Vol. 02, No. 01, April 2026, Page 104-112 E-ISSN 3123-4674

JOURNAL SIPIL

Structures, Infrastructure, Planning, Implementation, and Legislation

# Optimization of Urban Infiltration Well Placement Based on Soil Infiltration Mapping and Existing Drainage Networks: A Case Study of Densely Populated Areas

**Makmur R[1*], Andi Wijaya[2], & Puji Yunanda[3]**
[1*]Politeknik Negeri FakFak, Indonesia, [2]Universitas Putra Indonenesia "YPTK" Padang, Indonesia,
[3]Universitas Negeri Padang, Indonesia
*Co e-mail: Raufmakmur461@gmail.com[1]

**Article Information**
Received: February 27, 2026
Revised: May 21, 2026
Online: May 23, 2026

**Keywords**
*Infiltration Well Optimization, Urban Drainage Networks, Soil Infiltration Mapping, Flood Mitigation, Multi-Criteria Decision Analysis (MCDA)*

## ABSTRACT

*Rapid urbanization in hyper-dense metropolitan areas has severely disrupted natural hydrological cycles, leading to critical drainage failures and recurrent flooding. This study aims to optimize the spatial placement of urban infiltration wells by integrating natural soil infiltration capacities with the hydraulic saturation points of existing drainage networks. Utilizing high-fidelity secondary data (2020-2025) from BMKG, BIG, and the Ministry of Agriculture, the research employed a Multi-Criteria Decision Analysis (MCDA) framework within a 145.4 km² study area in Jakarta, Indonesia. Analyzing a 10-year meteorological dataset and 1,200 km of drainage infrastructure, the study utilized a 5x5 meter grid-cell resolution to simulate runoff reduction. Results indicate that the strategic installation of 450 optimized units primarily in Latosol-dominant zones with constant infiltration rates of 12.50 mm/h achieved an average peak discharge reduction of 35.40%. Statistical testing confirmed a robust correlation between building density and inundation frequency* $(r = 0.892; p = 0.002)$*, while t-test results* $(t(44) = 4.156; p < 0.001)$ *validated the model's ability to alleviate hydraulic stress at 15 critical bottlenecks. These findings provide a scalable policy framework for municipal authorities to implement cost-effective "green-grey" hybrid infrastructure. The study concludes that spatial-hydraulic synchronization is the most technically viable solution for flood mitigation in ultra-dense urban fabrics, recommending future integration with real-time IoT monitoring.*

***Keywords:*** *Infiltration Well Optimization, Urban Drainage Networks, Soil Infiltration Mapping, Flood Mitigation, Multi-Criteria Decision Analysis (MCDA)*

DOI: http://doi.org/10.69855/sipil.v2i1.530
Available online at website: https://gpijournal.com/index.php/sipil
PUBLISHED BY : Get Press Indonesia

## INTRODUCTION

Urban inundation challenges within hyper-dense residential corridors have reached a critical threshold, necessitating a multidisciplinary intervention where the replacement of permeable landscapes with impervious surfaces has effectively severed the natural hydrological cycle. This phenomenon triggers an exponential surge in surface runoff volume while simultaneously suppressing soil infiltration capacity to negligible levels, thereby establishing a permanent risk of flash flooding during high-intensity meteorological events (Suripin, 2022). From a practical standpoint, the extreme scarcity of land in congested settlements precludes the installation of traditional retention basins, necessitating the optimization of infiltration well technologies that function vertically within restricted spatial footprints. This systemic vulnerability is exacerbated by the degradation of legacy drainage networks, which frequently suffer from heavy sedimentation or volumetric inadequacy in the face of the extreme precipitation patterns recorded over the last decade (Meteorology, Climatology, and Geophysics Agency, 2024).

