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ORIGINAL RESEARCH PAPER

Economics and cost effectiveness of a rain garden for flood-resistant urban design

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ABSTRACT

BACKGROUND AND OBJECTIVES: Rapid urbanization negatively affects the hydrologic cycle and makes cities vulnerable to disastrous flash floods. It can additionally cause erosion and water pollution in natural ecosystems. Global climate changes have exacerbated such issues, further upsetting hydrologic patterns. Therefore, many regions have considered the rain garden as green infrastructure, which can help mitigate urban runoff. However, design guidelines and the means of assessing rain garden cost effectiveness in the Global South are limited. Furthermore, as many countries in the Global South experience a tropical climate, design guidelines developed in the temperate Global North may not be directly transferable. The need for more information on design and cost effectiveness can make designers and decision makers hesitate to implement such a new strategy. The main objective of the present study is to create a design approach and simultaneously specify the cost of the infiltration rate of the rain garden in urban areas.

METHODS: This study focuses on the ability of rain garden design to determine accurately the cost of materials used for construction. Sand and gravel are used in different sand ratios in the filter media layer, namely 1:1, 1:2, 1:3, and 1:4. The storage layer uses gravel only and has only one design. The aim is to determine the change in infiltration rate with an increase in the amount of sand. Knowing the amount of sand can determine the cost per infiltration rate.

FINDINGS: The results showed that the most efficient design was a rain garden with a soil:sand ratio of 1:4, which increased the infiltration rate per cost by 2.00 millimeters per hour per United States Dollar per square meter. The lowest efficiency option was a soil:sand ratio of 1:1, which increased the infiltration rate per cost by 1.33 millimeters per hour per United States Dollar per square meter.

CONCLUSION: This study will serve as a guide for designers to design a rain garden area according to the needs of the area, having determined the construction cost per infiltration rate. However, spatial requirements, construction costs, and social factors may influence future decisions on rain garden design and must be studied further.

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
35	**7**	**2**

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INTRODUCTION

Rapid growth in urban areas has increased stormwater runoff. The water permeability of the soil surface decreases continuously owing to the vast and rising expansion of constructed works which have been reducing the natural land surface in urban areas. Structures such as buildings and roads are necessary living facilities, which are increasingly required as the population grows (Mardianti and Purba, 2023). In addition, climate change, unpredictable increases in rainfall, insufficient existing drainage systems for stormwater runoff catchment, and low sewerage treatment capacity result in prolonged waterlogging and affect life and traffic in urban areas. Therefore, methods to create a better infiltration rate on existing land surface areas are an exciting prospect for alleviating such problems. Water sensitive urban design (WSUD) in Australia or low impact development (LID) in the United States are examples of common approaches to improving soil surfaces for higher infiltration rates (Huang *et al.,* 2015; Li *et al.,* 2019). Rain gardens or bioretention systems are especially well known and could be implemented in urban areas, as they are well permeable to the original soil (Morash *et al.,* 2019; Sharma and Malaviya, 2021; Suharyanto *et al.,* 2023). A rain garden is a system of soil layers to increase the permeability of the soil surface. It consists of three main layers: 1) filter media, 2) transition layer, and 3) storage layer (Parker and Zingoni de Baro, 2019; SSQTA, 2020). The efficiency indicator is the increased infiltration rate of the entire system, which must increase the permeability of the original soil (Qin *et al.*, 2021; Shi, Zhao *et al.,* 2022). Mixing sand into the soil is the typical method of increasing porosity and hence the water infiltration rate of the soil (Sittisom *et al.,* 2022). However, the key factor in design and construction is cost (Van der Meulen, 2019; Zeng *et al.,* 2021). How much the soil must be changed to achieve improved infiltration rates is not yet known, but adding a proportion of sand to increase the infiltration rate raises the cost (Zeng *et al.,* 2021). The study aims to design a rain garden to determine the construction cost and infiltration rate efficiency to inform further application guidelines. This study has been carried out in Thailand in 2023.

