

# COMPARATIVE ANALYSIS OF INFILTRATION WELLS EFFICACY USING GEOSTUDIO SIMULATION AND FULL-SCALE EXPERIMENTAL TEST

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**ABSTRACT:** This study evaluates the performance of infiltration wells using full-scale field experiments and 3D numerical modeling with GeoStudio SEEP/W, focusing on sandy soils. Infiltration wells are essential for improving groundwater recharge, lowering urban runoff, and controlling flood risks. However, differences in soil qualities and external environmental circumstances are the leading causes of the frequent disparities between modeled predictions and field observations. The process consists of two primary steps: numerical modeling to duplicate these conditions and compare results and field testing to measure the amount of water absorbed by the soil during an hour. Detailed records of the attributes of the soil, including water content and grain-size distribution, as well as hydraulic conductivity, were made. The field results indicate a logarithmic increase in water infiltration, reflecting rapid initial infiltration that gradually plateaued, demonstrating the changes in soil saturation. However, the numerical model predicted a more consistent infiltration rate across similar intervals, highlighting a significant field-model discrepancy. Comparative analysis revealed that soil heterogeneity and initial moisture content significantly influence the infiltration rates, which were not accounted for entirely in the numerical model. External factors such as atmospheric conditions and unanticipated groundwater movement complicate accurate modeling. Enhancement of model parameters, incorporating comprehensive soil data, and integration of laboratory experiments are suggested to bridge the gaps between the numerical and field measurements. Furthermore, this research contributes to the sustainable management of groundwater resources by optimizing the design and implementation of infiltration wells, providing valuable insights for both practical implications and academic endeavors.

*Keywords: Infiltration well, Sandy soil, GeoStudio SEEP/W, 3D numerical modeling, Full-scale test model*

## 1. INTRODUCTION

Surface water is crucial in reducing water scarcity by improving water quality, enhancing water storage, supporting agricultural productivity, promoting water reuse and desalination, and reducing water stress [1–3]. One hydrological cycle that aids in the preservation of groundwater (shallow groundwater) is rain. Most water flows straight to rivers and the sea during the rainy season, which in certain areas causes flooding and inundation where poor drainage management is linked to these issues [4–5]. On the other hand, climate change significantly impacts water deficiency [6–7]. Due to the increment of water demand and over-exploitation of groundwater along with the city and industrial development process, problems such as groundwater level decrease, the formation of large-scale depression cones, soil settlement, intrusion of seawater, and growing challenge in afterward use of groundwater [8–10].

One of the mitigation solutions is infiltration wells. These wells have been recognized as one of the effective methods for improving groundwater and flood mitigation [11–16]. Infiltration wells are an effective method because they do not take up a lot of land, and the construction process does not take much

time [17]. The greater the capacity of water that can be absorbed into the ground by infiltration wells, the greater the water reserves in the ground, and the excess surface water that causes flooding can be minimized [18–19]. Infiltration wells are purposefully designed structures with various benefits for society, such as helping the surface water percolate into the subsurface, recharging the aquifers, and reducing urban discharge [20–22]. Despite their potential, a comprehensive study is needed to understand their effectiveness and implications in different geotechnical and hydrological contexts.

Designing effective infiltration wells requires thoroughly examining some parameters [23–24]. One of the most vital parameters is soil permeability, which is essential in the hydrological performance of infiltration wells [25]. Accurate determination of soil permeability through laboratory and field measurements is essential to estimate the water behavior in the soil [26]. The design of infiltration wells depends on the soil permeability because it enhances stormwater management by reducing peak runoff flow and increasing infiltration [27–28]. Sustainable management of groundwater resources requires accurate groundwater recharge estimation, which is essential for measuring good outcomes for

aquifers in hydrological balance [29–31].

Numerical methods, such as those implemented in the GeoStudio SEEP/W program, are effective tools to determine soil seepage under various studies, such as precipitation cases and determine the flood runoff reduction using infiltration wells [12], [18], [32–34]. However, there remains a need to validate the numerical study result with full-scale field data.

Small-scale laboratory modeling on granular soil by analyzing with this software was conducted by [35]. The research results produced infiltration velocity values in small-scale laboratory observations of 0.0077 cm/sec, 0.1324 cm/sec using Darcy's law, and 0.1688 cm/second using GeoStudio 2D software.