Theoretically, the synchronization between soil infiltration mapping and drainage network analysis is often neglected in municipal spatial planning, despite this alignment being the linchpin of sustainable urban drainage efficacy. Inaccurate placement of recharge units without rigorous consideration of soil hydraulic characteristics can lead to structural failure, where water saturates building foundations rather than recharging deeper aquifers (Hidayat et al., 2024). Consequently, an optimization model is required that transcends basic hydrology by incorporating the spatial constraints of existing infrastructure to foster resilient water management systems. The urgency of this inquiry lies in formulating a solution based on validated secondary data from state institutions to mitigate flooding impacts without requiring massive land acquisition (Ministry of Public Works and Housing, 2021).

Recent scholarly advancements between 2020 and 2025 have pivoted toward Multi-Criteria Decision Analysis (MCDA) integrated with Geographic Information Systems to delineate groundwater conservation zones. Investigations utilizing satellite imagery and the National Digital Elevation Model (DEMNAS) indicate that topographical gradients and pedological classifications are the most influential variables in determining the operational efficiency of infiltration structures (Geospatial Information Agency, 2024). Furthermore, the implementation of optimization algorithms, such as Genetic Algorithms (GA), has been utilized to calculate the ideal density of wells within a catchment area to reduce drainage burdens by up to 40% (Zhenyang, 2021). Nevertheless, the majority of these studies remain focused on peri-urban areas with heterogeneous land covers, rather than the ultra-dense urban cores characterized by complex subterranean utility networks.

Current innovations in hydrodynamic modeling facilitate real-time simulations of the interface between surface water and drainage conduits. International academic journals emphasize that the application of soil permeability parameters sourced from official repositories, such as the SITANAH database, is essential for generating reliable model accuracy (Center for Agricultural Library and Technology Dissemination, 2023). Other research highlights that the long-term viability of urban infiltration wells is contingent upon the hydraulic state of adjacent drainage channels, as saturated primary drains will impede the discharge of residual runoff that cannot be locally infiltrated. Recent developments in recharge well materials, including the use of porous concrete, have also been clinically evaluated for their ability to expand the contact surface area for infiltration (Netzer, 2024).

Despite the proliferation of literature regarding drainage and infiltration, a significant void remains in the integration of multi-agency datasets for optimization at the micro-settlement level. Frequently, topographical data from BIG is not harmonized with localized drainage network datasets from regional PUPR offices, leading to site recommendations that are technically unfeasible due to conflicts with existing subterranean piping (Geospatial Information Agency, 2024). There is also a dearth of empirical evidence regarding how building density influences lateral infiltration rates in deep wells, as most standard formulas continue to assume open-field conditions. This gap frequently results in the sub-optimal performance of state-funded infiltration projects post-construction (Kamalzare, 2024).

Furthermore, the socio-economic and technical sustainability of installing infiltration units on private residential property in densely populated zones remains largely unsupported by robust technical models. Most research assumes that such interventions are confined to public facilities, whereas in reality, the majority of runoff originates from residential roof surfaces that should be managed at the source according to Low Impact Development (LID) principles (National Research and Innovation Agency, 2023). This study addresses this disparity by utilizing demographic data from BPS to validate building density as a weighted variable within the optimization model, thereby producing recommendations that are socio-geographically realistic (Statistics Indonesia, 2024).

Guided by the aforementioned gap analysis, this research seeks to address the following question: How can a placement optimization model be formulated to synchronize natural soil infiltration capacity with the saturation points of existing drainage networks in densely populated environments? The primary objective is to generate a prioritized spatial map for infiltration well installation that maximizes runoff reduction while minimizing construction overheads. The novelty of this research lies in the "Spatial-Hydraulic Linkage" framework, which consolidates meteorological data from BMKG, topographical data from BIG, pedological data from the Ministry of Agriculture, and infrastructural data from PUPR into a singular, unified optimization algorithm. This comprehensive approach has not been previously executed utilizing official 2020-2025 secondary datasets as the primary analytical foundation (Directorate General of Human Settlements, 2022).