Hydrology principle and stormwater runoff

The hydrologic cycle, commonly called the water cycle, lacks a definitive starting point. Nevertheless, it is crucial to assign precipitation, which encompasses rainfall, hail, and snow, as the first step in the cycle. This water condenses in the atmosphere and returns to the Earth's surface. Before reaching the ground, a portion of the precipitation is intercepted by natural features, such as leaves and plant branches, and human-made structures, such as rooftops, in a process referred to as interception. In cases where the amount of precipitation surpasses the soil's capacity to absorb it, the excess water flows over the land surface as overland flow (Monger *et al.,* 2022). When water naturally flows from high areas to low ones and then to a river, it is called surface runoff. After that, some water that infiltrates the soil (infiltration) will flow to lower areas, a phenomenon called interflow. Water that infiltrates deeper and accumulates in aquifers is called groundwater, which can flow into lower areas, rivers, and the sea. As the water flows, it receives thermal energy from the sun. This water then disperses into the atmosphere through evaporation, which is the process by which a liquid changes into a gas. Transpiration is the process by which plants release water vapor into the atmosphere through tiny pores in their leaves. Evaporation can occur from any wet surface, while transpiration is specific to plants. When more vapor condenses in the atmosphere, it becomes precipitation again (Sittisom *et al.,* 2022). The hydrologic cycle can be written as a hydrologic balance equation to describe the relationship using Eq. 1 (Sittisom *et al.,* 2022).

$$P = Q + G + E + T + I + S \tag{1}$$

where P is rainfall, Q is surface runoff, G is underground water volume, E is surface water evaporation, T is plant transpiration, and S is water changes on the soil surface. However, the critical consideration is alleviating the severity of prolonged waterlogging caused by stormwater runoff. Therefore, the equation is applied in designing a rain garden.

Rain garden design

The rain garden is an area intended to efficiently catch stormwater runoff in urban areas (water sensitive design). Rain gardens and bioretention are very similar. The design of rain gardens appears in many standards used in water catchment areas, for example in Singapore's Waters Design Guidelines: Active, Beautiful, Clean (PUB, 2014) and Low

Impact Development: Technical Guidance Manual (Puget Sound Action Team, 2012), which has been implemented in many states in the United States of America (Batalini de Macedo *et al.,* 2022). The rain garden is often located in low areas to slow down the water and reduce the stormwater runoff flow rate. It also temporarily collects water in instances where the rain garden is designed as a basin. It often looks like a garden. Hence, a rain garden can be created in many kinds of public areas, such as traffic islands, gardens in residential projects, and city parks. Apart from the stormwater runoff reduction, it also enhances aesthetics and increases green areas (Bąk and Barjenbruch, 2022; Wilbers *et al*., 2022). The critical function of a rain garden is the ability to enhance the underground infiltration rate. Therefore, the design of each layer and the material properties of each is essential. Various designs are described in the literature; for example, the Australian guidelines (Melbourne Water, 2013) recommend the layer design as follows: ponding depth layer 20–30 cm, filter media layer 30 cm, transition layer 10 cm, storage layer 30–40 cm. The materials are sand and sandy loam for the filter media layer, small gravel for the transition layer, and large gravel for the storage layer. An example of landscape architecture design is presented in Fig. 1.

In addition, Wanitchayapaisit *et al.* (2022) designed two variations of a rain garden for rainwater management in Chiang Mai, Thailand: 1) ponding depth layer 60 cm, planting soil layer 30 cm, storage layer 40 cm; and 2) ponding depth layer 40 cm, planting soil layer or filter media layer 70 cm, storage layer 20 cm. The materials for the two designs are soil mixed with sandy loam (filter media layer) and gravel (storage layer). The results showed that the efficiency of rainwater harvesting of variant 1) was higher than that of variant 2). However, variant 2) was more efficient than the unchanged original soil and many other designs (Yuan *et al.,* 2017; Zhou and Guo, 2022). Moreover, the rain garden reduces runoff pollution (Chen *et al.,* 2023; Makbul *et al.,* 2021). An area with a higher infiltration rate serves to reduce the duration and severity of stormwater runoff; the retention of increased volumes of water in the drainage systems of urban areas is prevented. Common critical gaps in creating rain gardens are as follows. 1) In the Thai context, although the design guidelines of a rain garden have yet to be standardized, the variety of designs results in difficulty in implementation. Furthermore, the design is implemented in specific areas and depends on the knowledge and experience of each designer, which may need clarification. Because of that, the technique proposed by Wanitchayapaisit *et al.* (2022) is an appropriate approach for estimating the construction cost for infiltration rates because the design takes into account the characteristics of weather, soil, and rainfall in the areas under consideration. 2) The cost per infiltration rate still needs to be standardized, and it is difficult to design appropriately to serve an area's needs and the break-even points. The permeability rate obtained by mixing sand with soil in various ratios (Sittisom *et al.,* 2022) was used as a guideline for this study. 3) The literature review revealed a problem in determining rain gardens' cost per infiltration rate.

