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Localized K_s Assessment for Bioretention in Thailand: Improving SWMM Accuracy

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ABSTRACT

Urbanization in Thailand has significantly reduced natural infiltration surfaces, intensified stormwater runoff, and increased the demand for effective urban drainage solutions. Bioretention systems, guided by water-sensitive urban design (WSUD) principles, offer a promising approach for enhancing infiltration and mitigating urban flooding. However, the effectiveness of bioretention depends critically on the accurate estimation of saturated hydraulic conductivity (K_s), a key input parameter in hydrological models such as the Storm Water Management Model (SWMM). Despite international guidelines, local K_s values for tropical soils and vegetation remain scarce, limiting model reliability. This study aims to determine its suitability as a filter media layer in bioretention systems developed specifically for the Thai context. Two surface conditions, vegetated and unvegetated, were tested using coarse construction sand as filter media. The results showed a significantly higher Ks (an 18.55% increase, $p<0.001$) in the vegetated system (306.57 ± 4.58 mm h-1) compared to the unvegetated system (258.61 ± 4.98 mm h-1), confirming a significant influence of vegetation on infiltration capacity. The localized K_s data produced in this study fall within international bioretention design standards and offer a practical alternative to SWMM's default parameters. A sensitivity analysis using SWMM and actual Chiang Mai rainfall data demonstrated the critical impact of these localized K_s values, showing that integrating them can reduce simulated runoff volumes by up to 30% for high-frequency storms, thereby enhancing the predictive accuracy of urban stormwater models. This research contributes to bridging the gap between hydrological modeling and site-specific environmental conditions in Southeast Asia.

Keywords: saturated hydraulic conductivity (K_s), bioretention, Storm Water Management Model (SWMM), urban green infrastructure, Water-Sensitive Urban Design (WSUD)

INTRODUCTION

The accelerated pace of urbanization in Thailand, characterized by rapid population growth and extensive land-use changes from natural landscapes to impervious surfaces, has profoundly altered the natural hydrological cycle (Li et al., 2019). This transformation has led to a significant reduction in pervious areas capable of absorbing stormwater, consequently increasing surface runoff volumes and velocities (Wanitchayapaisit et al., 2022). Major Thai urban centers, such as Bangkok and Chiang Mai, are particularly vulnerable, experiencing more severe and more frequent flooding during the annual monsoon season (Kiguchi et al., 2021). The projected escalation of these risks further emphasizes the urgency of effective solutions (Garshasbi et al., 2025). The traditional reliance on grey infrastructure (drainage pipes and pumping stations) often proves inadequate in managing these escalated stormwater volumes, highlighting the urgent need for more resilient and sustainable urban drainage solutions (Li et al., 2019). Utilizing principles derived from Water-Sensitive Urban Design (WSUD) or Low Impact Development (LID) offers a strategic approach to enhance urban livability and mitigate flood severity. However, implementing these Nature-Based Solutions (NBS) in low- and middle-income countries, including those in Southeast Asia, often faces unique socioeconomic, political, and local data challenges (Lechner et al., 2020). These approaches recognize the value of green infrastructure components in managing water and providing ecosystem services for metropolitan area sprawl (Nasr et al., 2024). Among these strategies, bioretention stands out for its efficiency in enhancing water infiltration and transforming traditional grey infrastructure into functional green infrastructure. Its performance and ability to address the dynamics of landscape transformation and governance of urban waterways are critically governed by its physical design, particularly the precise choice of filter media and vegetation (Funai & Kupec, 2017; Numsuk, 2025).

In bioretention design, accurately determining the saturated hydraulic conductivity (K_s) value for the filter media layer presents a persistent and critical challenge. As the pivotal factor dictating water flow, K_s is the primary control on infiltration capacity and drainage performance. However, K_s inherently varies depending on many factors, including geological attributes, diverse environmental contexts, variations in vegetation cover (Wuepper et al., 2020; Yang et al., 2021), and specific construction practices. An improperly characterized K_s can undermine the system's intended benefits (Fassman-Beck & Saleh, 2021; Weiss & Gulliver, 2015). While international guidelines provide general ranges, these are often derived from temperate climates and may not reliably reflect the unique conditions prevalent in tropical regions like Thailand (Zhang et al., 2022). The scarcity of empirical, site-specific K_s data for bioretention systems under Thai climatic conditions and with locally available materials represents a substantial knowledge gap, severely compromising the applicability and accuracy of current design practices for WSUD systems.

This study assessed the K_s of locally available construction sand to determine its suitability as a filter media layer in bioretention systems developed specifically for the Thai context. Experiments were conducted using a mesocosm setup that simulated a bioretention environment, comparing vegetated and unvegetated surfaces. The integration of vegetation, which is also a component of biophilic design to enhance urban park resilience (Ristianti et al., 2024), was considered vital. For the vegetated system, *Ruellia simplex* C.Wright was chosen as the vegetated cover. This perennial herb was selected based on its known resilience and adaptability to diverse soil and climatic conditions (Royal Botanic Gardens, Kew, 1870; Wunderlin et al., 2025), which contributes to the overall landscape quality and user satisfaction (Akay, 2025). While this study incorporated a vegetated surface condition, it did not explicitly account for plant-specific factors such as root morphology or biomass.

Furthermore, the performance of sophisticated hydrological modeling tools such as the widely used Storm Water Management Model (SWMM) is highly dependent on reliable input parameters (Zhang et al., 2023). Inaccuracies in K_s can propagate through the entire hydrological simulation, leading to substantial and misleading predictive errors (Yue & Gao, 2025). Therefore, obtaining empirically validated and distinctly localized soil hydraulic properties, specifically K_s, is crucial for the precise design of individual green infrastructure components, and critically, for significantly enhancing the reliability of large-scale hydrological simulations and promoting truly effective urban water management planning. Beyond the hydrological benefits, these systems contribute to the urban environment by enhancing social well-being and potentially offering restorative benefits that renew attention and reduce stress in dense urban settings (Sornubol & Lekagul, 2024; Suppakittpaisarn et al., 2017). This study addresses this data gap directly. This is the first mesocosm study estimating K_s for Thai construction sand with and without vegetation, providing localized parameters for SWMM. The findings are intended to provide insights into determining an appropriate K_s value suitable for the Thai context, serving as a critical reference for future bioretention design and aiding in the establishment of effective urban green spaces and water catchment areas.

METHODOLOGY

Bioretention Design

A mesocosm experiment was conducted outdoors at the Faculty of Engineering, Chiang Mai University, to simulate bioretention system performance under controlled yet realistic urban environmental conditions. The bioretention system followed typical international design principles, comprising three distinct layers. From the surface downward, these were the filter, transition, and drainage layers (Melbourne Water, 2020; Radinja et al., 2019). The concept centers on effective water management by utilizing suitable materials and spatial configurations to enhance infiltration rates.