Modelling with variations in diameter from 0.5 m to 1.4 m on silty clay soil, the infiltration discharge at an infiltration well diameter of 1 m, the modelling results were  $2.6753 \times 10^{-11}$  m<sup>3</sup>/sec and  $2.6754 \times 10^{-11}$  m<sup>3</sup>/sec analyzed using the Darcy's law conducted by [36].

The primary objective of this study is to assess the accuracy of infiltration discharge predictions. The infiltration data was obtained from full-scale model infiltration wells installed in the field, followed by numerical analysis with the assistance of GeoStudio SEEP/W 3D software. Furthermore, a comparative study between full-scale and numerical data was conducted. By validating the infiltration discharge analysis through field-scale tests and 3D modeling, this research aims to provide valuable insights, draw meaningful conclusions, and lay the groundwork for future investigations in the geotechnical domain.

## 2. RESEARCH SIGNIFICANCE

This research contributes significantly to the geotechnical and hydrological engineering field by offering practical solutions for managing groundwater resources by implementing infiltration wells in sandy soils. The significance of this study is to enhance the knowledge about infiltration dynamics by simulating infiltration wells using GeoStudio SEEP/W 3D. In the full-scale methods, actual soil and water interaction can be observed in a controlled setting, yielding more precise and scalable results. The findings of this study are expected to improve infiltration well design, which leads to enhanced groundwater resources, reduce urban runoff, and minimize the possibility of flooding.

## 3. METHODOLOGY

The study of infiltration wells consists of two main stages. The first stage involves full-scale field testing to determine the volume of water that the soil can absorb within 60 minutes. The full-scale field test was carried out by adapting ASTM D-3385 standards, which stated that the recording time is 60 minutes after the constant rate is reached [37]. The second

stage is validating the analysis using GeoStudio SEEP/W to model water flow and evaluate the consistency of field results. These two stages provide a comprehensive overview of the effectiveness of infiltration wells in groundwater management.

The soil parameters used were derived from the soil employed in the full-scale test. Soil testing in the laboratory involved analyzing soil samples extracted at a depth of 2.00 m, and the summary of the soil parameter data is presented in Table 1. The hydraulic conductivity value was obtained from field testing using the Sosrodarsono method [38].

Table 1. Soil parameters

Index Properties	Units	Well A	Well B	Well C
Water content	%	45.13	40.13	52.61
Specific gravity		2.34	2.605	2.505
Void ratio		0.98	0.88	1.24
Liquid limits	%	63.38	47.81	70.97
Plastic limits	%	26.61	21.04	41.88
Plasticity index	%	36.78	26.78	29.09
Hydraulic conductivity	cm/sec	8.82 $\times 10^{-3}$	7.11 $\times 10^{-3}$	1.17 $\times 10^{-2}$
Grain-size				
- Gravel	%	1.83	2.98	0
- Sand	%	50.79	54.44	57
- Silt	%	47.39	42.58	43
- Clay	%	0	0	0

### 3.1 Field Observation with Full-Scale Infiltration Wells

The primary goal of this field observation is to evaluate the effectiveness of infiltration well. This is achieved by quantitatively measuring the infiltration volume from each well in a certain period. These measurements are not only to assess the well's capacity to handle inflow but also serve as a direct metric to observe their performance under various conditions.

Understanding the infiltration capacity of infiltration wells is essential because it relates to their ability to restore the groundwater and mitigate surface water runoff. Both of these reasons are common problems that occur in urban areas. The optimum design can be achieved by understanding the infiltration behavior well under specific conditions.

The infiltration wells were constructed using concrete walls, each with a depth of 2.00 meters and a diameter of 0.80 meters, shown in Figure 1, and the schematic of the full-scale model in Figure 2. Two PVC pipes were strategically installed in each well to facilitate water level measurement and refilling. A bio-floc pond was used as a reservoir to provide a consistent water source for filling the wells. The

filtration system of the infiltration wells consisted of 30-centimeter-thick layers of sand, palm fiber, and gravel. Water levels were monitored using a purpose-built device equipped with a pipe capable of measuring water fluctuation.

