Nakhara: Journal of Environmental Design and Planning (2022)
Volume 21(3), Article 228
DOI: https://doi.org/10.54028/NJ202221228
Article Type: Research Article

The Determination of Soil Infiltration Rate of Urban Bioretention Design Process in Chiang Mai, Thailand

Prattakorn Sittisom[1], Rapee Tangsongsuwan[2], Sikarint Munlikawong[1], Wongkot Wongsapai[1], Sitthikorn Sitthikankun[1], Damrongsak Rinchumphu[1,*]

[1] Faculty of Engineering, Chiang Mai University, Thailand
[2] Department of Highways, Thailand

* Corresponding e-mail: damrongsak.r@cmu.ac.th

Received 2022-12-03; Revised 2022-12-14; Accepted 2022-12-15

ABSTRACT

Stormwater runoff is an issue that is increasingly affecting urban areas because areas that previously were permeable have been developed, and are now impermeable, comprising hard surface areas, whether concrete floors, roads, or buildings. As the size of the problem area increases, the amount of stormwater runoff that needs to be cleared from urban areas increases, and it takes longer for the stormwater to be cleared. The existing basic public drainage systems can no longer sufficiently support the increasing stormwater runoff, directly affecting commuting and lifestyle. These problems have led to the design concept of bioretention, which can be used to increase the efficiency of water infiltration of existing soil areas since a higher water infiltration rate can help relieve the burden on the basic public drainage system and alleviate the abovementioned problems. Bioretention design consists of three layers: the drainage layer at the bottom, the transition layer, and the filter media layer at the top. The critical objective is to design the filter media layer (the top layer) to have a greater infiltration rate than the original soil. This research, therefore, comprises an experiment in which sand is mixed with the original soil to achieve these increased infiltration rates. Three different soil-to-sand ratios were field tested within the area of the Faculty of Engineering, Chiang Mai University, Chiang Mai, Thailand with double-ring infiltrometer technique to test the infiltration rate, 1:1, 1:2, and 1:4. This research also applied Horton's Theory of Perforation Prediction Equations; the experiments demonstrated that adding sand can increase the water infiltration rate. The infiltration rates for soil-to-sand ratios of 1:1, 1:2, and 1:3 are 16.09, 21.53, and 28.90 mm/hr., consecutively.

In addition, understanding the relationship between infiltration rate and sand ratio makes it possible to determine the permeation rate as required. Furthermore, knowing the sand ratio is useful for future planning to achieve the appropriate design.

Keywords: bioretention, filter media layer, infiltration, double-ring infiltrometer, Horton theory, water sensitive urban design

INTRODUCTION

Growing populations continue to force the expansion of urban areas, and urban communities need to effectively develop the newly built or rebuilt areas in a sustainable way. One key issue is that construction related to urban expansion, whether it is a residential housing project, commercial building, department store, or thoroughfare, creates a change in the surface permeable water area; it becomes an impermeable water area, resulting in increased stormwater runoff. In addition, because the existing drains in a given urban area were initially designed for different circumstances, they are no longer sufficient for increased runoff, causing flooding problems with rainwater waiting too long to be drained away. These problems directly affect the lives of people living and traveling in the affected areas (Meng et al., 2022; Teang et al., 2021). Slow drainage and resulting flooding cause traffic congestion, and some routes cannot be traveled for several hours (7HD Online, 2022; Thairath Online, 2022). The stormwater runoff issues in Muang District, Chiang Mai Province, have begun to have noticeable adverse effects; however, the burden on public sewers can be alleviated through the use of water-sensitive urban design (WSUD) or low-impact development (LID), which can increase the potential of existing soil surface areas to have increased water infiltration rates. This type of design consists of techniques such as bioretention, continuous permeable pavement systems, green roofs, infiltration trenches, rain barrels or cisterns (rainwater harvesting), rain gardens, rooftop (downspout) disconnection, and vegetative swales (Iftekhar & Pannell, 2022; Liu et al., 2022; Meng et al., 2022; United States Environmental Protection Agency, 2022). However, bioretention is a suitable and popular technique for enhancing soil surface capacity for stormwater runoff in urban areas (Lisenbee et al., 2022; Osman et al., 2019; Wang et al., 2019).

Bioretention is designed to increase the rate of infiltration of the soil surface. The system consists of 3 main layers: (1) filter media layer, (2) transition layer, and (3) drainage layer. The performance indicator is the increased infiltration rate of the entire system (Senior Stormwater Quality Technical Advisor, 2020), which needs to improve the water infiltration rate so that it is significantly greater than the original soil. The most common way to increase porosity is to mix sand into the soil; this relatively simple primary method can increase the water infiltration rate of the soil.

