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Case Study

Evaluation of total infiltration and storage capacities for different soil types in Sarawak using SWMM

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Abstract

Climate change and irresponsible urbanization practices are anticipated to further exacerbate flood risk. The different soil types' physical, chemical, and biological characteristics significantly impact surface water movement, porosity, permeability, and infiltration potential. Therefore, soil infiltration is perhaps the most challenging and crucial process to characterize on a field scale. Various methods have been developed to measure the infiltration rate empirically and theoretically. However, the relationship between different soil types and infiltration rates in Sarawak remains unknown as no previous study has been conducted. This study uses the Storm Water Management Model (SWMM) to evaluate the infiltration rates for five different soil types: clay, clay loam, loam, sandy loam, and sand. 30 samples of various types and soil depths were examined at intervals of 0.5 m, 1.0 m, 1.5 m, 2.0 m, 2.5 m, and 3 m. The study was carried out using a standardized slope of 0.7% and an impervious land of 25% with a catchment size of 2 acres. Extreme rainfall data on the 5th and 6th of December 2021 was input into the infiltration model. Results showed that the difference between initial and final water storage of all the investigated soil depths for clay, clay loam, loam, sandy loam, and sand was found to be 48.42 mm, 51.20 mm, 58.01 mm, 66.96 mm, and 115.54 mm, respectively. The findings demonstrated that clay has the lowest water storage capability, followed by clay loam, loam, and sandy loam. Sand could store a comparatively large amount of rainwater. In contrast, sand has the highest infiltration rate with 2.541 mm/h, followed by sandy loam with 1.835 mm/h, loam with 1.432 mm/h, clay loam with 1.039 mm/h. Clay has the lowest infiltration rate, with 0.852 mm/h. This research concluded that sandy soil could significantly reduce surface runoff and help reduce flood risk in urban regions.

Keywords Final storage · Infiltration · Low Impact Development (LID) control · Porosity · Soil

1 Introduction

The urban soil properties are altered by urbanization, resulting in changes in water movement, soil permeability, hydraulic conductivity, and infiltration capacity [1, 2]. As a result of the reduced soil capacity to infiltrate water due to urbanization, the hydrological cycle is affected significantly, resulting in changes in river and stream flow regimes [3–5]. Surface runoff increases with impermeable surface increment due to reduced soil infiltration capacity [6, 7].

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Sustainable Urban Drainage Systems (SUDS) are commonly used in stormwater management to improve soil infiltration rates, reduce impermeable surfaces, and reduce the consequences of runoff generation in urban settings [8, 9]. SUDS attempt to restore the natural water cycle by reducing runoff volumes, attenuating peak flows, and enhancing water quality through a variety of mechanisms, such as infiltration, filtration, and biological water uptake [2]. Some SUDS involving infiltration processes include infiltration basins, swales, filter strips, bioretention facilities, green roofs, and permeable pavements [10]. For these SUDS, water was infiltrated into the subsurface to form groundwater and then discharged into natural streams or rivers as baseflow.

The hydrological performance of SUDS is heavily reliant on the infiltration capacity of the soils, which is dependent on soil hydraulic properties such as water retention, unsaturated hydraulic conductivity curves, initial water content etc. [11–13]. As a result, adequate quantification and modeling of water infiltration in SUDS is critical. According to Archer et al. [14], improved infiltration control could assist in overcoming a variety of problems, including flooding at upper catchment, surface and groundwater pollution, dropping water tables, and ineffective irrigation of agricultural fields. Since infiltration is the mechanism that moves and distributes water from the surface to the soil profile, the soil infiltration rate is likely the most significant factor affecting surface irrigation's uniformity and effectiveness [15, 16]. It is extremely crucial to predict cumulative infiltration for estimating the amount of water entering the soil and its distribution since infiltration impacts both the advance and recession processes.

The factors that affect the infiltration process include the physical, chemical, and biological characteristics of the soil surface, the initial distribution of water in the soil, the movement of water across the surface, the depth of water on the soil surface, inflow rate, cut-off time, length of run and depth of percolation [17, 18]. However, all these factors vary over a field. Therefore, soil infiltration, perhaps, is the most challenging and crucial process to characterize on a field scale, affecting surface irrigation uniformity and efficiency [19]. In the past decades, various methods have been developed to measure the infiltration rate empirically and theoretically. Besides, a few computer models also have been developed to simulate the infiltration rate.