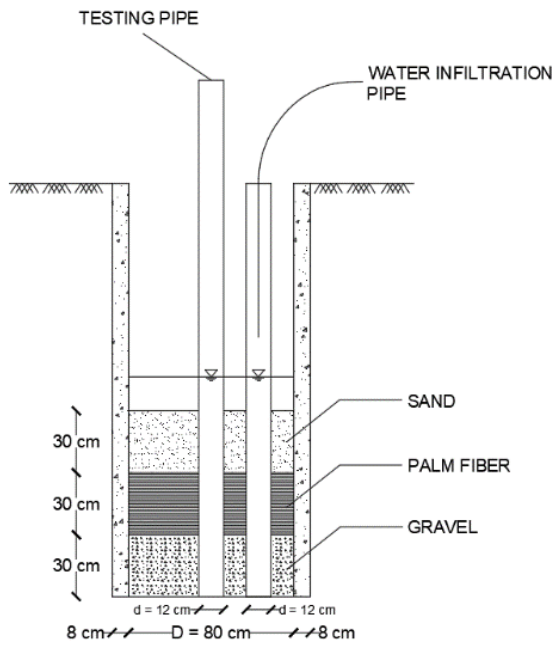


Fig. 1 Configuration of infiltration well

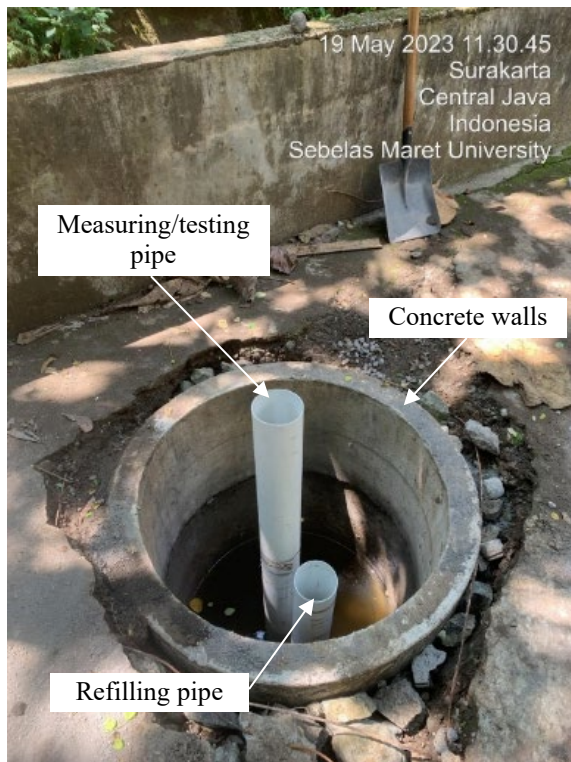


Fig. 2 Schematic of a full-scale infiltration well

The wells were constructed following standard

geotechnical engineering practices, ensuring structural integrity and appropriate placement of filter layers. Once constructed, the wells were initially filled with water to full capacity.

The water level in each well was then monitored using the installed pipe. The decrease in water level was recorded at 60-minute intervals using the monitoring device. This monitoring process was repeated for a sufficient duration to capture significant data on infiltration rates. Regular monitoring intervals ensured accurate and consistent data collection, which is essential for reliable analysis.

To validate the results, field testing was conducted on three infiltration wells, designated wells A, B, and C. Wells B and C served as observation wells to compare and validate results. Figures 1 and 2 illustrate these wells' layout and configuration. This replication allowed for a comprehensive evaluation and comparison of the wells' performance.

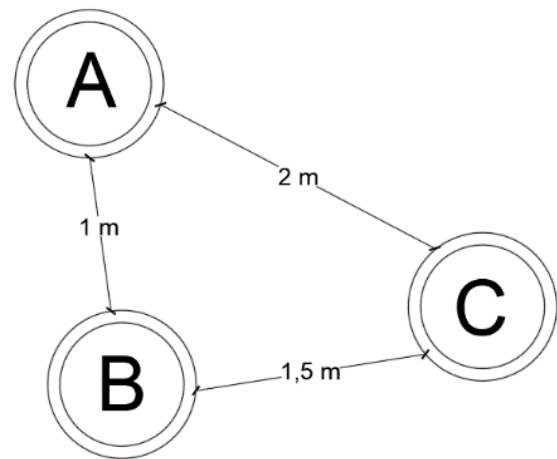


Fig. 3 Layout of full-scale field test infiltration well

### 3.2 Infiltration Discharges Analysis Using GeoStudio SEEP/W

The primary objective of this analysis is to evaluate the infiltration discharge of full-scale infiltration wells using GeoStudio SEEP/W three-dimensional modeling software and compare the results with empirical field data.

The geometry of the infiltration wells was modeled in GeoStudio SEEP/W to replicate the full-scale test configuration. The distances modeled were 1.00, 1.50, and 2.00 meters, as depicted in Figure 3. These distances were selected to reflect varying conditions observed in the field. The numerical modeling figure is shown in Figure 4.