To ensure that the bioretention design is effective, the optimum ratio of soil to sand needs to be identified in order to increase the infiltration rate appropriately. Furthermore, increasing the amount of sand in the soil often increases costs. Therefore, this study created a simulated study area within the Faculty of Engineering, Chiang Mai University, to compare the water infiltration rate of soil mixed with sand at ratios 1:1, 1:2, and 1:4 to prove the relationship between soil-to-sand ratio and infiltration rate. The objective is to test different mixing ratios against water infiltration rates, and use the most suitable value as a standard for designing water management areas in urban communities.

LITERATURE REVIEW

This literature review helps to clarify the fundamental theories comprising WSUD and LID. The key topics in the literature review are (1) hydrology principles and stormwater runoff (2) bioretention design (3) infiltration and the double-ring infiltration technique, and (4) a summary of the literature review.

Hydrology principles and stormwater runoff

The hydrologic cycle is the continuous circulation of water on Earth. It has no beginning or end; therefore, the order of occurrence cannot be determined. Nevertheless, the discussion of the cycle will begin with precipitation, which is the phenomenon in which water falls from the sky under the influence of Earth’s gravity. Be it rain, sleet, or snow, the precipitation will fall to the surface of land or ocean, with some residues in buildings and trees (interception). When the amount of water falling is greater than the infiltration rate on the soil surface (overland flow), then surface water flows from high areas to low areas, and eventually to a river (surface runoff). Part of the water that infiltrates into the soil (infiltration) will flow into the river (interflow); the other part has deeper penetration and accumulates in the aquifer layer until it becomes groundwater (groundwater) which can flow and eventually converge into rivers and the sea. Earth's water receives thermal energy from the sun and evaporates into the atmosphere (evaporation and transpiration). The steam in the atmosphere collects, forms clouds, and becomes precipitation again, completing the water cycle, and creating hydrologic balance (hydrologic balance). To expand on the relationship between rainfall, surface runoff, groundwater volume, the rate of water evaporation on the surface of the soil, plant transpiration rate, water infiltration rate, and the rate of change of water storage by considering any area as an open system (Rinchumphu & Anambutr, 2017), the water balance equation can be written as in equation (1)

$$P = Q + G + E + T + I + S \qquad (1)$$

where P is rainfall, Q is surface runoff, G is underground water change, E is surface water evaporation, T is plant transpiration, and S is changed to water on the soil surface.

The key to bioretention design is precise rainfall estimation, but rainfall cannot be accurately predicted due to the fact that meteorological conditions change constantly and are different every year. Instead, the careful collection of statistical data on rainfall is necessary for estimating stormwater runoff, with the goal being to achieve the most accurate forecast possible.

The most important consideration in the development of potential filter media is the infiltration rate, as the goal of bioretention design is for the water filtration to be more efficient than it was before.

Bioretention Design

Bioretention appears in many standards used in the design of catchment areas, especially in foreign countries. For example, the concept is discussed in Singapore's *Active, Beautiful, Clean (ABC) Waters Design Guidelines* (Public Utilities Board [PUB], 2014), as well as in *Low Impact Development: Technical Guidance Manual*, which is used by many cities in the United States (Puget Sound Action Team, 2005). In presenting this section, two subcategories of the bioretention concept are discussed: 1) the working principles and benefits (concept and benefit) of bioretention, and 2) essential elements of design (specification) associated with stormwater runoff.

Working principle and benefits of bioretention

Areas with more significant water infiltration potential through bioretention are usually placed in low areas to make use of natural water flow. These areas have the primary function of slowing down the water. A bioretention area also acts as a temporary water collection point (in the case of a basin); it often looks like a garden or a typical lawn on the outside, but underground, there is a layer of soil designed to enhance the infiltration rate of that area.

Bioretention can be integrated into the overall design of a project development area. For example, bioretention areas can be placed on the side of the road or car park or integrated into the design of a garden or city park. In addition to reducing stormwater runoff and increasing the efficiency of water clearance, the infiltration rate of the area may enhance the project's aesthetics (Franti & Rodie, 2007).

Important elements of design

Effective bioretention design depends on the detailed design across the subsoil layer (cross-section) and detailing the properties of materials – the equipment of each layer (specifications). In searching for documents related to bioretention design, a number of academic documents and work manuals from various sources were found. The contents of each are similar; however, an easy-to-understand and complete example of the design is shown in the *Biofiltration systems in Development Services Schemes Guideline* (Senior Stormwater Quality Technical Advisor, 2020). The components of each layer can be described as follows.

a. Filter Media Layer

As the first layer of bioretention, the filter media layer plays an essential role in the total permeability of the system. The *Biofiltration Systems in Development Services Schemes Guideline* recommends a depth of 300 to 600 mm, designed to increase the porosity of this soil layer, which can use a variety of mixtures. Generally, gravel or coarse sand (sand) is chosen for this layer because, in addition to being a layer that drains well, it must be strong enough to support the weight and pressure from the activities above. In general, the properties of the absorbent layer are determined to be porosity and strength (Auckland Council, 2018; Puget Sound Action Team, 2005; Senior Stormwater Quality Technical Advisor, 2020).