- **Filter Media Layer:** This uppermost layer, crucial for infiltrating surface runoff and drainage, often incorporates materials like sand to enhance porosity. Vegetation is typically integrated here. The material selected for this layer is paramount, as its structure directly governs the critical processes of infiltration and water retention (Pan et al., 2018).
- **Transition Layer:** Located below the filter media layer, this layer is typically made up of fine sand or geotextile, preventing the downward migration of fines into the drainage layer.
- **Drainage Layer:** The bottom layer temporarily stores water before facilitating removal. This layer may also include perforated drainage pipes to ensure the timely removal of excess water (Goh et al., 2019; Li et al., 2021; Rinchumphu et al., 2024; Sagrelius et al., 2023; Tirpak et al., 2021; Vijayaraghavan et al., 2021).

This study employs a mesocosm testing system to simulate bioretention performance, a widely adopted technique for evaluating drainage layers and understanding their hydraulic performance (Zhang et al., 2021). The layered soil system is replicated within the mesocosm to measure water flow and observe soil behavior under simulated runoff conditions. The test enables quantification of water inflow and outflow to assess water flux, providing controlled insights into real-world performance. Mesocosms can assume various shapes, such as cylinders, squares, or rectangles. However, the most effective model for testing remains uncertain. For this experiment, a rectangular mesocosm measuring 60 cm in width, 180 cm in length, and 90 cm in height was constructed (Figure 2). Detailed construction, including structural reinforcement and waterproofing measures, was accurately carried out to ensure the accuracy and reliability of the experiments (Goh et al., 2017; Hermawan et al., 2019; Yang et al., 2021). The mesocosm experiment comprised six independent mesocosms—three vegetated and three unvegetated—constructed to the same specifications (Figure 2) such that each mesocosm served as an independent experimental replicate ($n = 3$ per treatment). For hydraulic characterization, each mesocosm underwent five duration K_s measurements. These five measurements were repeated on the same mesocosm (repeated measures).

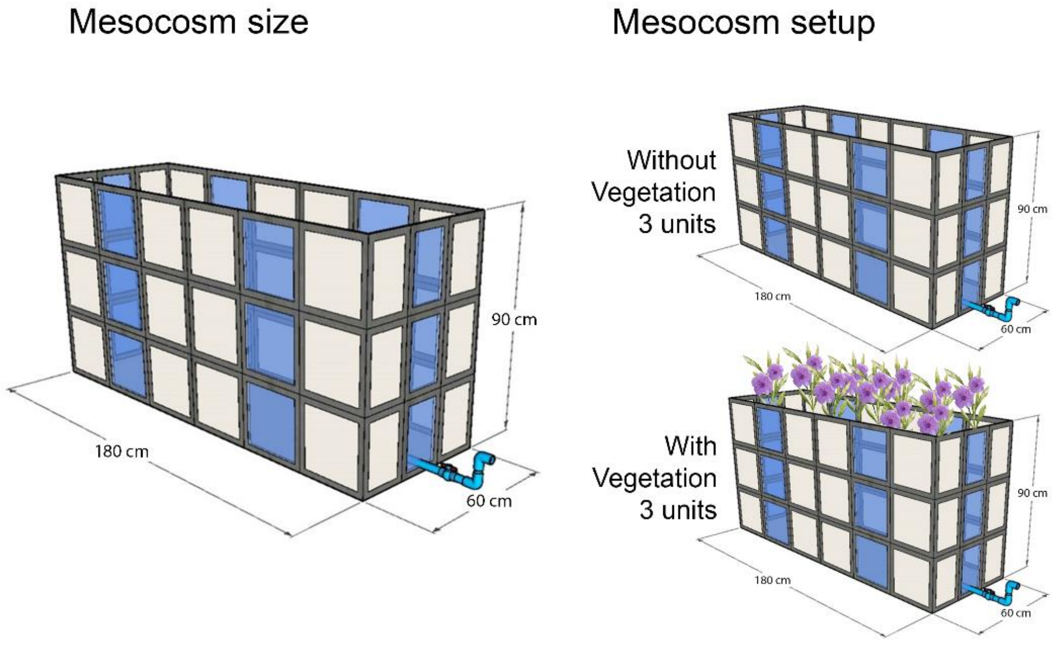
Figure 1

Ruellia Simplex C.Wright

Note. This figure demonstrates the plant species selected for the vegetated surface in this study, *Ruellia simplex* C.Wright. It is licensed under Canva's free content licenses. Researchers cross-checked each image for accuracy. From *Ruellia Simplex C.Wright*, by Royal Botanic Gardens, Kew, 1870, Plants of the World Online (https://powo.science.kew.org/taxon/urn:lsid:ipni.org:names:54585-1). Copyright 1870 by Royal Botanic Gardens, Kew.

Figure 2

Mesocosm Design Showing Dimensions and Experimental Treatments



Note. This figure illustrates the overall mesocosm design, including its dimensions and the differentiation between the Vegetated and Unvegetated experimental units. The Author created this figure.

Figure 3

Overview of the Mesocosm Experimental Setup During Testing

Note. This figure demonstrates the outdoor mesocosm system configured for the bioretention performance simulation at the Faculty of Engineering, Chiang Mai University, from the authors.

Standards for the design of bioretention layers serve as valuable guidelines, with Melbourne Water (2020) offering insights into layer depths and materials. The filter media layer, arranged from top to bottom, typically comprises well-graded sand with a particle size diameter ranging from 0.05 to 3.4 millimeters (mm), with a recommended depth of 400 to 600 mm. Subsequently, the transition layer is often composed of well-graded coarse sand containing <2% fines, such as A2 filter sand, with a recommended depth of 100 mm. The final drainage layer commonly consists of fine gravel, such as 2 to 7 mm washed screenings (excluding scoria), with a recommended depth of 150 mm (Payne et al., 2015).

However, for this mesocosm experiment, readily available materials within the region were utilized to ensure practical applicability in the Thai context (Wanitchayapaisit, et al., 2022). The filter media layer system was designed with three distinct components. First, the filter media layer itself consisted of coarse construction sand, set at a depth of 400 mm, with a Fineness Modulus (FM) typically ranging from 2.3 to 3.1, by ASTM C33 standards for coarse sand. It was followed by a transition layer of general construction fine sand, set at a recommended depth of 100 mm, having an FM typically ranging from 1.2 to 2.1, consistent with TIS 1776-2542 standards for fine sand. Lastly, the drainage layer comprised 3/8 inch gravel (approximately 9.5 mm), with a depth of 150 mm, a standard size for drainage applications (Sagrelius et al., 2023; Wanitchayapaisit et al., 2022), as shown in the example of media layers in Figure 4. Additionally, details of materials and parameter values for each layer are provided in Table 1. This practical guideline ensures that the findings are directly transferable to local green infrastructure projects but also reflect cost reduction and increased feasibility for future implementation.