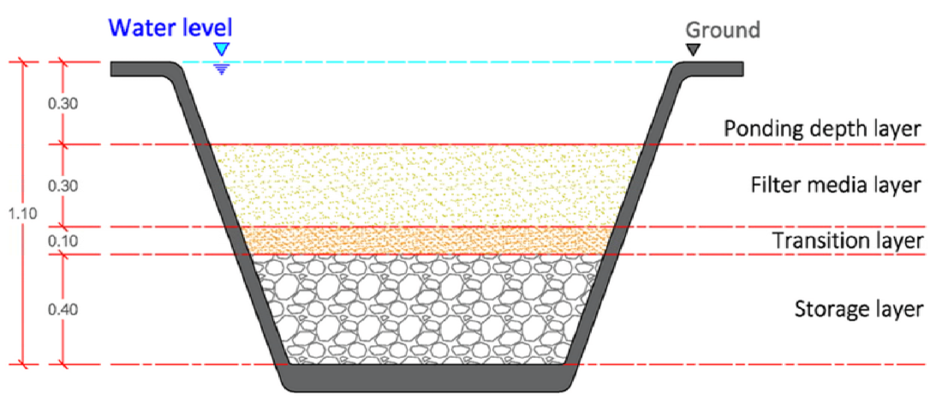

Fig. 1: Example of soil layer design for a rain garden (Melbourne Water, 2013)

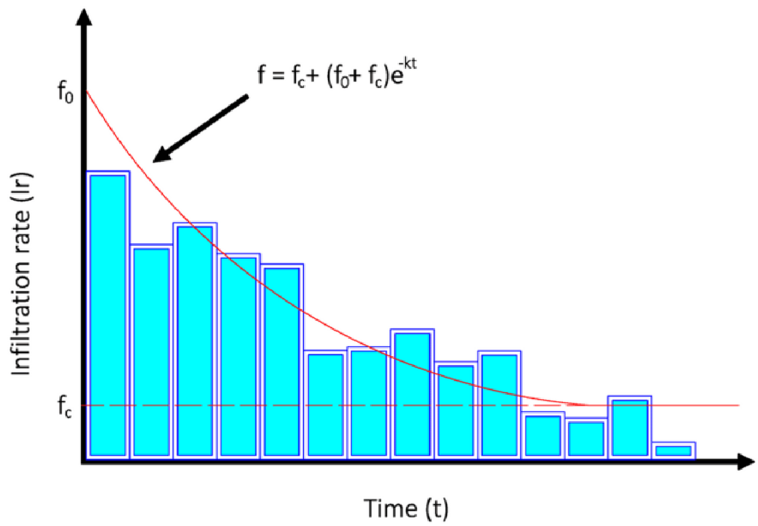

Fig. 2: Characteristics of the occurrence of the infiltration rate per time of change (Sittisom *et al.,* 2022)

The primary objective is to create a design approach considering both infiltration rate and cost for rain gardens in urban areas. Assess the efficiency of a rain garden, and it is essential to understand the principles and techniques used to measure infiltration rates.

Principle of the infiltration rate

As the water moves from high to low areas, it infiltrates into the soil; some of it becomes simply as soil moisture, whereas some parts penetrate deeper and become groundwater. The infiltration rate of soil relies on many factors, such as rainfall intensity, temperature, soil physical characteristics (Mongil-Manso *et al*., 2022), types of cover crops, land use characteristics, and initial soil moisture content (Abdelmoneim *et al.,* 2021; Sittisom *et al.,* 2022). Horton's theory is applied to calculate the quantity of permeable water in the soil.

The design and measurement of the infiltration rate of the rain garden can be written using Eq. 2 (Sittisom *et al.,* 2022).