Cerda [20] and Fox et al. [21] discovered that the infiltration rate decreased as the slope angle increased. Diamond and Shanley [22] assessed the infiltration rate in Ireland using a double-ring infiltrometer for freely drained, imperfectly drained, and poorly drained sites and found that the infiltration rate was 3.5 times higher in the summer than in the winter. Lake et al. [23] developed pedo-transfer functions (PTFs) to forecast soil physicochemical and hydrological properties for the Guilan Province of Iran. They discovered that the artificial neural network (ANN) method outperformed the multiple linear regression (MLR) method for estimating the infiltration rate. Joshi and Tambe [24] found that grass-covered areas with gentle slopes resulted in higher infiltration rates and minimal sedimentation, while bare land surfaces with steep slopes led to the lowest infiltration rate, generating more runoff with higher sedimentation rates.

Asry et al. [25] developed infiltration models to study the water infiltration in sustainable urban drainage systems (SUDS) for dry, wet, and intermediate-wet soils. Three physically-based infiltration models, CH1, CH2, and CH3, have been developed based on the Canoe Hydrobox (C.H.) platform to investigate the hydraulic gradient and the equivalent hydraulic conductivity using the Green-Ampt (G.A.) model.

The constant infiltration rates of clay, sand, and black cotton under various soil conditions were studied in Sangola, district Solapur, Maharashtra, by Dagadu and Nimbalkar [26] using the double-ring infiltrometer technique. The results demonstrated that Horton's and Green-Ampt models fit well with observed field data to estimate infiltration rates at any given period with the highest degree of correlation coefficient and the lowest degree of standard error. Rashidi et al. [15] used a double-ring infiltrometer to measure the infiltration rate and observed a relationship between soil infiltration rate and soil content.

Rashidi et al. [15] predicted soil infiltration rate by developing a relationship between soil infiltration rate and soil physical properties, including particle size distribution, sand content, silt content, clay content, bulk density, organic matter, and moisture content of soil using fifty-five multiple-variable linear regression models. The statistical results found that the relationship for the one-variable linear regression model, which is the simplest model, to predict soil infiltration rate is $0.391 * (\text{Sand content}) - 2.917$ with the correlation of coefficient (R^2) of 0.8905. Meanwhile, the equation to predict soil infiltration rate using a five-variable linear regression model, which is the most complicated model, is $28.13 - 0.220 * (\text{Silt content}) - 0.518 * (\text{Clay content}) + 4.592 * (\text{Bulk Density}) - 1.440 * (\text{Organic Matter}) + 0.022 * (\text{Moisture Content})$ with R^2 yielding to 0.9092.

Champatiray et al. [27] discovered that a double-ring infiltrometer outperformed a single-ring infiltrometer for measuring soil infiltration rates. However, double-ring infiltrometer test is time-consuming, arduous, and practically

difficult, especially in hilly terrain. Champatiray et al. [27] also found that plant root fractures, ground movement, and clay desiccation influenced the infiltration rate.

Tsai et al. [28] adopted the Storm Water Management Model (SWMM) to study the hydrological parameter sensitivity for a mostly forested Taiwanese reservoir watershed with pollution from tea plantations. Results revealed that SWMM can accurately simulate the infiltration rate for different soils using the Horton infiltration method. Baiti et al. [29] effectively modeled and analyzed the link between infiltration rate and soil permeability using SWMM for the Tangier Basin in Morocco.

Silveira [30] analyzed the infiltration rate for two Green Stormwater Infrastructure (GSI), namely a Philadelphia Tree Trench and an Infiltration Trench, at the University of New Hampshire (UNH) campus in Durham, United States, using SWMM. The SWMM model could only compute infiltration out the bottom of GSI systems. However, it was found that a sizable amount of additional water infiltrates horizontally out of the GSI system walls. Results indicated that the infiltration rates predicted by SWMM are 33% below the observed value generated by the GSI system. SWMM model performance was improved significantly after including the storage units to model infiltration systems.