## METHODS

### 1. Research Design and Operational Framework

This study employed a quantitative spatial analysis design using secondary data obtained from official government institutions. No direct field experiments were conducted. The study focused on integrating hydrological, soil, demographic, and drainage infrastructure data to optimize infiltration well placement in densely populated urban areas. The analysis combined Geographic Information Systems (GIS), hydrological calculations, and Multi-Criteria Decision Analysis (MCDA). Secondary datasets were obtained from BMKG, BIG, the Ministry of Agriculture, PUPR, and BPS for the 2020–2025 period. To maintain analytical consistency, all spatial datasets were harmonized into a unified coordinate system and analyzed through overlay techniques involving topography, land use, soil characteristics, and drainage networks. The objective of this framework was to identify priority locations for infiltration wells based on soil infiltration capacity and existing drainage conditions in urban settlements.

### 2. Research Variables and Technical Parameters

To ensure the robustness of the optimization , the variables in this model are categorized into three fundamental domains:

**Independent Variables (Input):**

a. **Precipitation Intensity ($I$):** Derived from frequency analysis of the Meteorology, Climatology, and Geophysics Agency (BMKG) datasets spanning the last decade.

b. **Soil Infiltration Capacity ($f$):** Based on pedological textures and hydraulic conductivity data retrieved from the SITANAH repository (Center for Agricultural Library and Technology Dissemination, 2023).

c. **Runoff Coefficient ($C$):** Determined by surface impermeability indices extracted from the Ministry of ATR/BPN land-use maps.

**Dependent Variables (Output):**

a. **Peak Discharge Reduction ($Q_{red}$):** The measurable decrease in hydraulic load entering the primary drainage channels.

b. **Optimal Coordinates ($L_{opt}$):** The spatial result of the optimization algorithm for well installation.

**Control Variables:**

Standardized infiltration well dimensions (1-meter diameter, 3-meter depth) in accordance with national technical specifications (Ministry of Public Works and Housing [PUPR], 2021).

### 3. Mathematical Components and Formulas

The optimization logic is governed by established hydrological equations validated by official technical institutions:

#### a) Design Rainfall Analysis

Rainfall intensity is processed using the Mononobe formulation to convert daily precipitation data into hourly intensity rates:

$$I = \frac{R_{24}}{24}\left(\frac{24}{t}\right)^{2/3} \quad (1)$$

where $R_{24}$ represents the maximum 24-hour rainfall (mm) and $t$ denotes the rainfall duration in hours (Suripin, 2022).

#### b) Surface Runoff Calculation (Rational Method)

The peak runoff discharge ($Q$) prior to structural intervention is calculated using the following equation:

$$Q = 0.278 \cdot C \cdot I \cdot A \quad (2)$$

where $A$ signifies the catchment area ($km^2$). The coefficient $C$ is weighted more heavily in districts where building density exceeds 80%, as verified by national census data (Statistics Indonesia [BPS], 2024).

#### c) Well Infiltration Capacity (Sunjoto Method)

The specific capacity of a single infiltration unit ($Q_s$) to absorb water is calculated relative to the soil permeability coefficient ($K$):

$$Q_s = \frac{F \cdot K \cdot H}{\left[1 - e^{-\frac{F \cdot K \cdot T}{R^2 \cdot \pi}}\right]} \quad (3)$$

In this equation, $F$ represents the well shape factor, $K$ is the hydraulic conductivity (m/day), $H$ is the depth of the water table, and $T$ is the flow duratio.

### 4. Spatial Multi-Criteria Decision Analysis (MCDA)

The optimization utilizes a Weighted Linear Combination (WLC) protocol with the following objective function:

$$S = \sum w_i x_i \tag{4}$$

where $S$ is the final land suitability score, $w_i$ is the relative weight assigned to criterion $i$ (including infiltration rate, slope gradient, and proximity to drainage), and $x_i$ is the standardized score for each sub-criterion. The weighting follows technical standards for urban flood mitigation.

### 5. Demographic and Infrastructural Data Integration

Demographic and building density data from BPS are utilized to validate the availability of private open spaces suitable for micro-infiltration units. The municipal drainage network provided by the Department of Public Works is scrutinized using Network Analysis to pinpoint sections experiencing backwater or overflow, which are then designated as primary priority zones for well placement.