The performance of bioretention systems in urban greening depends critically on filter-media properties that directly control water infiltration. K_s quantifies this behavior and is a primary parameter for assessing hydraulic performance and stormwater management efficiency (Cescon & Jiang, 2020; Weiss & Gulliver, 2015). This study provides the first mesocosm-based K_s estimates for Thai construction sand under both vegetated and unvegetated conditions, offering localized values for SWMM parameterization. Although international guidelines (Melbourne Water, 2020) recommend typical ranges, K_s is sensitive to local geology and climate (Wanitchayapaisit et al., 2022). Consequently, it is imperative to conduct site-specific testing to ascertain accurate K_s values for subsequent utilization in bioretention design and the broader planning of urban green infrastructure (Liu et al., 2014).

Table 1

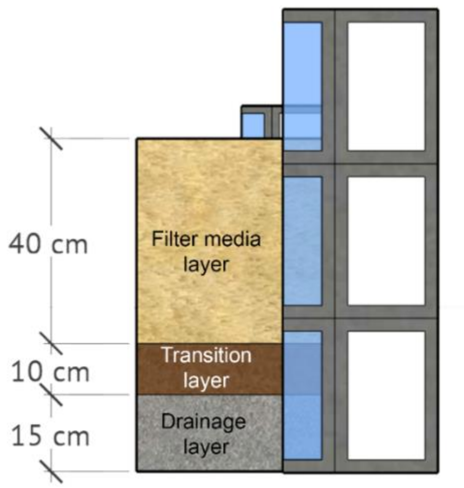
Bioretention Layer Specifications (Guidelines and Study Values)

Layer	Recommended range (guideline)	This study
Filter media	**400-600 mm** Well-graded sand (Melbourne Water, 2020; Payne et al., 2015)	**400 mm** Coarse construction sand (ASTM C33), FM 2.3–3.1
Transition layer	**100 mm** Well-graded coarse sand, <2% fines (Payne et al., 2015)	**100 mm** General construction fine sand, FM 1.2–2.1 (TIS 1776-2542)
Drainage layer	**150 mm** Fine gravel 2-7 mm washed screenings (Payne et al., 2015)	**150 mm** 3/8 in. (9.5 mm) gravel

Note. This table compares guideline-recommended bioretention layer depths and materials with the specific depths and locally sourced materials used in this mesocosm study.

Figure 4

Media Layer of Bioretention Design



Note. This figure demonstrates the media layer arrangement of a bioretention design. The author created this figure.

Hydraulic Conductivity

The K_s, a fundamental parameter quantifying the ease with which water moves through the saturated filter media, was determined using the falling head test methodology. The calculation of K_s relies on Darcy's Law, which describes the specific discharge rate of water flow through porous media (Neuman, 1977). Under the assumption of steady-state, one-dimensional vertical flow through a fully saturated medium, K_s is calculated by rearranging the general form of Darcy's Law, as shown in Equation 1. This approach is critical for accurately assessing the infiltration capacity of the bioretention system.

$$K_s = -\frac{Q}{A} \cdot \left(\frac{dL}{dH}\right) \tag{1}$$

Where:

Q is Volumetric flow rate of water through the soil material (m^3/s),

K_s is Hydraulic conductivity (mm h^{-1}),

A is the Area of the surface perpendicular to the flow (m^2), and

dH/dL is Change in head per unit distance (m/m) – Hydraulic gradient.

The application of Darcy's Law covers various contexts, as demonstrated by Ahammed et al. (2021), who employed WSUD techniques to mitigate strain on existing public drainage systems affected by escalating water volumes from impermeable surfaces due to urban expansion. Their study incorporated leaky wells, soakaways, and infiltration trenches, integrating the six independent variables of K_s, device size, average recurrence interval of rainfall events, critical storm duration, rainfall intensity, and roof size. This comprehensive approach proved effective in managing stormwater runoff. Likewise, Radinja et al. (2019) underscored the significance of the K_s value, which profoundly influences infiltration rates and is pivotal for modeling and designing stormwater runoff control measures and testing K_s using double-ring (DRI) and dual-head infiltrometers (DHI) to measure K_s. At the same time, the mini disk infiltrometer (MDI) assessed unsaturated hydraulic conductivity (K), which was recalculated in K_s to compare the results. Furthermore, a significant observation revealed spatial variability in the K value, ranging from 73% to 89%. It is advised that a range of K values should be employed for enhanced accuracy in K value determination, suitable for the specific soil conditions prevalent in each geographical area.

Recent literature indicates extensive efforts to predict K_s using modern techniques such as machine learning (ML) and pedotransfer functions (PTFs) (Agyare et al., 2007; Sihag et al., 2019; Singh et al., 2022; Veloso et al., 2022; Zhang & Schaap, 2019). However, despite advancements, these methods frequently encounter limitations related to data resolution, regional specificity, and consistent predictive accuracy, often leading to less than satisfactory results. Consequently, direct field testing and site-specific data collection remain vital for obtaining the most accurate and precise K_s values for a designated area.

However, a thorough examination of existing literature reveals ongoing efforts to determine K_s values through various methodologies, including ML techniques and PTFs. While these approaches aim to get accurate K_s values, challenges persist in achieving precise calibration, particularly concerning geological, geographical, environmental, or other spatially sensitive factors (Radinja et al., 2019; Veloso et al., 2022). Consequently, examining local K_s values is a pivotal reference for guiding bioretention design processes and can be utilized as a foundational dataset. By aggregating data from diverse localities, the challenge to formulate K_s value predictions through contemporary methodologies is mitigated, leading to more resilient and context-specific urban green spaces.

Mesocosm Setup and K_s Testing Procedure

The mesocosm setup was assembled outdoors near the Faculty of Engineering, Chiang Mai University, to provide a realistic environmental context. Mesocosm tests were performed using six independent units constructed to identical dimensions (60 cm width × 180 cm length × 90 cm height), with three vegetated units and three unvegetated units. Each mesocosm contained a layered profile with 400 mm of filter media, a 100 mm transition layer and a 150 mm drainage layer. Figure 5 illustrates the pertinent variables and the overall configuration associated with the experimentation. The saturated K_s of the filter media within the outdoor mesocosms was determined using a falling head test methodology.

Given the outdoor setting of the mesocosms, environmental factors were closely monitored. All test cycles were conducted exclusively during dry (no-rain) conditions to prevent rainfall from interfering with water volumes or head levels. Both ambient air temperature (to document environmental conditions) and water temperature were recorded during each test cycle.