The data were compared with field observations to check the model's accuracy. This comparison showed how the model's results matched the actual condition, confirming the model's reliability. The model's alignment with field data suggests it is suitable for similar applications.

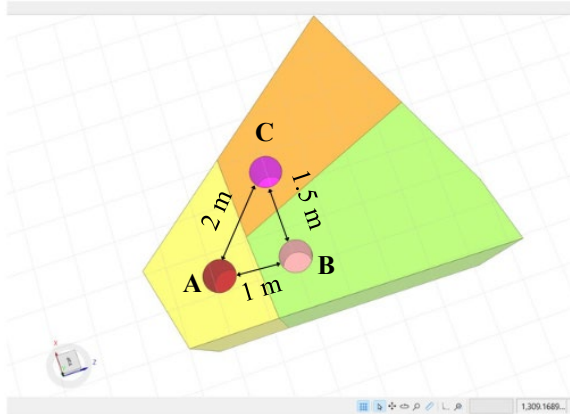


Fig. 4 Numerical modeling

The following soil parameters were input into the GeoStudio SEEP/W model to match the soil characteristics in each well, such as saturated soil water content, grain-size data ( $D_{10}$ ,  $D_{60}$ ), liquid limit, and hydraulic conductivity. These parameters were carefully selected to ensure the model accurately reflects the soil conditions of the test site.

The boundary condition type in the SEEP/W model used water total head, which is applied to the surface inside the well and marked with different colors, as shown in Figure 4. Boundary conditions were defined based on field observation data, specifically the water level within the wells during the tests. The water total head boundary condition is defined as a function. The function of these boundary conditions describes the relationship between time and water level decline.

The SEEP/W analysis generated infiltration discharge values for each mesh point in the model. The results were summarized and compared with the full-scale field infiltration discharges that were measured directly from the field test. The comparison aimed to validate the SEEP/W model's accuracy and provide insights into the infiltration well performance.

#### 4. RESULTS AND DISCUSSION

The calculation of infiltration volume in infiltration well A is derived from both full-scale tests in the field and modeling conducted with GeoStudio SEEP/W 3D software, presented in the following subsections. This study does not take vegetation into account in the numerical analysis. The primary reason for this is that the area surrounding the modeling site lacks vegetation. Consequently, the influence of vegetation on permeability and other factors has been negligible and thus has been disregarded in this research.

Furthermore, this research was conducted during the dry season. By selecting these conditions, we aimed to isolate the specific factors under investigation, minimizing the potential influence of external variables such as rainfall.

#### 4.1 Field Test Results

The field test results, shown in Figure 5, recorded infiltration discharge rates of 96.48  $\text{cm}^3/\text{sec}$ , 93.41  $\text{cm}^3/\text{sec}$ , and 97.46  $\text{cm}^3/\text{sec}$  in the first, second, and third tests, respectively. The consistent results showed that the soil condition was stable during the test. Variations in infiltration rates across the tests are attributed to differences in groundwater levels and other site-specific factors observable at greater depths, such as compaction or organic matter content. These tests were repeated three times to ensure validity and representativeness.

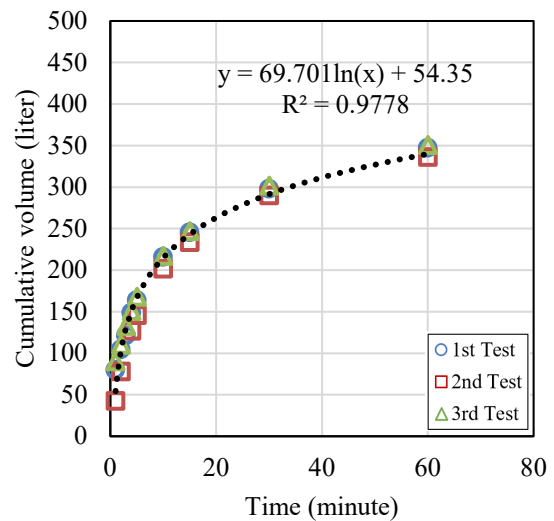


Fig. 5 Cumulative infiltration volume from field test

The black dots in Figure 5 form a logarithmic trend line representing the trend across the three tests. The logarithmic shape of the field test results suggests that the cumulative infiltration volume increases exponentially with time. This result is consistent with the research conducted by Nakashima and Kawai [39]. This behavior can be attributed to changes in soil saturation levels as the infiltration well is initially filled, transitioning from an unsaturated to a saturated state. Initially, water absorption is rapid due to unsaturated soil conditions. The plateau phase of the curves shows where the infiltration rate becomes limited due to the hydraulic conductivity of the saturated soil rather than the initial permeability and porosity of the unsaturated state.