b. Transition Layer

Coarse sand is commonly used as a layered material according to the development guidelines for biofiltration systems. This layer acts as a squeezer to prevent the soil of the filter media layer from moving down and mixing with the material in the drainage layer. In addition, the *Services Schemes Guideline* recommends well-graded coarse sand containing <2% fines such as A2 filter sand as a material for this class (Senior Stormwater Quality Technical Advisor, 2020).

c. Drainage Layer

This layer is the last water-receiving layer. Generally, gravel is used as a material, so water can accumulate within this layer for some time and seep into the soil naturally. The *Biofiltration Systems in Development Services Schemes Guideline* recommends fine gravel material such as 2-7mm washed screenings (not scoria). There is also an under-drainage pipe draining excess water into public waterways.

Bioretention design guidelines aim to improve the ability to receive stormwater runoff compared to the original soil. One of the essential steps in this process of designing areas for water management in urban areas is to calculate the volume of water that the area can manage. Initially, this can be divided into two approaches: (1) measuring stormwater runoff (runoff water: Q, whose unit is the volume per period), or (2) measuring the water infiltration (infiltration, I, which is generally expressed in units of the height of water per period). Both Q and I are related to rainfall values (precipitation: P generally has units of water height) and storage charge (storage: S, which may be divided into device storage, can be measured directly as the volume of the storage pan; the other part is stored on the soil surface; it may be included with the part of the infiltration into the soil surface (I)).

This section presents the theory of calculating various values, including standard methods for calculating the infiltration value. In addition, there are rational methods (RM) and curve number (CN) methods for measuring the rainfall (or runoff) of rainwater in any area, and the determination of water infiltration by double-ring infiltration techniques. However, the rational method (RM) and curve number (CN) methods have both been found to have initial limitations. Although RM is commonly used these days, both methods rely on the area flow coefficient, a constant obtained from experimentation. However, there are limitations in that the variety of flow coefficients does not cover the bioretention design scheme. While there is evidence to demonstrate the use of the CN method for calculating bioretention infiltration for urban areas, there needs to be more data showing a correlation between different coefficients corresponding to such patterns. Therefore, field research is required to compare actual infiltration values with the design model. There has yet to be such an experiment in Thailand; the application of double-ring infiltration techniques is a suitable choice for measuring the infiltration rates in this research and is detailed in the next section.

Infiltration and Double-ring Infiltration Technique

Infiltration Calculation Concept

Water moves through gaps in the soil into the subsurface, and the water from infiltration collects as moisture in the soil (soil moisture); some of it moves according to the gravity of the Earth deep (deep seepage or percolation), accumulating as groundwater. The amount of water infiltration depends on the intensity of the rain (rainfall intensity), temperature, soil physical characteristics, types of cover crops, land use characteristics, initial soil moisture content, and groundwater level. Therefore, each area will have different infiltration characteristics (Ahammed et al., 2021).

Horton's theory calculates the amount of permeable water in the soil (Wang et al., 2017) and measures the rate of infiltration of bioretention, which can be written as equation (2)

$$f_t = f_c + (f_0 - f_c)e^{-kt} \qquad (2)$$

Where,

f_t is the infiltration rate (millimeters per hour: mm./hr.)

f_c is a constant infiltration rate (millimeters per hour: mm./hr.)

f_0 is the initial infiltration rate (millimeters per hour: mm./hr.)

k is a constant showing a decrease in the soil infiltration rate

The review indicated that the infiltration rate of each type of basic soil texture was consistent with the preliminary idea that more porous soil texture affected the infiltration rate and resulted in higher permeability. The permeation rate is shown in Table 1.

However, following Horton's theory, another measure of the infiltration rate for soil design has been developed that uses an instrument called a double-ring infiltrometer (Abdelmoneim et al., 2021; Bodhinayake et al., 2004; Raju & Hussain, 2019), which is discussed in the next section.

Double-ring Infiltrometer Technique

Based on a review of the surface water flow analysis model, it was found that there are still limitations to using secondary and standard data when specific data for Thailand or a given area may be required instead. In searching for a way to deal with this limitation, it was found that determining the infiltration rate value can be used effectively to determine the design potential based on urban catchment management principles. One of the processes used to determine soil infiltration is double-ring infiltrometer techniques, using test methods according to ASTM D 3385-03, as illustrated in Figure 1.