The test was conducted as follows:

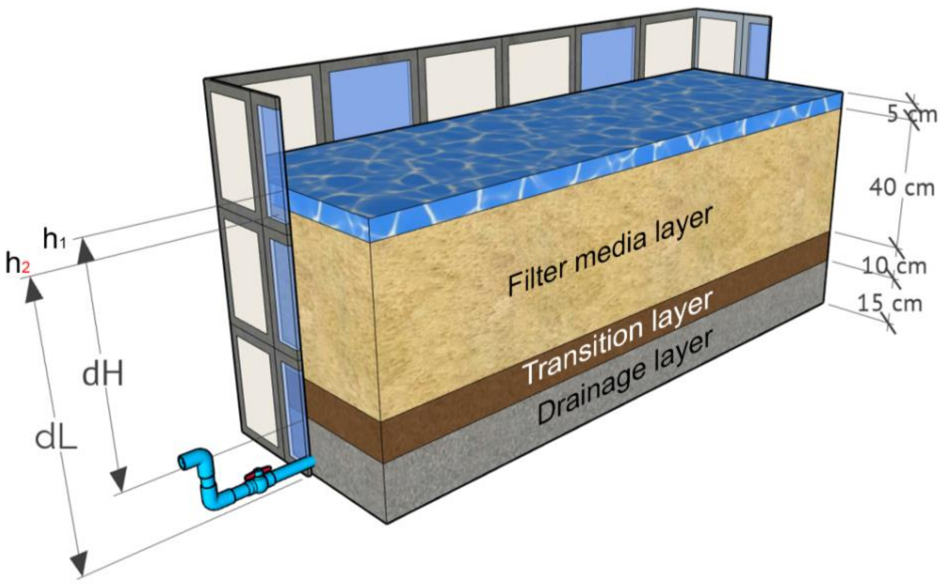
- The water outlet was opened and water was poured in until it overflowed through the outlet.
- The outlet pipe was then sealed, and the mesocosm was filled further with water to establish a constant ponding depth of 5 cm above the surface of the filter media layer. This water level represented the initial head (h1) for the test.
- The outlet pipe was reopened, and a stopwatch was started simultaneously. The time (t) it took for the water level to fall from (h1) (the 5 cm ponding depth) to the surface of the filter media layer was precisely recorded. This level represented the final head (h2).
- The total volume of water (V) that drained from the outlet during this time interval (t) was collected and measured.

To ensure the reliability of the results and the stability of the media (analogous to reaching steady-state conditions), the test cycle (defined by Steps 2-4) was repeated five times. This protocol aligns with standard hydrological studies involving LID facilities, which emphasize multiple repetitions to manage measurement uncertainty and ensure the representativeness of results (Zhang et al., 2022).

Following the assessment of the K_s value within the mesocosm, reflecting simulated bioretention conditions with and without vegetation cover, the acquired data were subsequently incorporated into the Darcy's Law equation for the computation of K_s, as depicted in Eq. 2 (Neuman, 1977). The subsequent section elaborates upon the experimentation's outcomes, providing valuable insights for urban green space designers.

Figure 5

Schematic Diagram of the Bioretention Mesocosm Setup



Note. This figure demonstrates the layered media and key hydraulic variables. The author created this figure.

Statistical Analysis

Statistical analysis was performed using an independent t-test. Statistical significance was set at $p<0.05$, with results reported as means ± standard error (SE). All statistical analyses were performed using Statistix software (version 10.0, Analytical Software, Tallahassee, FL, USA). Data visualization and graphical representations were generated using SigmaPlot (version 15.0, Systat Software Inc., San Jose, CA, USA).

RESULTS

The findings of the bioretention mesocosm study are presented in this section, focusing on the measured K_s for the two experimental conditions, with and without vegetation. Results are reported with full numerical precision and statistical validation to demonstrate the empirical contribution of the study.

Experimental Evaluation of K_s

The mesocosm tests were performed using six independent units: three vegetated units and three unvegetated units, each containing a layered profile of filter media (400 mm), transition (100 mm), and drainage (150 mm). Hydraulic characterization was assessed across five short-duration test rounds for both treatments (Table 2 and Figure 6), confirming the stability of the measurements. Table 3 summarizes the overall mean K_s (mean ± SE) for the vegetated and unvegetated mesocosms, which are the primary values utilized for statistical analysis and comparison to optimal design standards.

The K_s values for both treatments were stable across the five test rounds. The mesocosms with vegetation consistently exhibited a higher K_s than the unvegetated units. The overall mean K_s for the vegetated treatment was 306.57 ± 4.58 mm h^{-1} (mean ± SE, n=3 mesocosm means), which was 18.55% higher than the mean K_s for the unvegetated units, 258.61 ± 4.98 mm h^{-1}. An independent t-test performed on the mesocosm means confirmed that the difference in K_s between the vegetated and unvegetated units was highly significant ($p < 0.001$). This finding provides robust empirical evidence that the presence of vegetation substantially enhances the infiltration capacity of the bioretention media.

Table 2

Mean ± SD (Standard Deviation) (n=3) of Test R Results for K_s

Variable	Round 1	Round 2	Round 3	Round 4	Round 5
K_s (unvegetated units) (mm h^{-1})	256.20 ± 5.54	257.60 ± 3.82	260.37 ± 4.26	258.50 ± 5.65	260.37 ± 5.65
K_s (vegetated units) (mm h^{-1})	310.27 ± 2.15	307.07 ± 4.16	302.73 ± 2.59	303.90 ± 7.51	308.87 ± 6.50
P-value	***	***	***	**	**

Note. This table demonstrates the notable disparities found in K_s values between the vegetated and non-vegetated bioretention designs. **, *** differ significantly at 0.01, and 0.001, respectively.