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

where f_t is the infiltration rate measured in millimeters per hour (mm/h), f_c is a constant infiltration rate (mm/h), f_0 is the initial infiltration rate (mm/h), and k is a constant value showing a decrease in the soil infiltration rate.

To measure the infiltration rate for soil design following Horton's theory, an instrument called a double-ring infiltrometer is used (Raju and Hussain, 2019; Atta-Darkwa *et al.,* 2022).

Double-ring infiltrometer technique

The permeability determination approach is applied to discover the potential based on urban catchment management principles. One method used to determine soil permeability is the double-ring infiltrometer technique, according to ASTM D 3385-03, as illustrated in Fig. 3.

The double-ring infiltration technique (Fig. 3) is applied following the prediction equation in Horton's theory of permeability, which was first proposed in the 1940s (Abdelmoneim *et al.,* 2021; Geberemariam, 2019). The literature review showed that the single-ring infiltrometer technique is another practical technique for examining the infiltration rate. It is important to know the infiltration rate of the soil composite because infiltration measurement techniques are only applied to determine the soil permeability. To increase the soil infiltration rate, a basic technique to increase the soil porosity is to mix sand into the soil. The use of sand as filter media (Melbourne Water, 2013; Sittisom *et al.,* 2022) is a standard method to increase soil infiltration efficiency.

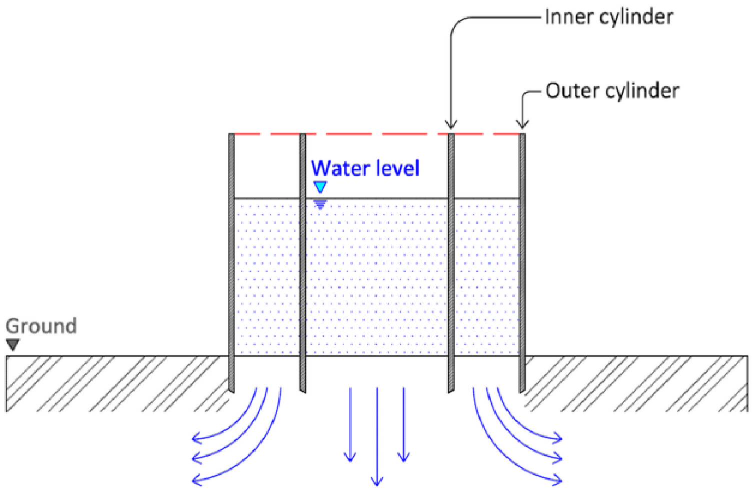

Fig. 3: Double-ring infiltration technique (Sittisom *et al.,* 2022)

The construction cost of a rain garden

The cost estimate is a process of estimating the quantity of materials and reasonable prices for actual projects. There are two types of cost estimate: approximate and detailed.

Approximate estimation

An approximate estimation is a method for price estimation that does not rely on detailed plans or precise quantities. This method can be conducted instantly and involves estimating areas, height, length, or quantities, relying on the experience of the estimator. The approximate price estimation may consist of price per unit of use, price per unit area or per unit volume, or assembly price per unit.

Detailed estimation

A detailed estimation takes into account all relevant components, such as the quantity of materials, material prices, labor costs, machine costs, operating costs, profits, taxes, interest, and other price-related details. This estimate requires a detailed plan that is complete and clear. It is accurate but takes more time than the approximate estimate (Sitthikankun *et al.,* 2021). The present study aims to determine the construction cost and infiltration rate efficiency of a garden design in order to construct further application guidelines for Thailand. The study was conducted using the rain garden design model of Wanitchayapaisit *et al.* (2022), which selected Chiang Mai University as the study site, located in the same area as this study. The material cost for rain garden construction was obtained from a survey in Chiang Mai in 2022.

MATERIALS AND METHODS

1) Rain garden design. In order to determine the construction cost, the size of the rain garden is first described. It consists of a ponding depth layer of 60 cm, a filter media layer of 30 cm, and a storage layer of 40 cm, as shown in Fig. 4.

2) Determination of infiltration rate. The sand-to-infiltration rate ratio can be calculated using Eq. 3 (Sittisom *et al.,* 2022):

$$Ir = 6.025e^{1.994(Sr)} \quad (3)$$

where I_r is the infiltration rate, and Sr is the sand ratio. Once the infiltration rate is determined, the next step is to determine the cost of the design.