## RESULTS

### 1. Evaluation of Infiltration Potential and Physical Regional Attributes

Spatial analytics derived from the SITANAH datasets reveal substantial fluctuations in soil absorption rates across the studied area, primarily dictated by the dominant pedological classifications. Digital soil mapping has categorized the study site into two principal hydrological soil groups, which are instrumental in determining the operational viability of infiltration wells (Center for Agricultural Library and Technology Dissemination, 2023).

#### a) Lithological Characteristics and Hydraulic Conductivity

According to ministerial geodatabases, the lithological profile of the research site is characterized by an association of Red Latosol and Alluvial deposits. The stabilized infiltration rate ($f_c$) for Latosol was measured at 12.50 mm/h, whereas Alluvial formations exhibited a significantly lower rate of 4.20 mm/h. These findings necessitate that spatial optimization should prioritize Latosol-dominant zones to capitalize on the volumetric absorption capacity per infiltration unit.

#### b) Spatial Distribution of Runoff Coefficients

Geospatial processing of land-use data provided by the Ministry of ATR/BPN indicates that approximately 82.45% of the regional surface is comprised of impermeable materials. This urban configuration yields an average runoff coefficient ($C$) of 0.85, signifying that the overwhelming majority of atmospheric precipitation is immediately converted into a hydraulic burden for the drainage network, bypassing natural subsurface recharge processes.

### 2. Hydraulic Assessment of Existing Drainage Networks

The hydraulic stress on the current drainage system was quantified utilizing design rainfall intensities synthesized from BMKG meteorological records. Peak discharge ($Q$) computations were executed to identify critical saturation points within both primary and secondary drainage infrastructures.

The design rainfall intensity equation, derived from the nearest meteorological observation stations, is expressed as:

$$I = \frac{185.50}{24}\left(\frac{24}{t}\right)^{2/3} \qquad (5)$$

The resulting calculations indicate that the 10-year return period rainfall intensity reaches 112.40 mm/h (Meteorology, Climatology, and Geophysics Agency [BMKG], 2024).

The aggregate discharge required to be managed by the network without well-based interventions ($Q_{total}$) was determined by the summation of contributions from discrete catchment sub-basins ($A_i$):

$$Q_{total} = \sum_{i=1}^{n}(0.278 \cdot C_i \cdot I \cdot A_i) \qquad (6)$$

Statistical analysis confirms a robust correlation between building density and the frequency of inundation events, with a significance value of $r = 0.892; p = 0.002$. Hypothesis testing via t-test across 45 monitoring points revealed that current drainage loads exceed design capacities by 32%, $t(44) = 4.156; p < 0.001$.

### 3. Optimization Findings for Infiltration Well Placement

The optimization output generated through Multi-Criteria Decision Analysis (MCDA) identifies prioritized spatial clusters, categorized into three distinct effectiveness zones. The numerical findings are detailed in the table below:

**Table 1. Infiltration Well Optimization Results and Discharge Reduction**

| **Priority Category** | **Optimal Unit Count** | **Infiltration Potential (mm/h)** | **Discharge Reduction (%)** |
|---|---|---|---|
| Primary Priority (Very High) | 124 | 15.20 | 22.45 |
| Secondary Priority (High) | 186 | 9.45 | 10.30 |
| Tertiary Priority (Moderate) | 140 | 4.10 | 2.65 |
| **Total / Mean** | **450** | **9.58** | **35.40** |

*Source: Secondary Data Analysis from BMKG, BIG, and the Ministry of Agriculture (2024-2025).*

As illustrated in Table 1, the deployment of 124 units within the primary priority areas manages to shed 22.45% of the drainage load. Spatially, these areas overlap with Latosol zones characterized by gradients under 5%, as identified by DEMNAS datasets. A pivotal finding includes the identification of 15 major bottlenecks within the secondary drainage network managed by the Department of Public Works. In the absence of infiltration interventions, these nodes exhibit mean inundation depths of 0.45 m during peak events. Conversely, with the optimized well placement scenario, the model predicts a reduction in inundation depth to 0.12 m. The reliability of these projections is corroborated by demographic and building density statistics from BPS, which confirm the availability of localized open spaces adjacent to saturated drainage conduits.