Table 3

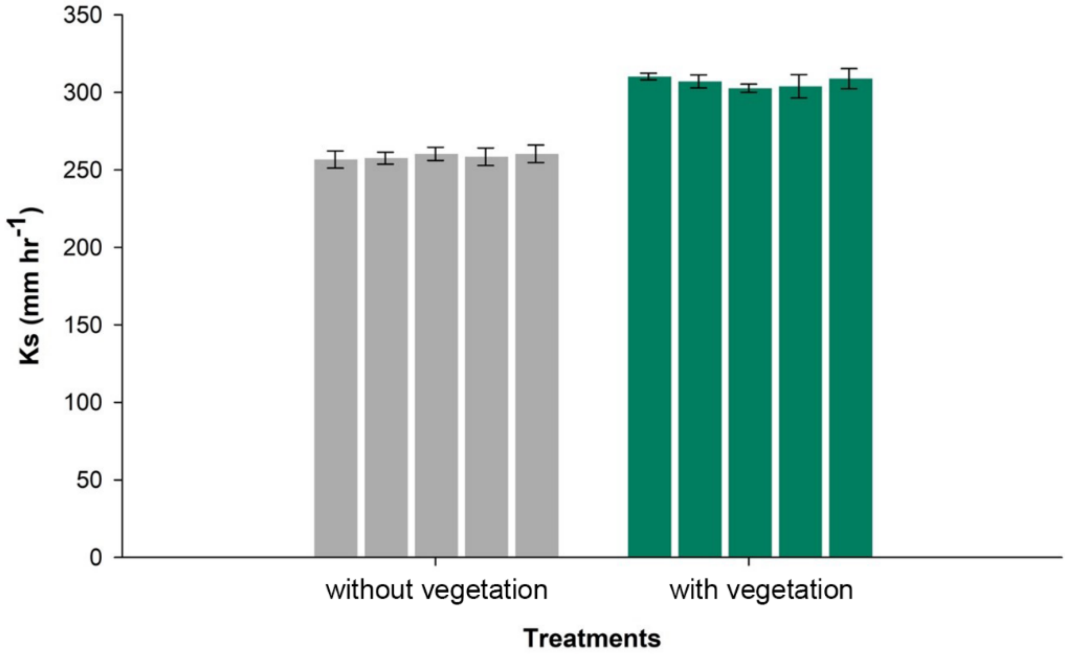
K_s (mean ± SE) for Vegetated and Unvegetated Units

Treatment	K_s (mm h^{-1}) mean ± SE (n=3)	% change vs non-vegetated
Unvegetated units	258.61 ± 4.98	—
Vegetated units	306.57 ± 4.58	+18.55

Note. n = 3 mesocosm means per treatment.

Figure 6

Comparison of K_s Values on Vegetated and Unvegetated Units



Note. This figure demonstrates the mean K_s values, highlighting the difference between vegetated and non-vegetated bioretention systems. The author created this figure.

Comparison of Optimal Standards

The empirically derived K_s value for the vegetated system (306.57 mm h^{-1}) falls within the internationally recognized optimal range of 100 to 300 mm h^{-1} for bioretention filter media, as specified by guidelines such as Melbourne Water (2020). Although slightly exceeding the upper limit, this result indicates that locally available coarse construction sand, when paired with vegetated units, is a suitable and high-performing filter media for tropical climates like Thailand, a finding crucial for promoting cost-effective, local Water-Sensitive Urban Design (WSUD) implementation.

The presented empirical data, demonstrating a highly significant 18.55% increase in K_s associated with vegetated units, fulfills the primary objective of this study. The following section moves beyond the statistical validation of these results to offer an in-depth interpretation. This discussion will focus on three critical and interrelated areas of the practical implications of substituting these localized K_s parameters into hydrological modeling (SWMM), as shown through a targeted sensitivity analysis, the resulting policy and design relevance for future bioretention implementation in the tropical context of Thailand, and the bio-physical mechanisms responsible for the observed hydraulic enhancement.

DISCUSSION

Empirical K_s and Model Sensitivity

Accurate parameterization is essential for urban hydrological models such as SWMM (Amerinia, 2023), where soil/infiltration parameters (including K_s) directly influence simulated runoff volumes and peak flows. While default K_s values are commonly used, our mesocosm measurements provide empirically validated parameters that reflect the unique local materials and conditions in Thailand. The mesocosm approach allows for controlled hydraulic characterization necessary for accurate modeling (Zhang et al., 2022). Obtaining localized, empirically validated K_s values is crucial for WSUD spatial prioritization and flood mitigation planning (Wu et al., 2023). The measured K_s values 258.61 mm h^{-1} for the unvegetated units and 306.57 mm h^{-1} for the vegetated units demonstrate an approximate 18.55% increase in K_s associated with vegetated units.

This difference in K_s is not merely a statistical figure: It materially affects catchment-scale runoff predictions, depending on storm intensity. To make the practical consequences of this localized data explicit, we provide a sensitivity example in Section 4.2 that substitutes the measured K_s values into a representative SWMM scenario and quantifies changes in total runoff and peak flow. This approach demonstrates how the inclusion of site-specific K_s data, rather than generalized values, can alter modeling outcomes and thus inform more reliable stormwater infrastructure sizing and management decisions (Funai & Kupec, 2017). Mesocosm experiments yielded critical insights by measuring the K_s of common construction sand in Thai bioretention systems under controlled and vegetated conditions (Farina et al., 2023). Integrating these precise, localized K_s values into large-scale urban drainage SWMM simulations significantly enhances model accuracy, leading to precise predictions of runoff, peak flows, and flood areas.

Sensitivity Analysis and Implications for SWMM Calibration

To explicitly demonstrate the practical consequences of substituting empirically derived K_s values into hydrological models, we conducted a sensitivity analysis using a representative SWMM scenario. The objective was to quantify how an 18.55% difference in K_s (from 258.61 mm h^{-1} to 306.57 mm h^{-1}) affects modeled runoff under varying rainfall conditions (Hao et al., 2019). For this analysis, results are shown for a representative 1.0 ha catchment (30% impervious, 70% pervious) subjected to 100 mm total rainfall. The bioretention geometry used was 400 mm filter media, 100 mm transition and 150 mm drainage layer (the total available unsaturated storage within the soil media layers was calculated as S_avail = 127 mm). The analysis simulated two key parameters related to soil moisture: suction head (Ψ = 30 mm), which represents the negative pressure required to draw water into the initially unsaturated soil, and initial volumetric moisture (θi = 0.15), representing the volume of water present in the soil media before the storm begins. These values are based on established literature for coarse sand media and are assumed for this scenario to assess the impact of K_s variability under typical bioretention conditions. The two storm scenarios simulated were a long storm (T=2.00 h) and a short, intense storm (T=0.25 h, 15 minutes).

To illustrate the conditional sensitivity of modeled runoff to localized K_s, we compare a simple $K_s \times T$ estimate with Green-Ampt solutions using the mesocosm-derived K_s values. These comparisons show when the use of a physically based infiltration formulation (Green-Ampt) changes runoff estimates relative to the simple $K_s \times T$ assumption.

As detailed in Table 4 (long storm), the simulation showed that the difference in K_s had a negligible effect on total runoff volume when the infiltration capacity comfortably exceeded the rainfall intensity and duration. This confirms that for long-duration, low-intensity rainfall events, media storage capacity and total infiltration time become the dominant factors, diminishing the relative impact of small K_s variations. Conversely, the results for the short, intense storm (Table 5) revealed a meaningful change in total runoff volume and peak flow. In this critical scenario, an 18.55% increase in K_s significantly reduced the total surface runoff. These findings highlight that for short-duration, high-intensity events, which are characteristic of tropical urban flash flooding, utilizing localized, vegetation-enhanced K_s data is crucial for accurately predicting drainage performance and avoiding the underestimation of flood mitigation benefits.