3) Determination of cost. The material cost for rain garden construction was obtained from a survey in the Muang Chiang Mai District, Chiang Mai, in January 2023. The price for general coarse sand was 14.29 United States Dollar per cubic meter (USD/m^3), and for 3/8 inch gravel was 20 USD/m^3. The original soil in the test area was used, so there was

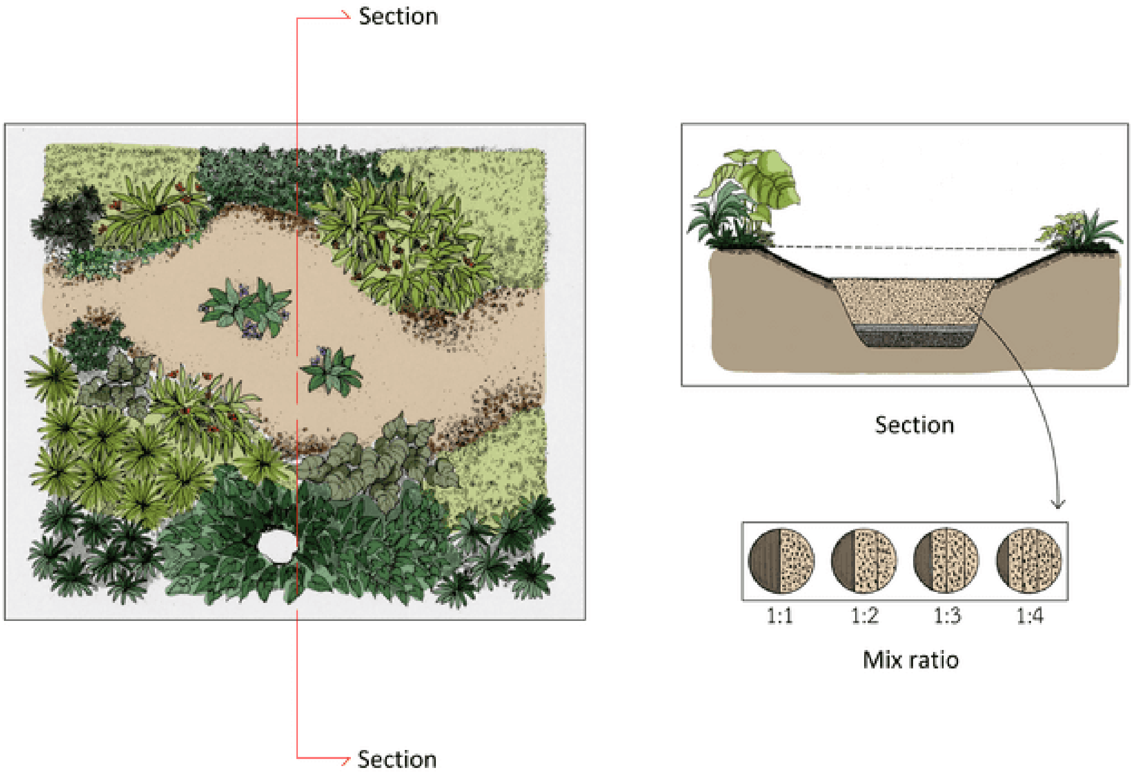

Fig. 4: Example of rain garden design.

no cost. Hence, the price takes into account only the cost of materials. Labor costs, transportation costs, and other costs are not considered. The price is the average price from the stores that have been found to stock the materials, as shown in Table 1.

Cost-efficiency calculation

Cost is inevitably an important factor in rain garden construction. After deciding on the garden design, estimating the construction material cost and determining the sand-to-infiltration rate ratio retrieved from Eq. 3, the permeability rate to cost can be calculated, as shown in Eq. 4 (Combes *et al.,* 2018; Hoang *et al.,* 2021).

$$\text{Cost efficiency}\left(C_e\right)=\frac{\text{Infiltration rate}\left(\text{Ir}\right)}{\text{Cost}\left(\text{C}\right)} \tag{4}$$

where the infiltration rate (I_r) and the cost (C) is for the coarse sand and 3/8 inch gravel.

