid Region: Case Study, New Cairo, Egypt. Water (Switzerland), 14(15), 2430. doi:10.3390/w14152430.

[6] Hassan, W. H., Nile, B. K., & Kadhim, Z. K. (2024). Effect of climate change on the flooding of storm water networks under extreme rainfall events using SWMM simulations: a case study. Modeling Earth Systems and Environment, 10(3), 4129–4161. doi:10.1007/s40808-024-01998-1.

[7] dos Santos, M. F. N., Barbassa, A. P., & Vasconcelos, A. F. (2021). Low impact development strategies for a low-income settlement: Balancing flood protection and life cycle costs in Brazil. Sustainable Cities and Society, 65(14), 102650. doi:10.1016/j.scs.2020.102650.

[8] Fuentes, C., Chávez, C., Quevedo, A., Trejo-Alonso, J., & Fuentes, S. (2020). Modeling of artificial groundwater recharge by wells: A model stratified porous medium. Mathematics, 8(10), 1–11. doi:10.3390/math8101764.

[9] Barbosa, S. A., Wang, Y., & Goodall, J. L. (2025). Exploring infiltration effects on coastal urban flooding: Insights from nuisance to extreme events using 2D/1D hydrodynamic modeling and crowdsourced flood reports. Science of the Total Environment, 968(October 2024), 178908. doi:10.1016/j.scitotenv.2025.178908.

[10] Zhang, X., Kang, A., Lei, X., & Wang, H. (2024). Urban drainage efficiency evaluation and flood simulation using integrated SWMM and terrain structural analysis. Science of the Total Environment, 957(November), 177442. doi:10.1016/j.scitotenv.2024.177442.

[11] Luo, P., Luo, M., Li, F., Qi, X., Huo, A., Wang, Z., He, B., Takara, K., Nover, D., & Wang, Y. (2022). Urban flood numerical simulation: Research, methods and future perspectives. Environmental Modelling and Software, 156(July), 105478. doi:10.1016/j.envsoft.2022.105478.

[12] Lentini, A., Meddi, E., Galve, J. P., Papiccio, C., & Vigna, F. La. (2022). Preliminary identification of areas suitable for Sustainable Drainage Systems and Managed Aquifer Recharge to mitigate stormwater flooding phenomena in Rome (Italy). Acque Sotterranee - Italian Journal of Groundwater, 11(4), 43–53. doi:10.7343/as-2022-590.

[13] Setiawan, B., Chrismaningwang, G., Purwana, Y. M., Surjandari, N. S., Dananjaya, R. H., & Fitri, S. N. (2024). Comparative Analysis of Infiltration Wells Efficacy Using Geostudio Simulation and Full-Scale Experimental Test. International Journal of GEOMATE, 27(122), 63–70. doi:10.21660/2024.122.4612.

[14] Liu, J., Cao, Z., Li, X., Wang, W., Hou, J., Li, D., & Ma, Y. (2022). Modelling urban flooding integrated with flow and sediment transport in drainage networks. Science of the Total Environment, 850(August), 158027. doi:10.1016/j.scitotenv.2022.158027.

[15] Martínez, C., Vojinovic, Z., & Sanchez, A. (2021). Multi-objective model-based assessment of green-grey infrastructures for urban flood mitigation. Hydrology, 8(3), 110. doi:10.3390/hydrology8030110.

[16] Xu, H., Wang, Y., Fu, X., Wang, D., & Luan, Q. (2023). Urban Flood Modeling and Risk Assessment with Limited Observation Data: The Beijing Future Science City of China. International Journal of Environmental Research and Public Health, 20(5), 4640. doi:10.3390/ijerph20054640.

[17] Montalvo, C., Reyes-Silva, J. D., Sañudo, E., Cea, L., & Puertas, J. (2024). Urban pluvial flood modelling in the absence of sewer drainage network data: A physics-based approach. Journal of Hydrology, 634. doi:10.1016/j.jhydrol.2024.131043.

[18] Zhao, L., Tian, W., Liu, K., Yang, B., Guo, D., & Lian, B. (2024). An empirical relationship of permeability coefficient for soil with wide range in particle size. Journal of Soils and Sediments, 24(8), 2926–2937. doi:10.1007/s11368-024-03743-8.

[19] Salata, S., Ronchi, S., Giaimo, C., Arcidiacono, A., & Pantaloni, G. G. (2021). Performance-based planning to reduce flooding vulnerability insights from the case of Turin (North-west Italy). Sustainability (Switzerland), 13(10), 5697. doi:10.3390/su13105697.

[20] Atayi, J., Zhou, X., Iliadis, C., Glenis, V., Kang, D., Sheng, Z., Quansah, J., & Hunter, J. G. (2025). Evaluating the Effectiveness of Soil Profile Rehabilitation for Pluvial Flood Mitigation Through Two-Dimensional Hydrodynamic Modeling. Hydrology, 12(3), 44. doi:10.3390/hydrology12030044.