This technique can be applied in conjunction with the permeability prediction equation. Many theories, such as the Horton theory, have been proposed since the 1940s (Ahammed et al., 2021; Geberemariam, 2019); Equation (2) shows the characteristics of the infiltration rate per change of time, as shown in Figure 2.

Table 1

Infiltration Rates of Soil Texture Type

Soil textures	Infiltration rate (mm./hr.)
Gravel and coarse sands	> 20
Sandy loams	10 – 20
Loams	5 – 10
Silty clay loams & clay soils	< 5

Note. Adapted from Minnesota Pollution Control Agency (2022) and Northeast Region Certified Crop Adviser (NRCCA) (2010)

Figure 1

Double-Ring Infiltration Techniques

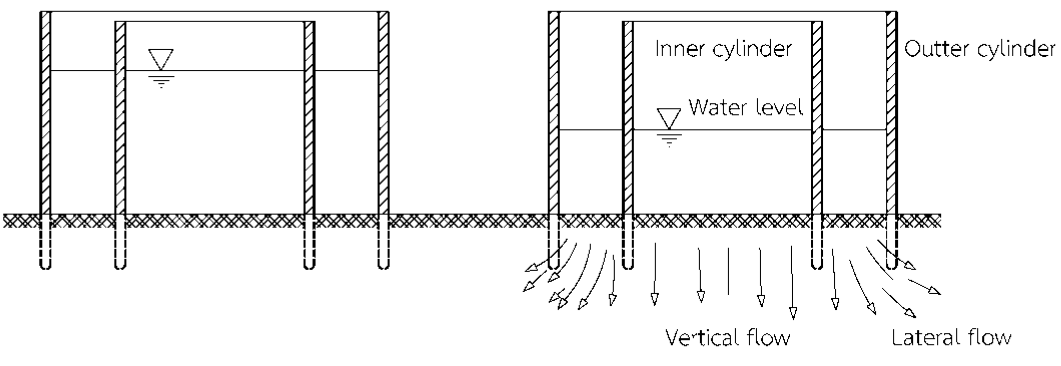
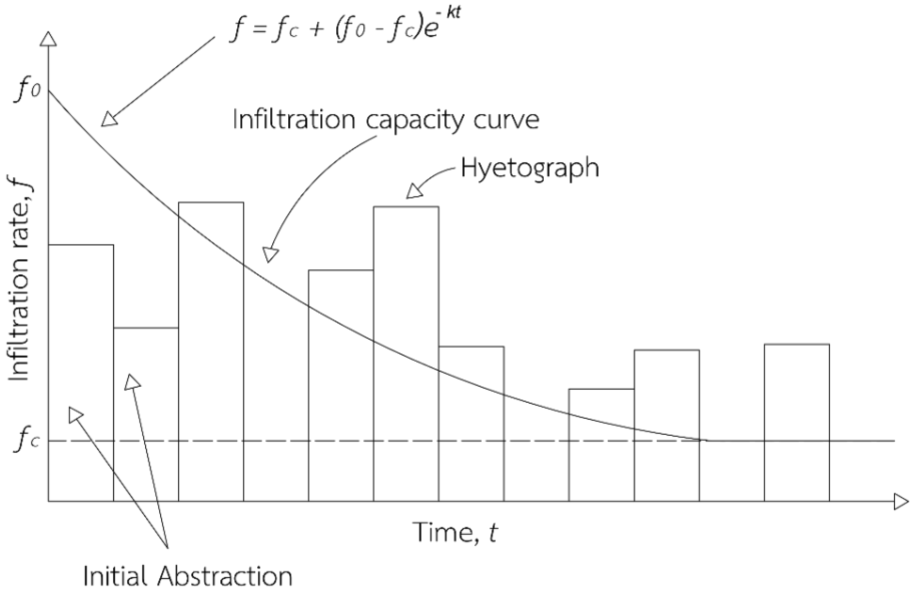


Figure 2

Characteristics of the Occurrence of the Permeation Rate per Time of Change



Summary of the literature review

The literature review which was undertaken in order to understand the relevant theories and essential issues related to research can be summarized as follows:

1) During the literature review, it was found that the models used in water management, especially in urban areas, cannot rely on conservative design guidelines ***(***Conventional stormwater management***).*** This fundamental concept focuses on managing excess surface water to drain quickly to other catchment areas within the city drainage system ***(***urban structure***).*** For example, design guidelines to allow each area more space to receive water may be limited to options such as building drainage, pumping stations, or a dam*/*dams to receive***.*** The design of the water management area plays an important role and is necessary for a city's water management in the modern era***.***

2) In researching problems in applying space design criteria to effectively receive rainwater, three significant problems were uncovered related to the application***:***

a. Diversity of foreign standards - there is no unique collection of principles and standards for filter media design. Instead, the design will depend on the knowledge and experience of each designer. Therefore, it can be confusing and difficult for newly interested designers, especially those in Thailand, to understand and implement appropriate principles.

b. No standardized infiltration rate can be used as a preliminary design reference with basic composite materials available in every locality; for example, mixing sand with soil lacks guidelines for implementation that are easy to understand. Furthermore, according to the literature review, it was found that, in urban areas, there is no easy-to-understand user interface that is suitable for mainstream users (landscape architects, urban designers).

c. The identified problems uncovered during literature reviews pointed to the need for research with the primary objective of testing the infiltration of the filter media layer at different ratios of soil-to-sand mixtures to design bioretention guidelines for urban areas. The methods used to achieve this are presented in the next section.