RESULTS AND DISCUSSION

Increasing the filter media layer's porosity by mixing more sand into the soil was found to raise the infiltration rate, but the cost also went up simultaneously. However, the application depended on the stormwater runoff characteristics in the design area. What was important was the cost of the infiltration rate that the designer considered reasonable, Sittisom *et al.* (2022) tested the filter media layer of bioretention using different mixing ratios. The sand-to-aggregate ratio and infiltration rate are summarized in Fig. 5.

In Fig. 5, I_r is the infiltration rate (mm/h), and Sr is the sand-to-aggregate ratio. Design the infiltration rate by using Eq. 4 and calculate by using the best design layer of rain garden from (Wanitchayapaisit *et al.,* 2022) is the ponding depth layer 60 cm, the filter media layer 30 cm, the storage layer 40 cm, which is estimated to be an area of 1 square meter (m^2). Price per unit volume will be the cost estimation

Table 1: Price survey of general coarse sand around Chiang Mai Province

Store name	Price (USD/m^3)	
	Sand	Gravel
Chuchai	12.86	17.14
Thanasap	14.29	21.43
CMR Sum dang det	15.71	20.00
P.Lansai	17.14	21.43
Huay Sai Lan Sai	11.43	20.00
Lan Sai Khun Yo	11.43	17.14
Lan Sai Ruamchok	17.14	20.00
New Chok Amnuai Sai	14.29	22.86
Average	14.29	20.00

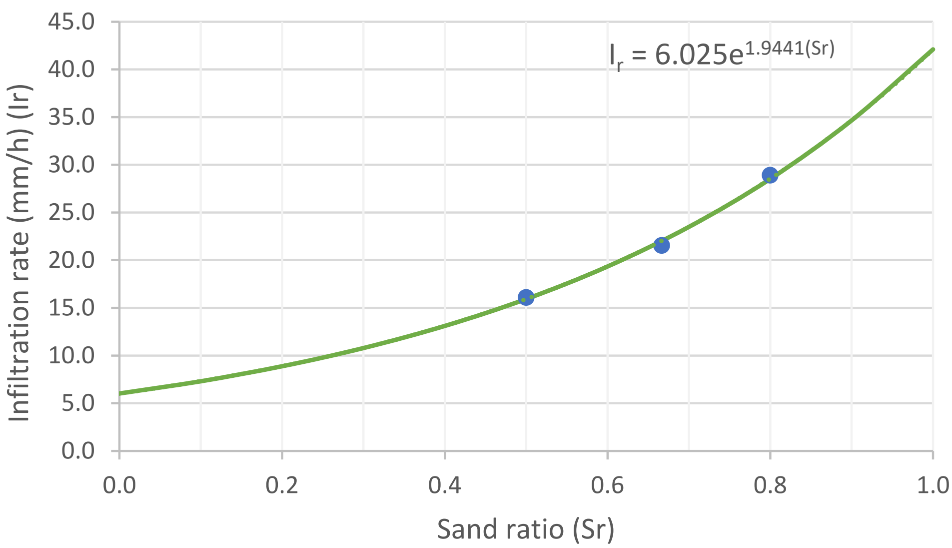

Fig. 5: The ratio of sand to aggregate with the infiltration rate (Sittisom *et al.,* 2022)

method used in this study because there is no plan, and the width and length of the rain garden need to be specified. As shown in Fig. 6, the price per unit volume method has a mistake in price of 10–25%.

Although there is a risk of a price mistake from the price per unit volume method, it has the advantage of arriving at an estimate more quickly than other estimation methods (Sitthikankun *et al.,* 2021). Therefore, this method was chosen in order to be able to use the price per volume to calculate the cost efficiency, as shown in Table 2.

The mixture rate to infiltration rate considered in 4 alternative could be used to determine the cost, as seen in Table 3.

The construction cost is an essential factor in building a rain garden. To be able to forecast the increased cost-to-infiltration rate, four alternatives are presented. The results of the relationship between the cost-to-infiltration rate and sand mixing ratio (Fig. 7) are beneficial for further costing of the rain garden design. Moreover, the information can be used to create the following equation: $C_e = 19.229e^{1.3584(Sr)}$ where Ce is Cost efficiency (mm/h/USD), and Sr is a sandto-aggregate ratio. The equation test value is 0.9998, which is a reliable value (Rinchumphu *et al.,* 2013).