Figure 5 also describes the typical behavior of infiltration where the driving force of gravity and capillary action initially pull water quickly to the soil matrix, but as saturation state is reached, the driving diminishes, and further, the water movement is resisted by hydrostatic and matric suction forces within the soil.

Table 2 summarizes the cumulative infiltration volumes per unit time, yielding values of 347.33 liters, 336.28 liters, and 344.82 liters for the first, second, and third tests. The curves in Figure 4

indicate similar shapes across all three tests, with negligible differences in infiltration volumes. The curves show a significant increase in volume from the first minute until the 60th minute, after which the rate tends to plateau as it approaches the groundwater level and pressure diminishes. The consistent increment of infiltration volume during the time interval up to the 60<sup>th</sup> minutes showed the well's efficiency in managing large volumes of water, which is crucial in practical application in areas prone to heavy rainfall.

Table 2. Cumulative infiltration volume from field test

Time (minute)	Cumulative volume (liters)		
	1 <sup>st</sup> Test	2 <sup>nd</sup> Test	3 <sup>rd</sup> Test
1	79.92	42.73	90.48
2	104.55	77.91	110.58
4	148.79	127.17	150.80
5	163.87	145.77	168.39
10	216.14	201.56	217.65
15	245.80	233.73	247.31
30	298.07	290.03	302.10
60	347.33	336.28	350.85

The error margin at the end of the test is 4.33%, which is quite reasonable for field conditions. These errors are subjected to potential inconsistencies in manual measurements and slight variations in test conditions, such as temperature and humidity.

These results imply that infiltration wells in sandy soils effectively mitigate heavy rainfall that leads to flooding in urban areas and contributes to sustainable water practices.

#### 4.2 3D Numerical Modeling Results

The field test results were numerically modeled using GeoStudio SEEP/W software. The modeling was performed under transient conditions to simulate real-time water infiltration through soil over one hour. The input data for the modeling included observed water level decreases from the field tests. The data were recorded and summarized at 1, 3, 7, 17, 35, and 75-minute intervals. These specific time intervals are chosen as they are expected to capture the rapid initial infiltration and the following steady-state infiltration.

The first, second, and third tests, using *K* values from Sosrodarsono [38] as detailed in Table 3, yielded cumulative volumes of 361.32 liters, 334.25 liters, and 486.84 liters, respectively, with an associated error rate at the end of the test is 45.65%. The possible explanations for the large error number include oversimplification of the complex soil behavior or inadequate representation of soil

heterogeneity.

The trend line in Figure 6 for the GeoStudio SEEP/W modeling results shows a second-degree polynomial shape, which significantly differs from the field test results in Figure 4. The cumulative volume increase remains relatively constant throughout the testing period, without the initial rapid increase and subsequent slowdown observed in the field tests. This discrepancy suggests that the model does not accurately capture the initial high infiltration rates and the eventual reduction as the soil becomes saturated.

Table 3. Cumulative infiltration volume from numerical modeling

Time (minute)	Cumulative volume (liters)		
	1 <sup>st</sup> Test	2 <sup>nd</sup> Test	3 <sup>rd</sup> Test
1	8.62	8.68	10.24
3	24.54	24.04	29.28
7	52.17	50.28	63.31
17	110.23	104.55	138.30
35	198.62	185.57	257.02
75	361.32	334.25	486.84

The discrepancy might be due to several factors, such as model simplification, soil layering, and initial and boundary conditions. It may be necessary to refine the material input, enhance model complexity, calibrate, and validate using a broader data set to improve the fidelity of the numerical model.