METHODOLOGY

This research comprises an experiment to determine infiltration rates associated with the use of sand mixed with original soil in various ratios, as shown in Table 1; using a double ring infiltrometer according to ASTM D 3385-03 is a test tool (Boeno et al., 2021; Li et al., 2019). The experiment was conducted at the Faculty of Engineering, Chiang Mai University. The results obtained from the experiment will be used as a preliminary standard for the design of the filter media layer.

Three soil-to-sand ratios were tested; the soil was the original soil in the test area and coarse sand for general construction was used. Each model and its ratio are listed in Table 2.

Each bioretention construction area is 2 m^2, with a depth of the filter media layer of 0.6 m, a transition layer of 0.10 m, and a drainage layer of 0.15 m. The total depth of 0.85 m. was established following the recommendations of *Biofiltration Systems in the Development Services Schemes Guideline*; simultaneous testing of all four configurations began one month after bioretention was set (Facility for Advancing Water Biofiltration [FAWB], 2009) with the following working steps.

Bioretention construction and infiltration rate testing procedures

1) Select a natural area that is not protected and has no moisture source other than nature

2) Construct the 3 bioretention test areas

3) Wait one month for the soil to set

4) Install the inner tank with the sharp edge facing down, and place a pad for hammering on top

5) Install the outer tank with the sharp edge facing down, and place a pad for hammering on top

6) Bring the measuring tape to install on the top of the inner tank to eliminate anything that may affect the measurement; put a plastic bag on the bottom of the inner tank before pouring water into the tank**.**

7) Pour water into the outer and inner buckets to a height of 10 centimeters, tear off the plastic bag, and start measuring immediately**.** Prepare enough water to test 25 liters, and for best results in the experiment, water of similar quality should be used in each test area**.**

8) Start measuring by observing the time and the water level in the tank **(**reference level**)** indicated on the measuring axis**.** Then record the value and check the decrease in the water level in the inner tank; record the time and water level on the data item**.**

9) For the first 105 minutes, water level measured every 15 minutes

10) From 105 minutes to 345 minutes, water level measured every 30 minutes

11) From 345 minutes onwards, water level measured every 60 minutes

Table 2

Soil-to-Sand Mixing Ratio of Filter Media

Number	Soil	Sand	The ratio of sand to aggregate
1	1	1	0.50
2	1	2	0.67
4	1	4	0.80

12) When the water is reduced to 5 cm. from the bottom of the tank, add more water and save new levels; levels in the inner and outer tanks should be similar. If the water level in the outer tank is higher than the water level in the inner tank, it will cause the infiltration rate of the tank to be lower than it should be because the water in the outer tank will block the infiltration of the inner tank.

13) Stop measuring when the infiltration rate reaches a constant value, collect the device; pull out the tank, and thoroughly clean the inner and outer tanks.

The water infiltration rates of 3 types of bioretention were measured using a double-ring infiltrometer; this information was then substituted into the Horton equations, where ft is the water infiltration rate at any time. The equation can be used to calculate the volume of rainwater infiltration over a specified time.

RESULTS AND DISCUSSION

The bioretention infiltration test uses three different mixing ratios created in September and tested in October, as shown in Figure 3.

The test results, as can be seen in Figure 3, show the water infiltration rate of 3 mixes:

1) the soil to sand ratio of 1:1 had a start infiltration of 36.26 mm./hr., constant at 16.09 mm./hr.

2) the soil-to-sand ratio of 1:2 had a start infiltration rate of 446.74 mm./hr., constant at 21.53 mm./hr.

3) the soil-to-sand ratio of 1:4 had a start infiltration rate of 67.62 mm./hr., constant at 28.90 mm./hr., with the highest infiltration rate out of the three types.

The test results show that increasing the porosity of the soil by mixing it with sand can increase the water infiltration rate of the filter media layer. However, if sand is mixed in too high a ratio, it will affect the weight of the area and the growth of plants above. However, it is not necessary to choose the maximum infiltration rate in each area; the required infiltration rate is influenced by the amount of rain that falls in the area. Therefore, a suitable infiltration rate must be used as a guideline; the filter medium design will provide the appropriate infiltration rate based on the soil-to-sand ratio. The infiltration rate associated with each soil-to-sand ratio is shown in Figure 3; it can be used as a guide for determining the required soil-to-sand ratio for any given area once the required infiltration rate is established.