Parnas et al. [31] evaluated the Green-Ampt, Horton, and Holtan infiltration methods for three urban sandy soils using two urban hydrological models: SWMM and STORM. Results showed that the Holtan infiltration method is the best, with the ability to account for the storage capacity, maximum infiltration rate, and evapotranspiration in the generation of infiltration capacity.

Sarawak has many soil types with varying hydraulic conductivity, resulting in different infiltration rates. The relationship between different soil types and infiltration rates in Sarawak is still being determined, as no such research has been carried out. Therefore, there is a need to explore the hydraulic conductivity of various soil types in Sarawak, such as Belat, Kabong, Paloh, Mukah, Rajang, Tatau, Semilajau, Pakan, Merapok, Kluang, Bijat, Saratok, Bemang, Bekenu, Seduau, Nyalau, Bandang, Abok, Nibong, Kabuloh, Tarat, Gading, Serin, Kerait, Merit, Semongok, to determine the relationship between soil types and infiltration rates, particularly in the Sarawak region.

According to Melasutra et al. [32], each household in Sarawak has about 10% of the open space in an urban residential area for vegetation, planting flowers, and developing into a playground. These open spaces may aid in infiltrating a certain percentage of rainfall, thus lowering overall surface runoff. Therefore, there is a need to develop easy-to-operate computer-based models with lower calibration effort for determining the total infiltration of various soil types available in Sarawak. Storm Water Management Model (SWMM) will be utilized in this study to estimate water movement beneath the soil surface using data from soil profile characteristics. The novelty of this study is to determine the total infiltration and storage capacities for different unique soil types in Sarawak using SWMM software.

2 Study area

Sarawak covers roughly 124,450 km² and is located between the northern latitudes of 0° 50' and 5° and the eastern longitudes of 109° 36' and 115° 40' E [33]. The total length of the coastline is 750 km. Sarawak and Kalimantan Borneo are divided by high hills and mountains, which are part of Borneo's core mountain range. These rise in elevation to the north, peaking at the Baram River's source on the steep Mount Batu Lawi and Mount Mulu. Sarawak's highest point is Mount Murud [34].

Sarawak has a tropical climate with two monsoon seasons: a northeast monsoon and a southwest monsoon. The northeast monsoon occurs between November and February and produces substantial rainfall. Nevertheless, the southwest monsoon, which occurs between March and October, brings slightly less rain. Generally, the climate is consistent throughout the year, with average daily temperatures ranging from 23 °C in the morning to 32 °C in the afternoon near coastal areas [35]. Compared to other major towns in Sarawak, Miri has the lowest average temperatures and the most prolonged daylight hours (more than 6 h per day).

In contrast, other locations only get 5 to 6 h of sunlight daily. The humidity is usually high, which is exceeding 68%. Annual rainfall varies between 3300 and 4600 mm, raining up to 220 days a year [36]. Highland areas' temperatures range from 16 to 25 °C during the day and as low as 11 °C at night [37].

There are three ecoregions in Sarawak. The coastline region is low-lying and flat, with many swamps and other wetland habitats. Pasir Panjang and Damai beaches in Kuching, Tanjung Batu beach in Bintulu and Tanjung Lobang and Hawaii beaches in Miri are among Sarawak's beaches [39]. Most cities and towns are located on hilly terrain, making up much of the inhabited territory. The ports of Kuching and Sibu are located along rivers, but Bintulu and Miri are along the coast.