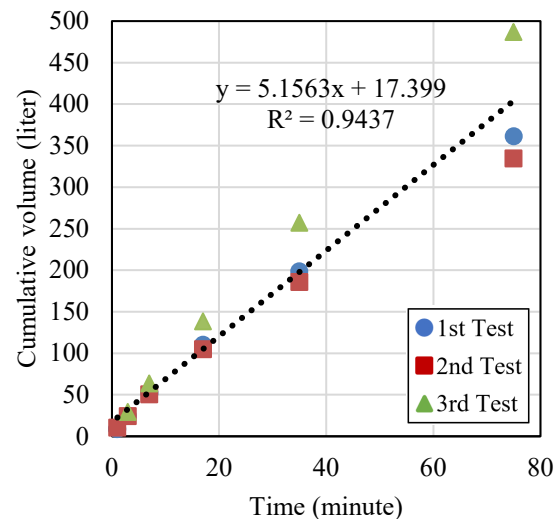


Fig. 6 Cumulative infiltration volume from numerical modeling

#### 4.3 Comparative Analysis

The comparison of the field test results and the numerical modeling outcomes shows significant differences in the infiltration volume and the behavior

of the infiltration process over time. The numerical model displayed a more constant infiltration rate. At the same time, the field test contrasts showed a rapid infiltration in the initial time, followed by a steady-state condition as the soil achieved a saturated condition.

Some reasons could lead to discrepancies between the field test and numerical modeling results. The first is soil heterogeneity, specifically in grain size distributions, organic content, and soil compaction level, which influence soil permeability. Hence the difference in infiltration rates. The numerical model's tendency to oversimplify real-world conditions can affect the accuracy of numerical model results.

Another important factor influencing the infiltration rate is the initial moisture content. The initial moisture content in the field was probably different, affecting soil saturation time. The model's initial moisture content assumption may be more uniform, which prevented it from presenting the actual field's initial rapid infiltration.

On the other hand, external variables such as temperature and atmospheric fluctuations can affect soil permeability and influence water infiltration by changing the soil density and viscosity. Unexpected groundwater from surrounding water bodies or from past land use can influence the moisture of the soil. Dynamic groundwater modeling might be needed to model these conditions.

Despite the potential simplification or idealization of the model, these dynamic external elements were not considered. The input parameters, including the soil water retention properties and hydraulic conductivity, significantly impact the modeling accuracy. The model and the actual field conditions may substantially differ if these parameters are misestimated.

The observed discrepancy between the results from the field and the model emphasizes the necessity of more thorough modeling techniques that cover a wide range of data. Further studies must optimize the input parameters and augment the model's capability to replicate the interaction between the soil and water. Long-term field studies may also yield data to enhance and validate the numerical method, which could result in a more accurate prediction of infiltration performance.

To acquire a deeper understanding of the primary infiltration mechanism, combining field observations with laboratory experiments is crucial. Precise control of variables can be conducted in the laboratory, providing valuable information to be implemented in real-world situations. Prospective research can bridge the knowledge gap between the field observations and modeling by addressing these issues, leading to better groundwater management techniques and more accurate predictions of infiltration wells' performance

## 5. CONCLUSIONS

This study investigates the cumulative volume of water absorbed by infiltration wells in full-scale field experiments, followed by 3D numerical modeling using GeoStudio SEEP/W. The analysis of full-scale field experiments compared to numerical modeling reveals significant differences, particularly in the trendline of cumulative water infiltration volumes absorbed by the infiltration wells.

In the full-scale field experiments, the trendline shows a logarithmic shape, with an initial increase in infiltration volume that tends to stabilize over time. In contrast, the numerical modeling exhibits a polynomial trendline with a relatively stable increase in infiltration volume from the beginning to the end of the experiments.

Further understanding of the impacts of external influences, soil heterogeneity, and parameter estimation is necessary to advance our knowledge of soil conditions for more accurate modeling.

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## 7. REFERENCES

- [1] Graveline N. and Mérel P., Intensive and Extensive Margin Adjustments to Water Scarcity in France's Cereal Belt. *European Review of Agricultural Economics*, vol. 41, no. 5, pp. 707–743, 2014.
- [2] Gorgoglione A., Gioia A., and Iacobellis V., A Framework for Assessing Modeling Performance and Effects of Rainfall-Catchment-Drainage Characteristics on Nutrient Urban Runoff in Poorly Gauged Watersheds. *Sustainability*, vol. 11, no. 4933, pp. 1–16, 2019.
- [3] Distefano T. and Kelly S., Are We in Deep Water? Water Scarcity and Its Limits to Economic Growth. *Ecological Economics*, vol. 142, pp. 130–147, 2017.
- [4] Qin H., Li Z., and Fu G., The Effects of low Impact Development on urban Flooding Under Different Rainfall Characteristics. *Journal of Environmental Management*, vol. 129, pp. 577–585, 2013.
- [5] Willems P. and Vrac M., Statistical Precipitation Downscaling for Small-Scale