[21] 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. doi:10.1029/2024WR037524.

[22] McMillan, H. K., Westerberg, I. K., & Krueger, T. (2018). Hydrological data uncertainty and its implications. Wiley Interdisciplinary Reviews: Water, 5(6), 1–14. doi:10.1002/WAT2.1319.

[23] Abdel-Kawy, A. O., Aboulatta, N. M., & El-Molla, D. A. (2021). Effects of core characteristics on seepage through earth dams. Water Practice and Technology, 16(4), 1248–1264. doi:10.2166/wpt.2021.053.

[24] Jassama, M. G., & Abdulrazzaqb, S. S. (2020). Analysis of seepage through Al-Wand Dam by using SEEP/W ModelAnalysis of seepage through Al-Wand Dam by using SEEP/W Model. Anbar Journal of Engineering Sciences, 11(1), 33–37. doi:10.37649/aengs.2020.171284.

[25] Ceccato, F., Yerro, A., Girardi, V., & Simonini, P. (2021). Two-phase dynamic MPM formulation for unsaturated soil. Computers and Geotechnics, 129(November 2020), 103876. doi:10.1016/j.compgeo.2020.103876.

[26] Boico, V. F., Therrien, R., Delottier, H., Young, N. L., & Højberg, A. L. (2022). Comparing alternative conceptual models for tile drains and soil heterogeneity for the simulation of tile drainage in agricultural catchments. Journal of Hydrology, 612, 128120. doi:10.1016/j.jhydrol.2022.128120.

[27] Shi, C., Wang, L., Zhang, C., Zhang, Y., & Zhang, W. (2024). A pipe domain seepage model based on outsourcing Voronoi network with particle flow code. Computational Particle Mechanics, 11(1), 249–261. doi:10.1007/s40571-023-00620-y.

[28] Szabó, Z., Szijártó, M., Tóth, Á., & Mádl-Szőnyi, J. (2023). The Significance of Groundwater Table Inclination for Nature-Based Replenishment of Groundwater-Dependent Ecosystems by Managed Aquifer Recharge. Water (Switzerland), 15(6), 1077. doi:10.3390/w15061077.

[29] Vishwakarma, D. K., Yadav, D., Kumar, R., Kumar, R., Bhat, S. A., Mirzania, E., & Kuriqi, A. (2025). Assessing the performance of various infiltration models to improve water management practices. Paddy and Water Environment, 23(1), 77–93. doi:10.1007/s10333-024-01000-9.

[30] Mesele, H., Grum, B., Aregay, G., & Berhe, G. T. (2024). Evaluation and comparison of infiltration models for estimating infiltration capacity of different textures of irrigated soils. Environmental Systems Research, 13(1), 26. doi:10.1186/s40068-024-00356-5.

[31] Wang, X., Huang, Z., Qin, H., & Dai, F. (2025). Sensitivity analysis of VG model parameters for infiltration in undisturbed loess under ponding conditions using the HYDRUS-1D model. Scientific Reports, 15(1), 1–15. doi:10.1038/s41598-025-11058-y.

[32] Shen, Y., Liu, D., Yin, J., Xiong, L., & Liu, P. (2020). Integrating hybrid runoff generation mechanism into variable infiltration capacity model to facilitate hydrological simulations. Stochastic Environmental Research and Risk Assessment, 34(12), 2139–2157. doi:10.1007/s00477-020-01878-x.

[33] Baharudin, N. A., Kassim, A., Ahmad, K., & Sirat, Q. A. (2023). The Application of Porous Material in the Capillary Barrier System for Residual Soil Slope Stabilization. Trends in Sciences, 20(3), 1-16. doi:10.48048/tis.2023.4465.

[34] Khurelbaatar, G., Van Afferden, M., Ueberham, M., Stefan, M., Geyler, S., & Müller, R. A. (2021). Management of urban stormwater at block-level (MUST-B): A new approach for potential analysis of decentralized stormwater management systems. Water (Switzerland), 13(3), 378. doi:10.3390/w13030378.

[35] Parnas, F. E. Å., Abdalla, E. M. H., & Muthanna, T. M. (2021). Evaluating three commonly used infiltration methods for permeable surfaces in urban areas using the SWMM and STORM. Hydrology Research, 52(1), 160–175. doi:10.2166/NH.2021.048.

[36] Wang, P., Su, X., Zhou, Z., Wang, N., Liu, J., & Zhu, B. (2023). Differential effects of soil texture and root traits on the spatial variability of soil infiltrability under natural revegetation in the Loess Plateau of China. Catena, 220(PA), 106693. doi:10.1016/j.catena.2022.106693.

[37] Vargas Ceron, M., Cecílio, D. L., Linn, R. V., & Maghous, S. (2025). Stability Analysis of Slope Subjected to Seepage Forces Considering Spatial Variability of Soil Properties. International Journal for Numerical and Analytical Methods in Geomechanics, 49(11), 2459–2491. doi:10.1002/nag.3993.