Integrating these precise, localized K_s values into large-scale urban drainage SWMM simulations offers several advantages (Shi et al., 2021). Replacing generic K_s values with field measurements significantly enhances SWMM accuracy, leading to precise predictions of runoff, peak flows, and flood areas. This facilitates optimal stormwater infrastructure sizing, prevents costly designs, and maximizes bioretention efficiency. Moreover, reliable model outputs, driven by accurate K_s data, support evidence-based policy, guiding urban development and sustainable infrastructure (Bibi & Kara, 2023; Wang et al., 2020). The practical value of this approach is further illustrated by applying the findings to a case study in Chiang Mai (Sittisom et al., 2022).

Case Study in Chiang Mai Rainfall

Rainfall data recorded at the Thai Meteorological Department (TMD) station in Chiang Mai (18°46′14.8″ N, 98°58′06.56″ E) during January–December 2024 show a distinct monsoonal pattern with an annual total rainfall of 1,129.2 mm. The monthly rainfall totals (Figure 7) reveal two contrasting climatic periods:

- Dry season (November-April): minimal rainfall, with monthly totals below 15 mm except for March (13.2 mm).
- Wet season (May-October): dominant rainfall period, contributing to approximately 93 % of the annual total.

Table 4

Simulated Runoff Sensitivity to K_s Under Long-duration Rainfall (T = 2.00 h)

Method	K_s (mm h^{-1})	Cumulative infiltration (mm)	Catchment runoff depth (mm)	Volume (m^3)
Simple	258.61	127 (capped)	30.00	300.00
Green-Ampt	258.61	127 (capped)	30.00	300.00
Simple	306.57	127 (capped)	30.00	300.00
Green-Ampt	306.57	127 (capped)	30.00	300.00

Note. Results for a 2.00 h storm (100 mm). Simple method uses K_s×T (capped by S_avail = 127 mm). Green-Ampt results obtained by solving the Green-Ampt equation (Ψ = 30 mm, θi = 0.15) and capping infiltration at S_avail where applicable.

Table 5

Simulated Runoff Sensitivity to K_s Under Short-Duration Rainfall (T = 0.25 h)

Method	K_s (mm h^{-1})	Cumulative infiltration (mm)	Catchment runoff depth (mm)	Volume (m^3)	% change vs simple
Simple	258.61	64.65	54.74	547.43	--
Green-Ampt	258.61	50.16	64.89	648.88	+18.5%
Simple	306.57	76.64	46.35	463.50	--
Green-Ampt	306.57	60.83	57.42	547.19	+23.9%

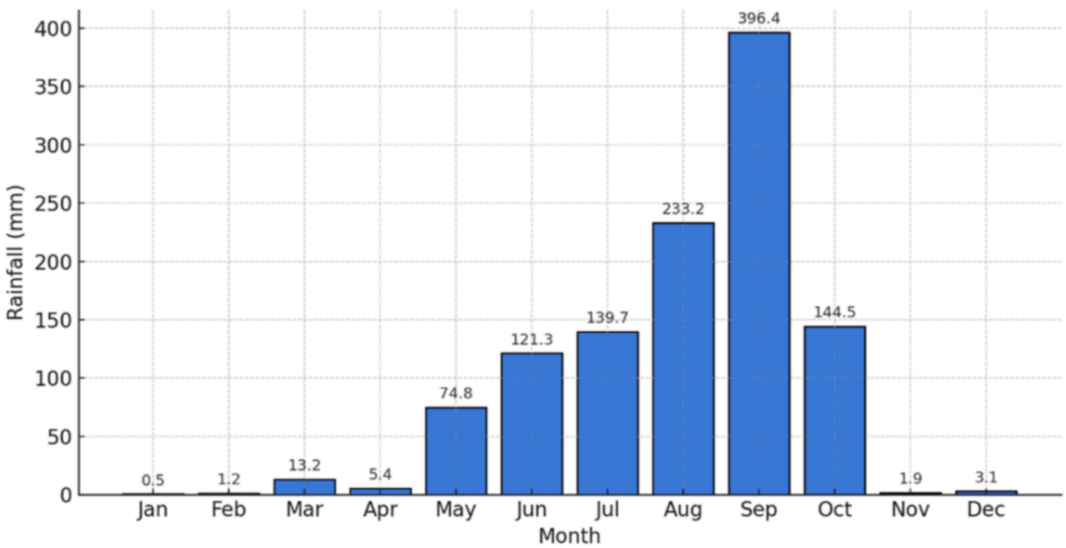
Note. Results for a 0.25 h storm (100 mm). % change = (Volume_Green-Ampt – Volume_Simple) / Volume_Simple × 100. The simple approach (K_s×T) assumes constant K_s throughout the event; Green-Ampt includes suction and antecedent moisture effects, reducing early infiltration and increasing runoff for short, intense events.

- Peak monthly rainfall occurred in September (396.4 mm), followed by August (233.2 mm) and October (144.5 mm) (Kritsanaphan et al., 2021) This seasonal variation typifies the tropical savanna climate, governed by the southwest monsoon system transporting moist air from the Indian Ocean into northern Thailand. Hourly rainfall analysis indicates short-duration, high-intensity convective storms, with a maximum hourly intensity of 39.1 mm h^{-1} and an average of 0.39 mm h^{-1}, demonstrating strong temporal variability. Diurnal analysis (Figure 8) shows that the most frequent and intense rainfall events occur between 01:00–04:00 and 19:00–22:00, consistent with nocturnal convection and mountain valley wind interactions in the Chiang Mai basin (Kritsanaphan et al., 2021). Cumulative rainfall trends (Figure 9) highlight monsoon onset around late May, rapid accumulation from June to September, and stabilization after October, signaling the transition to the dry season (Shrestha et al., 2014).

Hourly rainfall data were processed to develop the Intensity–Duration–Frequency (IDF) relationship for Chiang Mai using maximum moving averages for durations of 1, 2, 3, 6, 12, and 24 hours. Results (Figure 10) reveal that short-duration convective storms (1–3 h) generate the highest intensities (45–65 mm h^{-1}), whereas long-duration monsoon events (> 6 h) decline below 25 mm h^{-1} (Thai Meteorological Department, 2024). This behavior reflects the tropical monsoon rainfall pattern characteristic of northern Thailand.