- Hydrological Impact Investigations of Climate Change. *Journal of Hydrology*, vol. 402, no. 3–4, pp. 193–205, 2011.
- [6] Liu X., Liu W., Tang Q., Bo L., Wada Y., and Yang H., Global Agricultural Water Scarcity Assessment Incorporating Blue and Green Water Availability Under Future Climate Change Earth ' s Future. *Earth ' s Future.*, vol. 10, pp. 1–16, 2022.
- [7] Bisselink B., De Roo A., Bernhard J., and Gelati E., Future Projections of Water Scarcity in The Danube River Basin Due To Land Use , Water Demand, and Climate Change. *Journal of Environmental Geography*, vol. 11, no. 3–4, pp. 25–36, 2018.
- [8] Yagbasan O., Impacts of Climate Change on Groundwater Recharge in Küçük Menderes River Basin in Western Turkey. *Geodinamica Acta*, vol. 28, no. 3, pp. 209–222, 2016.
- [9] Huang F., Wang G. H., Yang Y. Y., and Wang C. B., Overexploitation Status of Groundwater and Induced Geological Hazards in China. *Natural Hazards*, vol. 73, no. 2, pp. 727–741, 2014.
- [10] Van Engelenburg J., Hueting R., Rijpkema S., Teuling A. J., Uijlenhoet R., and Ludwig F., Impact of Changes in Groundwater Extractions and Climate Change on Groundwater-Dependent Ecosystems in a Complex Hydrogeological Setting. *Water Resources Management*, vol. 32, pp. 259–272, 2018.
- [11] Frankl A., Deckers J., Moulaert L., Van Damme A., Haile M., Poesen J., and Nyssen J., Integrated Solutions for Combating Gully Erosion in Areas Prone to Soil Piping: Innovations from The Drylands of Northern Ethiopia. *Land Degradation & Development*, pp. 1797–1804, 2014.
- [12] Qi P., Zhang G., Xu Y. J., Wang L., Ding C., and Cheng C., Assessing the Influence of Precipitation on Shallow Groundwater Table Response Using a Combination of Singular Value Decomposition and Cross-Wavelet Approaches. *Water*, vol. 10, no. 598, pp. 1–16, 2018.
- [13] Bhaskar A. S., Hogan D. M., and Nimmo J. R., Groundwater Recharge Amidst Focused Stormwater Infiltration. *Hydrological Processes*, vol. 32, pp. 2058–2068, 2018.
- [14] Zhang J., Lei T., Qu L., Zhang M., Chen P., Gao X., Chen C., and Yuan L., Method to Quantitatively Partition The Temporal Preferential Flow and Matrix Infiltration in Forest Soil. *Geoderma*, vol. 347, no. 17, pp. 150–159, 2019.
- [15] Grebel J. E., Mohanty S. K., Torkelson A. A., Boehm A. B., Higgins C. P., Maxwell R. M., Nelson K. L., and Sedlak D. L., Engineered Infiltration Systems for Urban Stormwater Reclamation. *Environmental Engineering Science*, vol. 30, no. 8, pp. 437–545, 2013.
- [16] Venvik G. and Boogaard F. C., Infiltration Capacity of Rain Gardens Using Full-Scale Test Method: Effect of Infiltration System on Groundwater Levels in Bergen, Norway. *Land*, vol. 9, no. 12, pp. 1–18, 2020.
- [17] Firmansyah, Permana S., and Fathir M., Analysis of Infiltration Wells to Prevent Floods and Runoff in the Tarogong Kidul Area. *Journal of Construction*, vol. 20, no. 1, pp. 18–29, 2004.
- [18] Yoo C., Ku J. M., Jun C., and Zhu J. H., Simulation of Infiltration Facilities Using The SEEP/W Model and Quantification of Flood Runoff Reduction Effect by The Decrease in CN. *Water Science & Technology*, vol. 74, no. 1, pp. 118–129, 2016.
- [19] Situmorang M., Setiyadi S., and Hutabarat L. E., Infiltration Wells Utilizing Watershed Conservation for Flood Prevention. *IOP Conference Series: Earth and Environmental Science*, vol. 878, no. 1, pp. 1–6, 2021.
- [20] Armanuos A. M., Al-ansari N., and Yaseen Z. M., Assessing the Effectiveness of Using Recharge Wells for Controlling the Saltwater Intrusion in Unconfined Coastal Aquifers with Sloping Beds: Numerical Study. *Sustainability*, vol. 12, no. 7, 2685, pp. 1–26, 2020.
- [21] Haq S. A., *Harvesting Rainwater from Building*. Springer International Publishing, Switzerland, pp. 1–266, 2017.
- [22] Susilo E., Suripin, and Suharyanto, Field Performance of Shallow Recharge Well. *MATEC Web of Conferences*, vol. 195, pp. 1–6, 2018.
- [23] Sileshi R., Pitt R., Clark S., and Christian C., Laboratory and Field Studies of Soil Characteristics of Proposed Stormwater Bioinfiltration Sites. *Proceedings of the Water Environment Federation*, vol. 2012, no. 5, pp. 241–250, 2014.
- [24] Lazarovitch N., Simunek J., and Shani U., System-Dependent Boundary Condition for Water Flow from Subsurface Source. *Soil Science Society of America Journal*, vol. 69, pp. 46–50, 2005.
- [25] Locatelli L., Mark O., Steen P., Arnbjerg-nielsen K., Wong T., and John P., Determining The Extent of Groundwater Interference on The Performance of Infiltration Trenches. *Journal of Hydrology*, vol. 529, pp. 1360–1372, 2015.
- [26] Elhakim A. F., Estimation of Soil Permeability. *Alexandria Engineering Journal*, vol. 55, no. 3, pp. 2631–2638, 2016.