CONCLUSION

This study tested water infiltration rates on bioretention with a filter media layer that used a mixture of soil to sand in 3 different ratios to promote the design of bioretention filter media with basic materials readily available in any locality. In addition to the water infiltration rate effect of the three types, it can also express the relationship between the sand-to-aggregate ratio. The infiltration rate determined by the soil-to-sand mixing ratio is shown in graphical form in Figure 4; it should provide excellent guidance in bioretention design.

According to the literature review of the Minnesota Pollution Control Agency (2022) and Northeast Region Certified Crop Adviser (NRCCA) (2010), the infiltration rate of loam of 5 – 10 mm/hr and coarse sands of more than 20 mm./hr., as shown in Table 1. The data shown in Figure 4 is consistent with these reports and can be defined by the equation $I_r = 6.025e^{1.9941(Sr)}$ by testing equation R^2 at 0.999, which is a high level of reliability and usability (Rinchumphu et al., 2013). It shows that when the ratio of sand is at 0%, which is classified as loam soil texture, the infiltration rate = 6.02 mm/hr. At the same time, when the ratio of sand is 100%, the soil texture is classified as coarse sand, and the infiltration rate is 42.10 mm/hr. In addition to setting the infiltration rate as needed, knowing the required ratio of added sand is helpful for proper design planning, cost control, and efficient compliance with the needs of the area.

Figure 3

Water Infiltration Rate of 3 Different Mixing

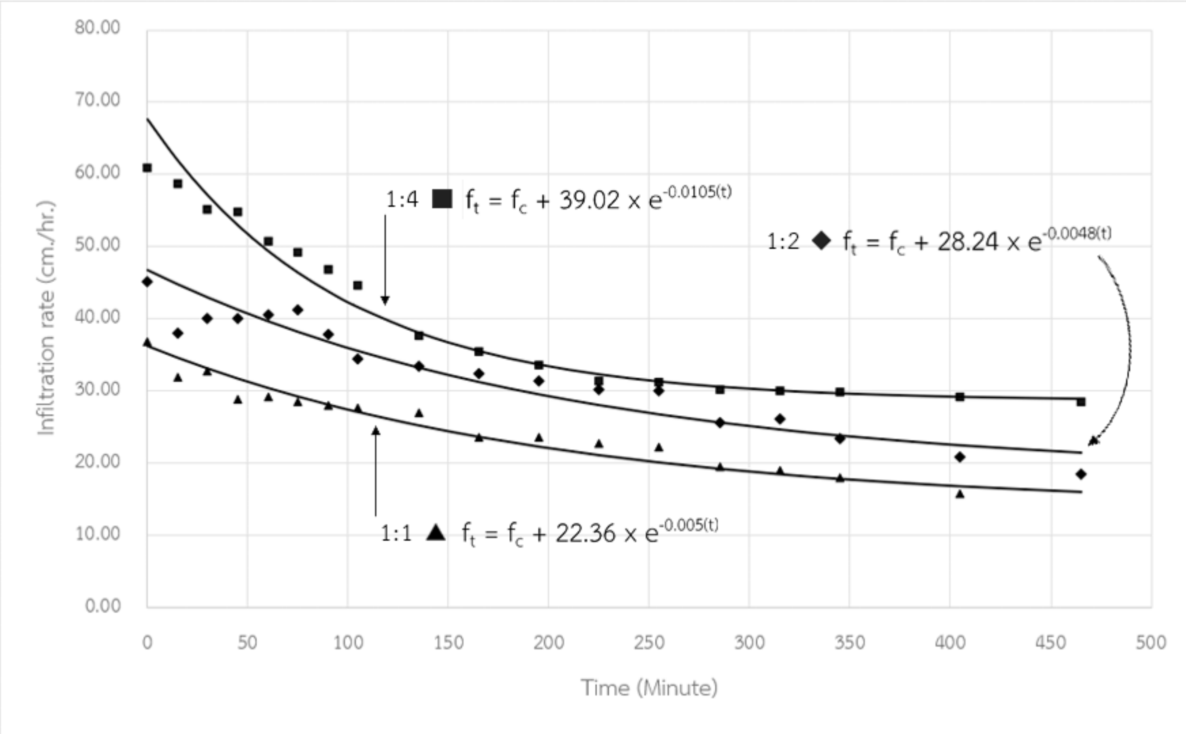
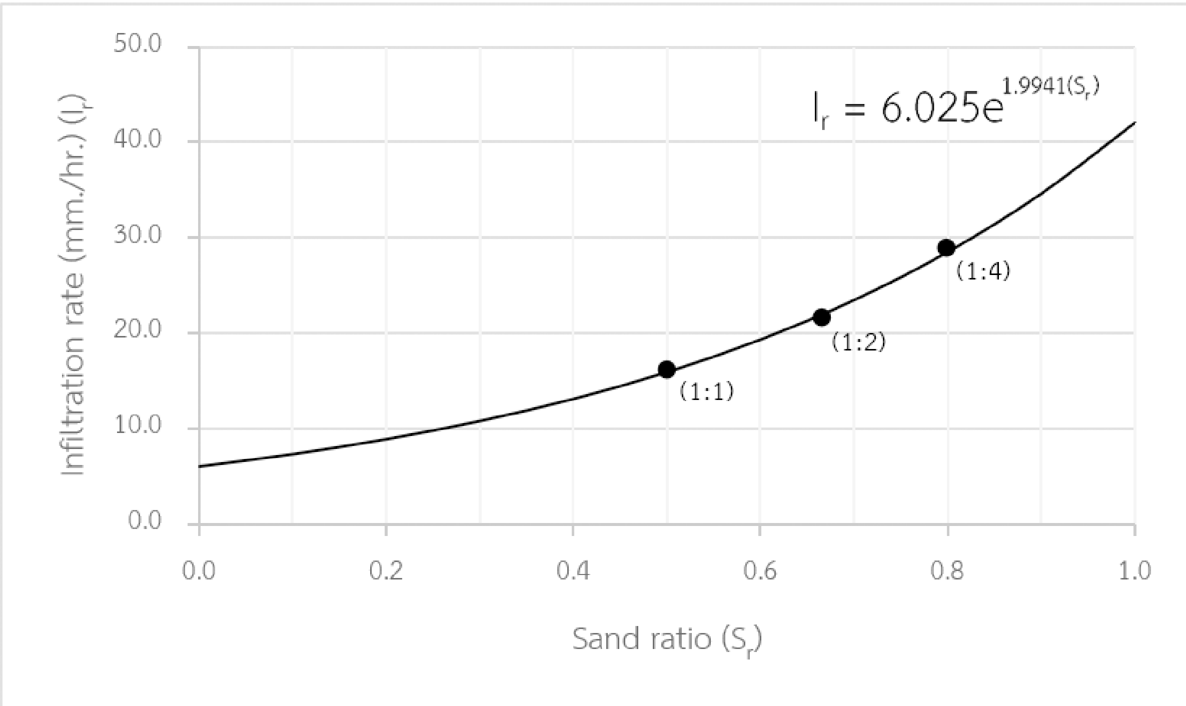