Figure 7

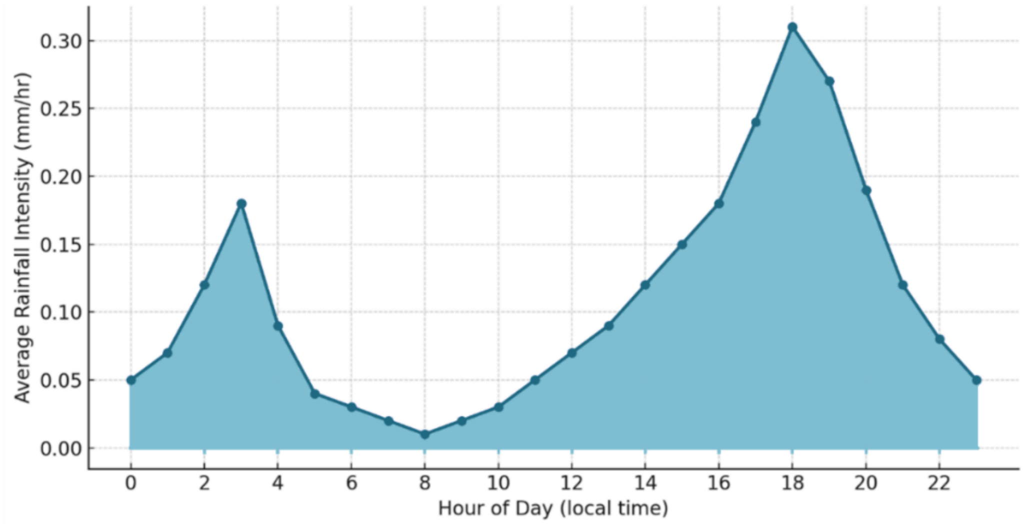
Monthly Rainfall Distribution, Chiang Mai (2024)



Note. Adapted from *Climatological data of Thailand: Monthly rainfall*, by Thai Meteorological Department, 2024, Thai Meteorological Department (https://www.tmd.go.th/). Copyright 2024 by Thai Meteorological Department.

Figure 8

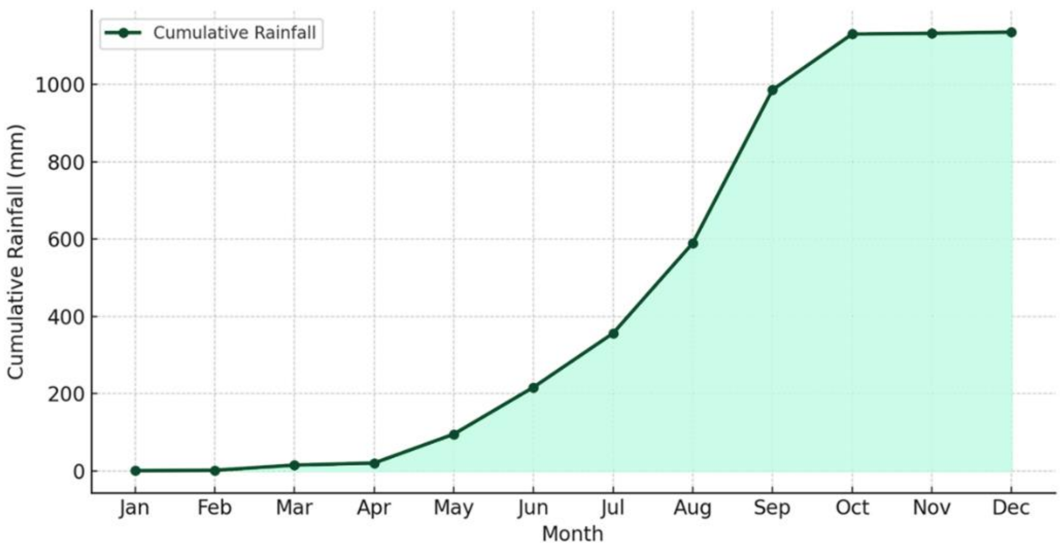
Diurnal Rainfall Distribution, Chiang Mai (2024)



Note. Adapted from *Climatological data of Thailand: Monthly rainfall*, by Thai Meteorological Department, 2024, Thai Meteorological Department (https://www.tmd.go.th/). Copyright 2024 by Thai Meteorological Department.

Figure 9

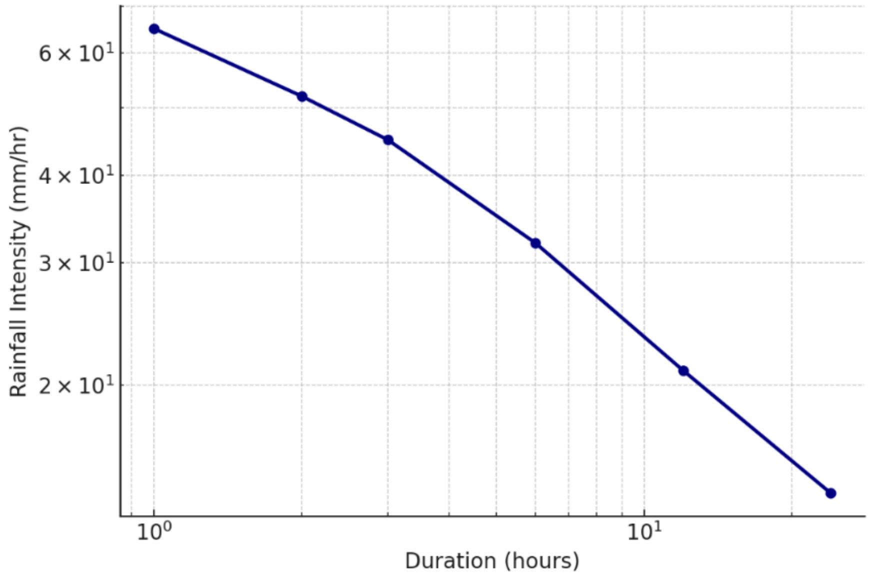
Cumulative Rainfall Trends, Chiang Mai (2024)



Note. Adapted from *Climatological data of Thailand: Monthly rainfall*, by Thai Meteorological Department, 2024, Thai Meteorological Department (https://www.tmd.go.th/). Copyright 2024 by Thai Meteorological Department.

Figure 10

IDF Curve, Chiang Mai (2024).



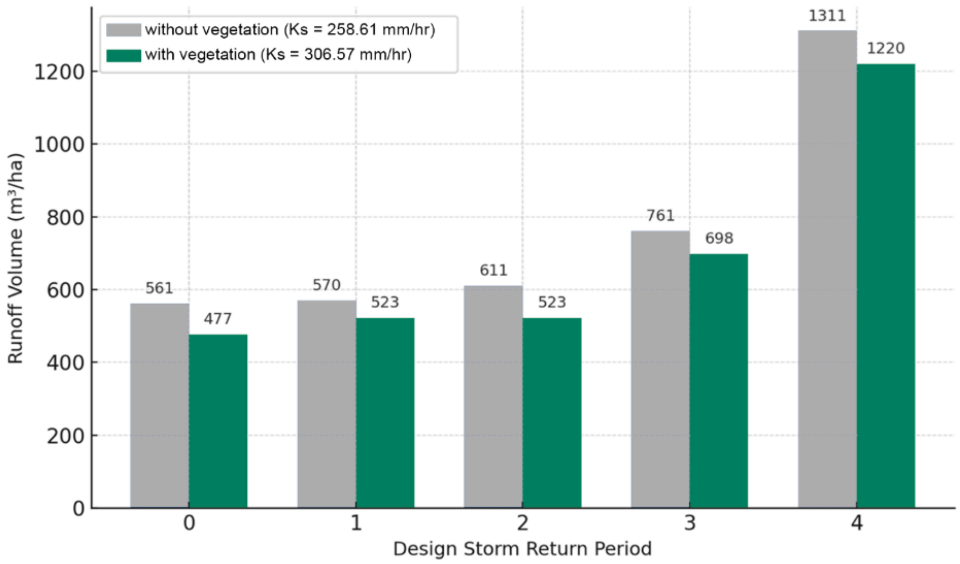
Note. Adapted from *Climatological data of Thailand: Monthly rainfall*, by Thai Meteorological Department, 2024, Thai Meteorological Department (https://www.tmd.go.th/). Copyright 2024 by Thai Meteorological Department.