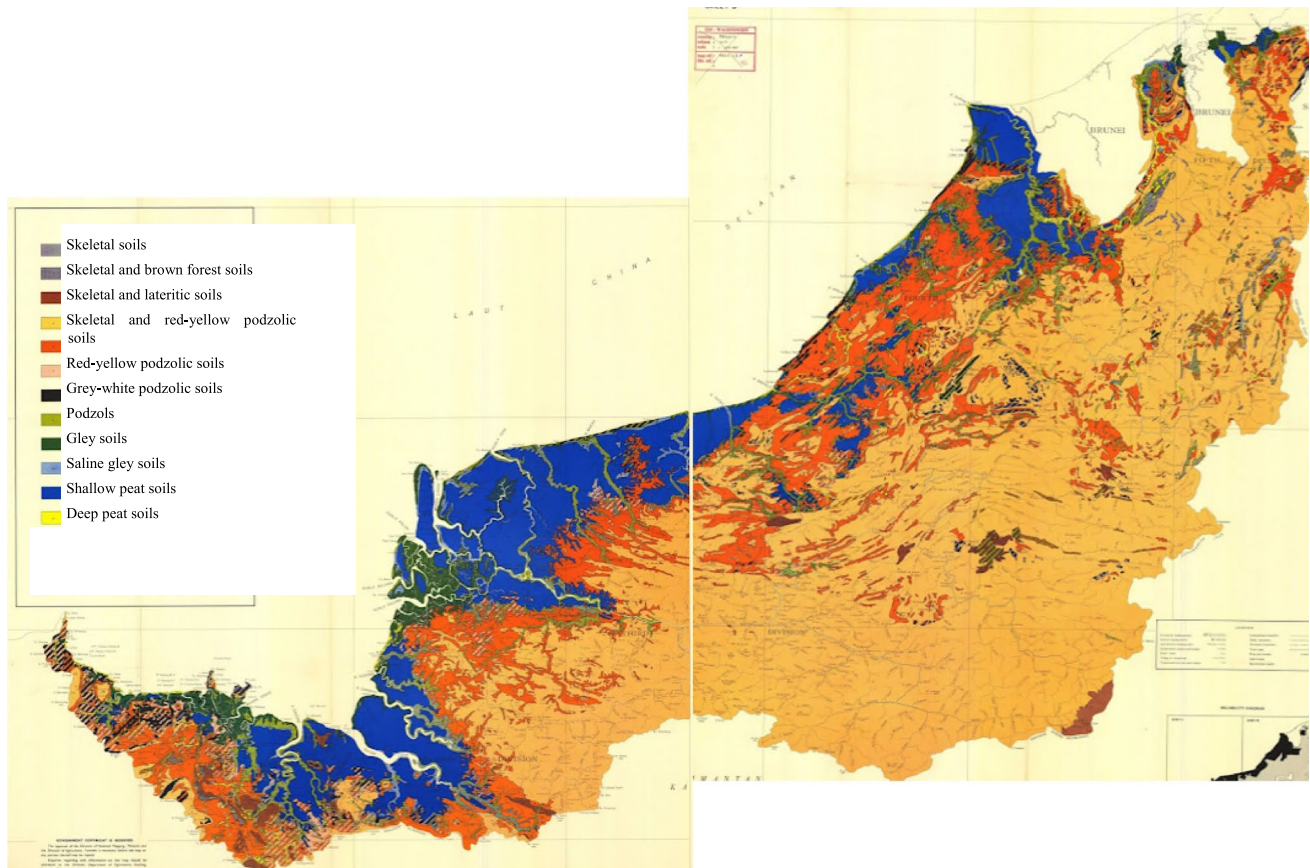


Fig. 1 Different types of soil in Sarawak [38]

The third region is the mountainous area near the Sarawak–Kalimantan international border, which includes settlements such as Bario, Ba'kelalan, and Usun Apau Plieran [40]. The Sarawak River, which flows through Kuching, is the main river in the Southern region of Sarawak [41]. The Rajang River, including its tributary, the Balleh River, is Malaysia's longest river, measuring 563 km. The rivers in Baram, Limbang, and Trusan flow into Brunei in the northern region.