- [27] Coutinho A. P., Lassabatere L., Montenegro S., Antonino A. C. D., Angulo-Jaramillo R., and Cabral J. J. S. P., Hydraulic Characterization and Hydrological Behaviour of A Pilot Permeable Pavement in An Urban Centre, Brazil. *Hydrological Processes*, vol. 30, no. 23, pp. 4242–4254, 2016.
- [28] Singh V. K., Kumar D., Kashyap P. S., Singh P. K., Kumar A., and Singh S. K., Modelling of Soil Permeability Using Different Data Driven Algorithms Based on Physical Properties of Soil. *Journal of Hydrology*, vol. 580, 124223, pp. 1–10, 2019.
- [29] Bouwer H., Estimating and Enhancing Groundwater Recharge. in *Symposium on groundwater recharge*, pp. 1–10, 1987.
- [30] Sophocleous M., Combining The Soilwater Balance and Water-Level Fluctuation Methods to Estimate Natural Groundwater Recharge: Practical Aspects. *Journal of Hydrology*, vol. 124, pp. 229–241, 1991.
- [31] De Vries J. J. and Simmers I., Groundwater Recharge: An Overview of Processes and Challenges. *Hydrogeology Journal*, vol. 10, pp. 5–17, 2002.
- [32] Ariani L., Faris F., and Rifai A., Geotechnical Assessment of Sublake Slopes and Liquefaction Hazard in Lake Toba , Indonesia. *International Journal of GEOMATE*, vol. 25, no. 111, pp. 153–161, 2023.
- [33] Zeng L., Liu J., Zhang J., Bian H., and Lu W., Effect of Colluvial Soil Slope Fracture ' s Anisotropy Characteristics on Rainwater Infiltration Process. *Advavances in Civil Engineering*, vol. 2018, no. 7351628, pp. 1–11, 2018.
- [34] Yamashita D. and Kanazawa S., Stress Analysis of Valley Fills Considering. *International Journal of GEOMATE*, vol. 24, no. 105, pp. 85–92, 2023.
- [35] Setiawan B., Crismaningwang G., Purwana Y. M., Fitri S. N., and Dananjaya R. H., Analysis of 2-Dimensional Models of Small-Scale Laboratory Infiltration Wells Using Geostudio Software. *Journal of Civil Engineering Research*, vol. 7, no. 1, pp. 71–76, 2023.
- [36] Setiawan B., Chrismaningwang G., and Rifa'i F., Analysis of Seepage Discharge in Infiltration Wells with Diameter Variations Using Geostudio Seep/W Software. *Civil Engineering Matrix*, vol. 11, no. 4, pp. 362–368, 2024.
- [37] ASTM D3385-03. Standard Test Method for Infiltration Rate of Soils in Field Using Double-Ring Infiltrometer. no. August. ASTM International, West Conshohocken, PA, USA, pp. 4–11, 2003.
- [38] Sosrodarsono S. and Takeda K., Backfill Type Dam. PT Pradnya Paramita, Jakarta, Indonesia, pp. 1–327, 1977.
- [39] Nakashima K. and Kawai K., Influence of Seepage Flow Histories on. *International Journal of GEOMATE*, vol. 20, no. 79, pp. 42–47, 2021.