Figure 4

The Ratio of Sand to Aggregate With the Infiltration Rate



ACKNOWLEDGMENT

This research was supported by CMU Junior Research Fellowship Program.

REFERENCES

7HD Online. (2022*). Fon thalom nam thūam Chīang Mai thanon lāi sāinām thūam sūng kānčharā čhọ̄n nai mư̄ang sāhat* [Heavy rain floods Chiang Mai; many roads are flooded the traffic in the city is terrible]. https://news.ch7.com/detail/596237

Abdelmoneim, A. A., Daccache, A., Khadra, R., Bhanot, M., & Dragonetti, G. (2021). Internet of things (IoT) for double ring infiltrometer automation. *Computers and Electronics in Agriculture, 188*, 106324. https://doi.org/10.1016/j.compag.2021.106324

Ahammed, F., Rohita Sara, G., Paul Kai, H., & Yan, L. (2021). Optimum numbering and sizing of infiltration-based water sensitive urban design technologies in South Australia. *International Journal of Sustainable Engineering, 14*(1), 79–86. https://doi.org/10.1080/19397038.2020.1733131

Auckland Council. (2018). *Rain garden construction guide: Stormwater device information series.* https://www.aucklandcouncil.govt.nz/environment/stormwater/docsconstructionguides/rain-gardens-construction-guide.pdf

Bodhinayake, W., Si, B. C., & Noborio, K. (2004). Determination of hydraulic properties in sloping landscapes from tension and double-ring infiltrometers. *Vadose Zone Journal, 3*(3), 964–970. https://doi.org/10.2136/vzj2004.0964

Boeno, D., Gubiani, P. I., Lier, Q. d. J. V., & Mulazzani, R. P. (2021). Estimating lateral flow in double ring infiltrometer measurements. *Revista Brasileira de Ciência do Solo, 45,* 0210027.

Facility for Advancing Water Biofiltration. (2009). *Adoption guidelines for stormwater biofiltration systems*. Facility for Advancing Water Biofiltration.

Franti, T., & Rodie, S. (2007*). Stormwater management, rain garden design for homeowners*. The University of Nebrsaka-Lincoln NebGuide.