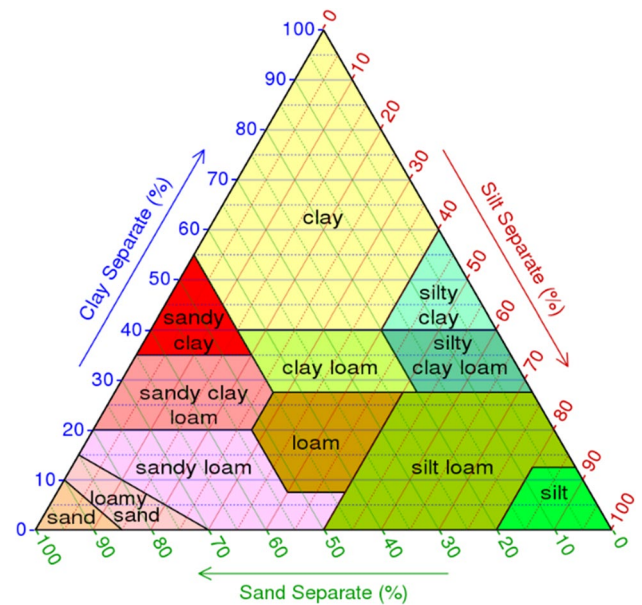
Figure 1 presents different soil types in Sarawak. The two geological zones in Sarawak are Sunda Shield and geosyncline regions. The Sunda Shield stretches from the Batang Lupar River (near Sri Aman) and forms the southern tip of Sarawak. The geosyncline region extends from Batang Lupar River and constitutes Sarawak's central and northern regions. Schist, created during the Carboniferous and Lower Permian periods, is the oldest rock type in southern Sarawak. Whereas andesite, the youngest igneous rock in the region, can be found near Sematan. The late Cretaceous epoch began the geological creation of the central and northern areas. Shale, sandstone, and chert are some stone types found in central and northern Sarawak [42]. The Miri Division, located in eastern Sarawak, is a region of Neogene strata with organic-rich rock formations rich in oil and gas reserves. Mudstones formed during the Middle Miocene-Lower Pliocene age are available at Lambir, Miri, and Tukai, are rich in organic components. Lithosols and podsol comprise 60% and 12%, respectively, of Sarawak soil. Abundant Alluvial soil is found in coastal and riverine regions. Peat swamp forest covers 12% of Sarawak's land area. Limestone with well-developed karst topography and cave systems can be found across Sarawak. However, Limestone is concentrated in certain areas, such as the Bau district in the west and the Kalimantan border in the south [42].

The soil types in Sarawak can generally be divided into five types: sand, sandy loam, loam, clay loam, and clay. The textural classification triangle for different soil types is presented in Fig. 2. Various soil types fall under five different categories of soils, and their unique names are listed in Table 1. Sand is a granular material made up of small rock and mineral particles that have been coarsely split. Sand comes in various components but is defined by its grain size. Sand composition varies depending on rock sources. Silica or silicon dioxide (SiO_2), usually in the form of quartz, is the most prevalent ingredient of sand in inland continental and non-tropical coastal settings. Calcium carbonate is the second most frequent type of sand, mainly formed by various life forms, such as coral and shellfish, over the last

Table 1 Various types of sand, sandy loam, loam, clayey loam, and clay that are found in Sarawak [42]

Sand	Sandy loam	Loam	Clay loam	Clay
Belat	Kabong	Paloh	Mukah	Rajang
Tatau	Semilajau	Pakan	Merapok	Kluang
Bijat	Saratok	Bemang	Bekenu	Seduau
	Nyalau	Bandang	Abok	Nibong
			Kabuloh	Tarat
			Gading	Serin
				Kerait
				Merit
				Semongok

Fig. 2 Textural classification triangle for different soil types [43]



500 million years. Sand can also comprise calcium sulfate minerals such as gypsum and selenite. Belat, Tatau, and Bijat are the sand in Sarawak.

Sandy loam soils are composed of 60% sand, 10% clay, and 30% silt particles. Coarse sandy loam, fine sandy loam, sandy loam, and very fine sandy loam are the four classifications of sandy loam soils. Sand particle size is measured in millimeters, and the concentration of sand particles in the soil is used to identify which category the soil belongs. In sandy loam soils, visible sand particles are mixed into the soil. Sandy loam soils have a high sand content, giving them a gritty texture. Sandy loam soils can quickly drain excess water in gardens and lawns but can't hold considerable amounts of water or nutrients for the plants. Plants cultivated in this soil require more frequent irrigation and fertilizer than those planted in soils with higher clay and silt concentrations. Some examples of sandy loam in Sarawak are Kabong, Semilajau, Saratok, and Nyalau.