[38] Chen, X., Yu, Z., Yi, P., Hwang, H. T., Sudicky, E. A., Tang, T., & Aldahan, A. (2024). Effects of soil heterogeneity and preferential flow on the water flow and isotope transport in an experimental hillslope. Science of the Total Environment, 917(February), 170548. doi:10.1016/j.scitotenv.2024.170548.

[39] Al-Janabi, A. M. S., Dibs, H., Sammen, S. S., Yusuf, B., Ikram, R. M. A., Alzuhairy, S. H., & Kisi, O. (2025). Comparison Analysis of Seepage Through Homogenous Embankment Dams Using Physical, Mathematical and Numerical Models. Arabian Journal for Science and Engineering, 50(11), 8143–8152. doi:10.1007/s13369-024-09224-x.

[40] Al-Janabi, A. M. S., Ghazali, A. H., Ghazaw, Y. M., Afan, H. A., Al-Ansari, N., & Yaseen, Z. M. (2020). Experimental and numerical analysis for earth-fill dam seepage. Sustainability (Switzerland), 12(6), 1–14. doi:10.3390/su12062490.

[41] Li, Y., Sun, Q., Fu, Y., & Wei, J. (2025). Solving the Richards infiltration equation by coupling physics-informed neural networks with Hydrus-1D. Scientific Reports, 15(1), 1–14. doi:10.1038/s41598-025-02978-w.

[42] Banerji, A. K., Kumar, A., Banerjee, S., Nayek, K., Ghosh, S., & Kumar, R. (2025). Utilization of waste BOF slag in porous concrete pavement to enhance sustainability. Technologies and Innovations for Sustainable Development, 60–73. doi:10.1201/9781003487012-8.

[43] Peng, Y., Fei, L., Shen, F., Zheng, R., Wang, Q., & Fan, Q. (2025). A green-Ampt model considering unsaturated zone and pore air pressure. Geoderma, 455(February), 117198. doi:10.1016/j.geoderma.2025.117198.

[44] Paronuzzi, P., Fedrigo, D., & Bolla, A. (2024). Rainfall Infiltration through Stratified Colluvial Deposits: Analytical Approach vs. Numerical Modelling. Geosciences (Switzerland), 14(2), 53. doi:10.3390/geosciences14020053.

[45] Liao, H., Ji, Q., Jiang, Z., & Yuan, B. (2025). Study on Seepage Characteristics and Production Capacity Characteristics of Complex Structural Wells in Non-Homogeneous Gas Reservoirs Based on Hydroelectric Simulation. Energies, 18(11), 1–18. doi:10.3390/en18112794.

[46] Zhou, Y., She, D., Wang, Y., Xia, J., & Zhang, Y. (2022). Evaluating the Impact of Low Impact Development Practices on the Urban Flooding over a Humid Region of China. Journal of the American Water Resources Association, 58(6), 1264–1278. doi:10.1111/1752-1688.13032.

[47] Feng, Y., Liu, Y., Chen, J., & Mao, X. (2022). Simulation of the Pressure-Sensitive Seepage Fracture Network in Oil Reservoirs with Multi-Group Fractures. Fluid Dynamics and Materials Processing 18(2), 395–415. doi:10.32604/FDMP.2022.018141.

[48] Pristianto, H., Suhardjono, Bisri, M., & Suhartanto, E. (2024). Improving Infiltration Modeling for Papua'S Small Watershed By Using Rstudio Software Analysis. International Journal of GEOMATE, 26(115), 44–52. doi:10.21660/2024.115.4213.

[49] Bernello, G., Mondino, E., & Bortolini, L. (2022). People's Perception of Nature-Based Solutions for Flood Mitigation: The Case of Veneto Region (Italy). Sustainability (Switzerland), 14(8), 1–13. doi:10.3390/su14084621.

[50] Guo, K., Guan, M., Yan, H., & Xia, X. (2023). A spatially distributed hydrodynamic model framework for urban flood hydrological and hydraulic processes involving drainage flow quantification. Journal of Hydrology, 625. doi:10.1016/j.jhydrol.2023.130135.

[51] Karimi, P., Safaval, P. A., Behzadi, S., Azizi, Z., Zarkash, M. M. K., & Kalashami, H. K. (2022). Flood Risk Zoning Using Geographical Information System Case Study: Khorramabad Flood in April 2019. Acta Hydrotechnica, 35(63), 89–100. doi:10.15292/acta.hydro.2022.07.

[52] Wen, Y., Hu, C., Zhang, G., & Jian, S. (2020). Response of the parameters of excess infiltration and excess storage model to land use cover change. Journal of Hydrology and Hydromechanics, 68(2), 99–110. doi:10.2478/johh-2020-0006.