Geberemariam, T. K. (2019). Finite difference method to design sustainable infiltration based stormwater management system. *Preprints 2019*, 2019020024.

Iftekhar, M. S., & Pannell, D. J. (2022). Developing an integrated investment decision-support framework for water-sensitive urban design projects. *Journal of Hydrology, 607*, 127532. https://doi.org/10.1016/j.jhydrol.2022.127532

Li, M., Liu, T., Duan, L., Luo, Y., Ma, L., Zhang, J.,& Chen, Z. (2019). The scale effect of double-ring infiltration and soil infiltration zoning in a semi-arid steppe. *Water, 11*(7), 1457.

Lisenbee, W. A., Hathaway, J. M., & Winston, R. J. (2022). Modeling bioretention hydrology: Quantifying the performance of DRAINMOD-Urban and the SWMM LID module. *Journal of Hydrology, 612*, 128179. https://doi.org/10.1016/j.jhydrol.2022.128179

Liu, A., Egodawatta, P., & Goonetilleke, A. (2022). Ranking three water sensitive urban design (WSUD) practices based on hydraulic and water quality treatment performance: Implications for effective stormwater treatment design. *Water, 14*(8), 1296. https://www.mdpi.com/2073-4441/14/8/1296

Meng, X., Li, X., Nghiem, L. D., Ruiz, E., Johir, M. A., Gao, L., & Wang, Q. (2022). Improved stormwater management through the combination of the conventional water sensitive urban design and stormwater pipeline network. *Process Safety and Environmental Protection, 159*, 1164–1173. https://doi.org/10.1016/j.psep.2022.02.003

Minnesota Pollution Control Agency. (2022). *Design infiltration rates*. Storm Water. https://stormwater.pca.state.mn.us/index.php/Design_infiltration_rates

Northeast Region Certified Crop Adviser (NRCCA). (2010). *Soil hydrology AEM*. Cornell University. https://nrcca.cals.cornell.edu/soil/CA2/CA0211.1.php

Osman, M., Wan Yusof, K., Takaijudin, H., Goh, H. W., Abdul Malek, M., Azizan, N. A., & Sa'id Abdurrasheed, A. (2019). A review of Nitrogen removal for urban stormwater runoff in bioretention system. *Sustainability, 11*(19), 5415. https://www.mdpi.com/2071-1050/11/19/5415

Public Utilities Board. (2014). *Active, beautiful, clean (ABC) waters design guidelines*. Singapore's National Water Agency.

Puget Sound Action Team. (2005). *Low impact development: Technical guidance manual*. Pierce County Extension.

Raju, Y. K., & Hussain, M. (2019). Fitting Infiltration Equations using Double Ring Infiltrometer to Design and Evaluate Irrigation Methods. *International Journal of Recent Technology and Engineering (IJRTE), 8*(4), 7751–7754. https://doi.org/10.35940/ijrte.D5379.118419

Rinchumphu, D., & Anambutr, R. (2017). Determination of stormwater runoff infiltration on rain water absorbing garden for landscape architecture. *Journal of Environtmental Design, 4*(2), 85–101.

Rinchumphu, D., Eves, C., & Susilawati, C. (2013). Brand value of property in Bangkok metropolitan region (BMR), Thailand. *International Real Estate Review, 16*(3), 296–322.

Senior Stormwater Quality Technical Advisor. (2020). *Biofiltration systems in Development Services Schemes: Guideline*. Melbourne Water.

Teang, L., Wongwatcharapaiboon, J., Irvine, K., Jamieson, I., & Rinchumphu, D. (2021). *Modelling the impact of water sensitive urban design on pluvial flood management in a tropical climate* [Paper presentation]. The 12th Built Environment Research Associates Conference, BERAC2021, Bangkok, Thailand.

Thairath Online. (2022). *Fon thalom Chīang Mai nam thūam khang rọ̄kān rabāi saphāp kānčharā čhọ̄n titkhat nap sip čhut* [Rain hits Chiang Mai Floodwaters waiting to be drained; traffic congestion counts 10 points]. https://www.thairath.co.th/news/local/north/2507955

United States Environmental Protection Agency. (2022). *Storm Water Management Model (SWMM)*. https://www.epa.gov/water-research/storm-water-management-model-swmm#green

Wang, X., Sample, D. J., Pedram, S., & Zhao, X. (2017). Performance of two prevalent infiltration models for disturbed urban soils. *Hydrology Research, 48*(6), 1520–1536. doi:10.2166/nh.2017.217

Wang, M., Zhang, D., Cheng, Y., & Tan, S. K. (2019). Assessing performance of porous pavements and bioretention cells for stormwater management in response to probable climatic changes. *Journal of Environmental Management, 243*, 157–167. https://doi.org/10.1016/j.jenvman.2019.05.012