Loam mainly comprises sand, silt, and a smaller amount of clay. The mineral composition ratio of sand, silt, and clay by weight is roughly 40%, 40%, and 20%, respectively [44]. Loam soils generally contain more nutrients, moisture, and humus than sandy soils. It has better drainage and infiltration of water and air than silt and clay-rich soils. In most dictionaries, the primary definition of loam is soil with hummus (organic content) and does not mention particle size texture [45]. Paloh, Pakan, Bemang, and Bandang are the examples of loam in Sarawak.

Clay loam has a clay content ranging from 20 to 30%. Because clay-rich loams are so dense, they tend to be heavy. High clay density is the two main flaws of the clay loam. Clay loam swells to retain water when wet, making it difficult to deal with. Poor drainage might also inhibit plant growth. Dry clay shrinks but stays packed, resulting in dense clods and soil surface cracks. Clay loam usually has many plant nutrients and can support a wide range of plants and crops. Clayey loam examples available in Sarawak are Mukah, Merapok, Bekenu, Abok, Kabuloh, and Gading.

Clay is a fine-grained natural soil material that is rich in clay minerals. When wet, clays become plastic due to a molecular film of water surrounding the clay particles. When dry, they become hard, brittle, and non-plastic [46]. There are many clay soil types in Sarawak, including Rajang, Kluang, Seduau, Nibong, Tarat, Serin, Kerait, Merit, and Semongok.

Field measurement is a practical approach to measuring the exact infiltration rates of different soil types. The soil consists of an inorganic fraction of mineral material derived from the bedrock of the soil base and an organic fraction derived from the decayed vegetation or humus layer [47]. The texture and types of soil would affect the drainage system. Hence, knowing the suitable soil types is very important for future planning and design of drainage systems. The characteristics and infiltration rate for different soil types found in Sarawak will be modeled using SWMM.

3 Methodology

The flow process for calibration and development of an infiltration model using SWMM is illustrated in Fig. 3. Three soil samples for each soil type were collected randomly from various fields of the experimental site. The investigation involved five different types of soil, namely sand, sandy loam, loam, clay loam, and clay. Therefore, fifteen soil samples in total were gathered. Soils' physical properties, such as sand content (SA), silt content (SI), clay content (CL), bulk density (BD), organic matter (OM), and moisture content (MC) of the soil samples were measured using laboratory tests as described by the Soil Survey Laboratory Staff [48] to obtain the necessary parameters for calculating soil infiltration rate models. A double-ring infiltrometer with a typical inner ring diameter of 45 cm and an outer ring diameter of 60 cm was used to measure the soil's infiltration rate. Double-ring infiltrometer is a well-known technique for determining or estimating soil infiltration rates. The infiltrometer was installed in the selected location, filled with water, and the initial reading was recorded. The water depth in the infiltrometer was measured and recorded at frequent intervals until the infiltration rate became constant.

After measuring the soil's infiltration on sites, the relevant soil properties will be input into the Stormwater Management Model (SWMM) for model calibration and development. SWMM was first established in 1971, and this dynamic simulation of the rainfall-runoff model could predict the runoff quality and quantity in metropolitan areas [49]. The computational engine was rewritten and developed by adding low-impact development (LID) capabilities in SWMM [50] after multiple significant modifications over the past 50 years.

The SWMM model consists of three routing methods and five infiltration models. The routing methods offered are steady flow, kinematic wave, and dynamic. Horton, Modified Horton, Green-Ampt, Modified Green-Ampt, and Curve Number are the five infiltration models available in SWMM [51]. In this study, the routing approach selected is Dynamic Wave method combined with Horton infiltration approach.

The second stage entails inserting the maps and determining the study catchment area. The study area map was loaded into the model using the *View-Backdrop-Load* function in SWMM. Other essential catchment area characteristics, such as the size of the study area, surface slope, and percentage (%) of impervious area, are also required for model creation.