The simulation results clearly demonstrate that an increase in the K_s, induced by vegetation growth and the formation of root-zone macropores, markedly enhances the infiltration performance of the bioretention system and consequently reduces surface runoff (Hatt et al., 2009). Under the updated scenarios, the runoff volume decreased from 561 $m^3\ ha^{-1}$ for the unvegetated condition (K_s = 258.61 mm h^{-1}) to 477 $m^3\ ha^{-1}$ for the vegetated condition (K_s = 306.57 mm h^{-1}) for the 2-year design storm, representing an overall reduction of approximately 15%. A maximum reduction of nearly 30% was observed for the 5-year return period, during which infiltration processes exerted dominant control over the hydrological response (Rossman & Huber, 2016).

As the return period and storm magnitude increase, the difference between the two K_s scenarios progressively diminishes, declining to approximately 7% for the 50-year storm event. This attenuation effect reflects the gradual saturation of the infiltration capacity, beyond which additional rainfall is primarily converted into direct surface flow (Rossman & Huber, 2016; Sinsabvarodom et al., 2025). The comparative trend illustrated in Figure 11 emphasizes that vegetation-induced enhancement of K_s is most effective for moderate, high-frequency storm events, thereby contributing significantly to the reduction of peak runoff volumes. These findings underscore the critical role of vegetation in improving the hydraulic performance of bioretention media under tropical monsoonal climates. Incorporating locally derived K_s values into hydrological modeling frameworks such as SWMM provides a robust, site-specific basis for optimizing the design and performance evaluation of sustainable urban drainage systems in northern Thailand (Sinsabvarodom et al., 2025).

Figure 11

Runoff Sensitivity under Chiang Mai (2024) Rainfall Conditions



Note. This figure illustrates the simulated runoff volumes derived from the Chiang Mai 2024 design storms. The author created this figure.

As illustrated in Figure 11, the simulated runoff volumes derived from the Chiang Mai 2024 design storms were evaluated for two infiltration capacities representing distinct field conditions, corresponding to the K_s values obtained from Tables 2 and 3. The unvegetated scenario exhibited slightly higher runoff volumes compared to the vegetated condition, owing to its lower saturated hydraulic conductivity and reduced infiltration potential.

We therefore recommend the mandatory inclusion of site-specific, empirical K_s in SWMM calibrations for bioretention designs in Thailand, along with targeted sensitivity tests using representative local hyetographs to quantify and manage uncertainty in runoff volume and peak flow (Kanso et al., 2018). This step is vital for transitioning from generalized assumptions to data-driven water management planning and policy.

The Role of Vegetation in Enhancing K_s

Our empirical K_s estimates therefore address a key input uncertainty relevant to model calibration and scenario analysis for Thai urban catchments (Knighton et al., 2016; Niazi et al., 2017; Yue & Gao, 2025). The significant empirical difference highlights that vegetation, such as *Ruellia simplex* C.Wright, substantially improves the K_s of the filter media. This improvement is likely attributable to the various ways plant roots modify soil structure (Shi et al., 2021), including creating macropores, enhancing aggregate stability, and adding organic matter, all of which facilitate water infiltration (Lu et al., 2020). The dense root systems physically infiltrate the soil matrix, forming an intricate network of interconnected channels (macropores) that serve as preferential pathways for water flow, significantly bypassing the slower matrix flow (Nur Hannah Ismail et al., 2023). This bio-physical interaction not only increases the initial infiltration capacity but also contributes to the long-term sustainability and resilience of bioretention systems (Skorobogatov et al., 2020), making them more robust against clogging and compaction. This finding supports the creation of urban green spaces that both mitigate stormwater runoff and enhance local hydrology (Zhou et al., 2008).

Effective integration necessitates strategic initiatives: developing GIS databases of urban soil types with measured K_s, continuing targeted field/lab studies for broader soil/media, fostering researcher-planner collaboration, and creating accessible public data repositories (Chen et al., 2025; Reyes et al., 2024; Tresch et al., 2018; Wilby, 2019). Ultimately, moving beyond generic parameters for effective, resilient urban stormwater management is crucial, emphasizing localized K_s for improved bioretention design and SWMM accuracy.

The most significant contribution of this study lies in addressing a critical input uncertainty for hydrological modeling. The provision of empirically derived K_s parameters is vital for improving the predictive accuracy and reliability of models like SWMM, enabling urban planners to move beyond generalized assumptions toward data-driven, sustainable solutions. Integrating this localized data, particularly the sensitivity analysis results, supports better stormwater infrastructure sizing and management decisions against the increasing challenges of climate change and rapid urbanization in Thailand. This strategic shift facilitates the creation of urban spaces that not only mitigate stormwater runoff but also enhances local hydrology, leading to more resilient and water-sensitive cities.

CONCLUSION

This study conclusively demonstrates that the integration of vegetation, specifically *Ruellia simplex* C.Wright, into the bioretention media substantially improves the saturated hydraulic conductivity (K_s) of the filter media. The mesocosm results provide robust empirical evidence, showing an approximate 18.55% increase in K_s in vegetated systems compared to unvegetated ones. This significant difference confirms the bio-physical role of root systems in enhancing water infiltration. By utilizing common Thai construction sand, this research provides crucial, localized K_s data for materials available in Thailand, directly informing the design of cost-effective and resilient green infrastructure in the tropical urban context.

It is important to acknowledge the limitations of this study for balance and transparency. The research utilized only one specific plant species (*Ruellia simplex* C.Wright), tested a single type of coarse sand media, and featured limited replication at the mesocosm scale. These factors suggest that the values derived for K_s are context-specific, and caution should be exercised in broad generalizations. We recommend that future research address these limitations by exploring a wider array of plant species, root characteristics, and media types to validate and generalize these findings across diverse tropical urban settings.

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