Fig. 7 shows that, when the filter media layer becomes more porous owing to the addition of sand, the infiltration rate also increases (Sittisom *et al.,* 2022), but the cost of sand and gravel rises as well. This can be used as a guideline for determining the

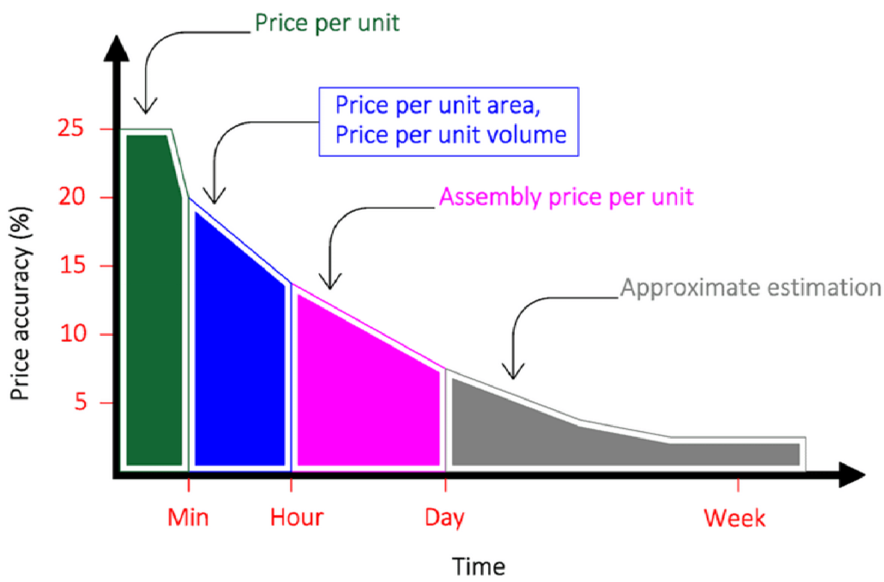

Fig. 6: The accuracy of cost estimation for each method (Sitthikankun *et al.,* 2021).

Table 2: The mixing ratio of the filter media layer in each type

Alternative ratio, soil, and sand	Soil volume (m^3)	Sand volume (m^3)	Gravel volume (m^3)	Infiltration rate (mm/h)	Cost (USD)	Cost efficiency (mm/h/USD)
1) 1:1	0.30	0.30	0.40	16.33	12.29	1.33
2) 1:2	0.20	0.40	0.40	22.77	13.72	1.66
3) 1:3	0.15	0.45	0.40	26.88	14.43	1.86
4) 1:4	0.12	0.48	0.40	29.70	14.86	2.00

Table 3: The cost to infiltration rate

1	Alternative 1: The cost of sand was USD 4.29. The cost of gravel was USD 8. The total cost was 12.29 United States Dollar per square meter (USD/m^2), with cost efficiency = 1.33 millimeters per hour per United States Dollar per square meter (mm/h/USD /m^2)
2	Alternative 2: The cost of sand was 5.71 USD. The cost of gravel was 8 USD. The total cost was 13.72 USD/m^2, with cost efficiency = 1.66 mm/h/USD/m^2
3	Alternative 3: The cost of sand was 6.43 USD. The cost of gravel was 8 USD. The total cost was 14.43 USD/m^2, with cost efficiency = 1.86 mm/h/USD/m^2
4	Alternative 4: The cost of sand was 6.86 USD. The cost of gravel was 8 USD. The total cost was 14.86 USD/m^2, with cost efficiency = 2.00 mm/h/USD/m^2

permeation rate to cost in the construction of a rain garden. Nevertheless, the limitation of this study was that the cost survey was conducted only in Chiang Mai and only during January 2023. For more appropriate and practical approaches to further rain garden developments, it is necessary to consider the differences in area and duration that affect the cost according to the theoretical principles of construction cost estimates. When designers can estimate the increasing cost accurately and quickly, more effective decisions can be made on the type and size of the rain garden.