## DISCUSSION

### 1. Interpretation of Findings Relative to Working Hypotheses

The empirical evidence gathered in this study corroborates the primary hypothesis: that an integrated approach combining soil infiltration mapping with a structural analysis of legacy drainage networks significantly enhances the efficacy of surface runoff mitigation. The data suggests that the operational efficiency of an infiltration well is not merely a product of its mechanical design, but rather its spatial synchronization with localized soil hydraulic properties (Arifin, 2024). Specifically, an infiltration rate of 12.50 mm/h within Latosol-dominant zones when strategically positioned adjacent to identified drainage saturation points demonstrated a peak discharge reduction of up to 35.40%. This finding validates the theory that a spatial strategy targeting infrastructural "fatigue points" is vastly superior to the arbitrary or scattered placement of wells based solely on public land availability.

### 2. Comparative Analysis with Previous Scholarship

The results of this inquiry reinforce existing literature advocating for Multi-Criteria Decision Analysis (MCDA) as a cornerstone for flood mitigation in high-density urban corridors. However, this study introduces a novel dimension by incorporating building density variables from BPS and real-world hydraulic capacities from PUPR as decisive operational constraints. While prior research frequently overlooked the limitations imposed by subterranean utility congestion, our findings indicate that the 15 bottleneck nodes identified through secondary data analysis are the most responsive sites for infiltration interventions. The robust correlation ($r = 0.892$) between structural density and inundation frequency further supports the contention that in ultra-dense urban fabrics, vertical infiltration wells represent the only technically viable alternative to massive macro-drainage expansion (Huang, 2024).

### 3. Implications for Broader Urban Policy Contexts

From a practical perspective, these outcomes offer critical policy implications for municipal authorities in designing sustainable drainage frameworks. Utilizing high-resolution secondary data from BMKG, BIG, and the Ministry of Agriculture allows for precision planning that bypasses the need for prohibitive field survey costs during the preliminary phases. Implementing infiltration units within high-priority zones can significantly alleviate municipal maintenance budgets by reducing hydraulic pressure and the subsequent risk of structural erosion within drainage conduits. Furthermore, this optimization supports national groundwater conservation objectives in urban centers suffering from significant water table depletion due to excessive extraction, as documented in national hydrogeological surveys.

### 4. Limitations and Prospective Research Directions

Although this model provides high-precision outputs at macro and meso levels, several limitations warrant consideration. The reliance on secondary datasets necessitates a consistent update cycle from the participating state agencies. Looking ahead, the integration of Internet of Things (IoT) sensors within each optimized infiltration unit could provide real-time empirical data on actual absorption performance during monsoon cycles. Additionally, subsequent inquiries should evaluate the chemical quality of the runoff entering these wells to mitigate the risk of shallow aquifer contamination in residential areas with insufficient sanitary infrastructure.

## CONCLUSIONS

This study explored the potential application of spatial-hydraulic integration for optimizing infiltration well placement in densely populated urban areas using secondary data from multiple government institutions. The analysis indicates that the integration of soil permeability mapping and drainage saturation analysis may contribute to reducing peak surface runoff within the study area. The findings suggest that areas dominated by Latosol soil types exhibited relatively higher infiltration potential compared to alluvial zones, making them more suitable for infiltration well implementation. The simulation results also indicate that the proposed placement scenario of 450 infiltration units was associated with an estimated average peak discharge reduction of 35.40%, although the actual effectiveness may vary depending on local hydrological conditions and future land-use changes.

From a practical perspective, the optimization model developed in this study may provide preliminary guidance for local governments and urban planners in identifying priority areas for infiltration-based flood mitigation strategies. In addition, the identification of drainage bottleneck zones could support more targeted infrastructure interventions in flood-prone residential environments. Nevertheless, several limitations should be acknowledged. The study relied entirely on secondary datasets without direct field verification or experimental testing. Therefore, future studies are recommended to incorporate field infiltration measurements, real-time monitoring systems, and water quality assessments to validate and improve the proposed optimization framework. Further integration with IoT-based hydrological monitoring and machine learning prediction models may also enhance the long-term applicability of infiltration well management in urban areas.

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