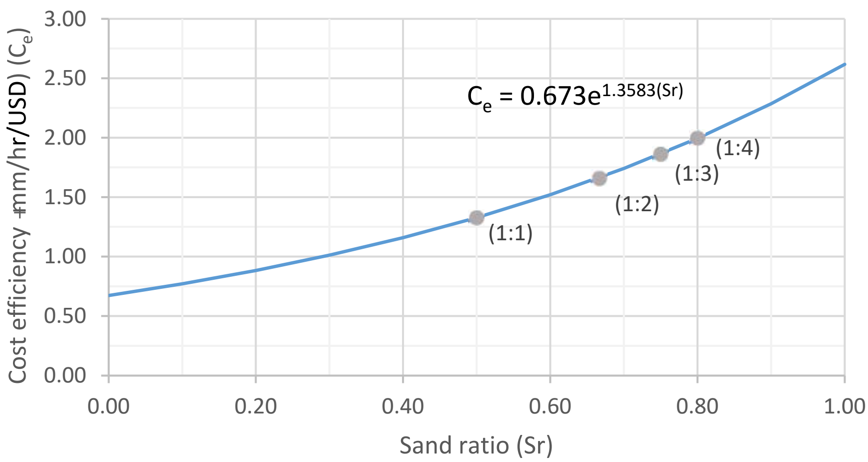

Fig. 7: Ratio of sand to cost.

CONCLUSION

This study shows that rain gardens can help reduce stormwater runoff in urban areas by delaying the runoff from inside the rain garden; they act like retention ponds and allow water to infiltrate the soil instead of flowing onto the surface. Increasing the permeation rate of the filter media layer by using sand as the base layer is a method that is feasible with easily obtainable materials. Water can penetrate through sand very well. The results set out the cost of rain garden construction, which could be helpful for those involved in making decisions about the design. In order to advance the use of rain gardens, the determination of construction costs and standardized designs are, therefore, important factors. The study examined the relationship between infiltration rate and the cost of building a rain garden across four different cost alternatives. Based on the study's results, an equation was developed to determine the infiltration rate per cost accurately. The equation was tested and found to have a highly reliable test value of 0.9998. This study yielded two main results. 1) The rain garden design consists of a ponding depth layer of 60 cm as the top layer, a filter media layer of 30 cm as the next layer, and a storage layer of 40 cm as the bottom layer. 2) It is possible to set the permeation rate per cost to design the rain garden to meet local needs. This flexibility allows urban planners and policymakers to tailor their rain garden design to meet the required permeation rate and budgetary limitations. This study had a limitation in the cost analysis, as the prices used to determine the costs were based on local prices in Chiang Mai, Thailand. For another location, it will be essential to consider the cost of local materials in that area. In order to create a more comprehensive dataset that includes different rain gardens suitable for use in Thailand, it is recommended that future studies investigate other aspects of rain gardening, such as cost-effectiveness, maintenance costs, and incentives available for creating rain gardens. Such studies would provide valuable information for urban planners and policymakers seeking to adopt rain gardens as part of their flood-resistant urban design strategy in Thailand.

AUTHOR CONTRIBUTIONS

D. Rinchumphu supervised the fourth author in analyzing and summarizing the test results, including giving advice on techniques and methods. S. Munlikawong researched and collected local material prices. C. Wanitchayapaisit participated in advising on the performance analysis of rain gardens and preparing illustrations. S. Sitthikankun, the corresponding author, collected all data, analyzed the results, and drew conclusions. N. Phichetkunbodee and N. Suriyanon contributed to the data analysis.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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ABBREVIATIONS

%	Percent
cm	Centimeter
C	Cost
C_e	Cost efficiency
E	Surface water evaporation
Eq.	Equation
Fig.	Figure
f_0	Initial infiltration rate
f_c	Constant infiltration rate
f_t	Infiltration rate at time (t)
G	Underground water volume
Ir	Infiltration rate
in	Inch
k	Constant value showing a decrease in the soil infiltration rate
LID	Low impact development
mm/h	Millimeters per hour
$mm/h/USD/m^2$	Millimeters per hour per United States Dolla per square meter
m^2	Square meter
m^3	Cubic meter
P	Rainfall
Q	Surface runoff
S	Water changes on the soil surface
Sr	Sand ratio
t	Time
T	Plant transpiration
USD	United States Dolla
USD/m^2	United States Dolla per square meter
USD/m^3	United States Dolla per cubic meter
WSUD	Water sensitive urban design

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