A total of 8 low impact development (LID) types are available in SWMM. The LID selected for model calibration and development is Bio-retention, which is analogous to stormwater infiltration in open spaces. Table 2 shows soil characteristics for several soil types, including porosity, field capacity, wilting point, and conductivity. These characteristics

Fig. 3 Flowchart for SWMM model development

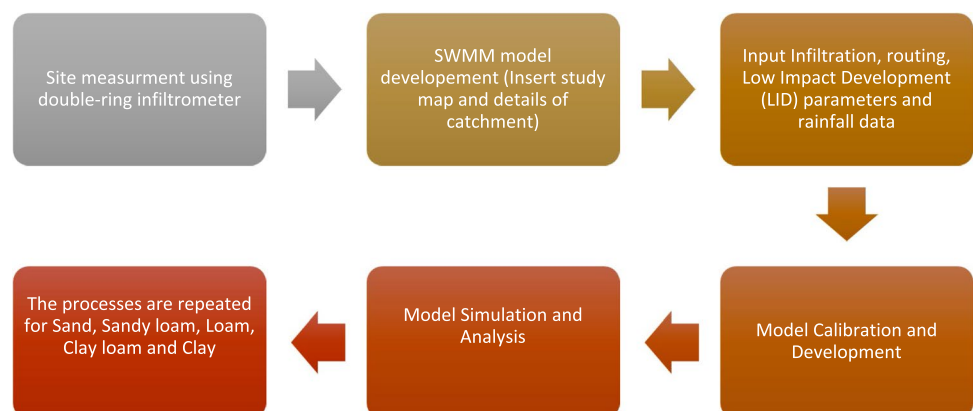


Table 2 Soil characteristics of different soil types

Soil types	Saturated hydraulic conductivity, K (in/h)	Saturated hydraulic conductivity, K (mm/h)	Suction head, Ψ (in)	Suction head, Ψ (mm)	Porosity, ϕ (fraction)	Field capacity, F.C. (fraction)	Wilting point, W.P. (fraction)
Sand	4.74	120.396	1.93	49.022	0.437	0.062	0.024
Sandy loam	0.43	10.922	4.33	109.982	0.453	0.190	0.085
Loam	0.13	3.302	3.50	88.900	0.463	0.232	0.116
Clay loam	0.04	1.016	8.27	210.058	0.464	0.310	0.187
Clay	0.01	0.254	12.6	320.040	0.475	0.378	0.265

Table 3 List of 30 samples available in SWMM LID control editor

Sample no.	Control name	Sample no.	Control name	Sample no.	Control name
1	Sand_0.5 m	11	Sandy loam_2.5 m	21	Clay loam_1.5 m
2	Sand_1m	12	Sandy loam_3m	22	Clay loam_2m
3	Sand_1.5 m	13	Loam_0.5 m	23	Clay loam_2.5 m
4	Sand_2m	14	Loam_1m	24	Clay loam_3m
5	Sand_2.5 m	15	Loam_1.5 m	25	Clay_0.5 m
6	Sand_3m	16	Loam_2m	26	Clay_1m
7	Sandy loam_0.5 m	17	Loam_2.5 m	27	Clay_1.5 m
8	Sandy loam_1m	18	Loam_3m	28	Clay_2m
9	Sandy loam_1.5 m	19	Clay loam_0.5 m	29	Clay_2.5 m
10	Sandy loam_2m	20	Clay loam_1m	30	Clay_3m

indicate soil behavior for various soil types and will be entered as LID Control in the LID Usage Editor. SWMM investigates 30 samples with varying depths in the soil tab, which are at depths of 0.5 m, 1 m, 1.5 m, 2 m, 2.5 m, and 3 m, respectively. Table 3 presents the list of 30 samples investigated with SWMM soil tab.

There are four tabbed sets of process layers to configure, each with data entry fields for the vertical layers and a drainage system that makes up a LID control for a Bio-retention cell. These tabbed sets include the surface layer, soil layer, storage layer, and drain system. The surface layer page describes the surface attributes of all sorts of LID controls. The features of the surface layer include berm height or storage depth, vegetative volume fraction, surface roughness, and surface slope. There is no berm, so this study's berm height is 0. Surface roughness is set at 0.1 by default. The surface slope of the catchment was determined to be 0.7 by calculations.

The soil layer describes the properties of the engineered soil mixture used in bio-retention and the optional sand layer beneath the permeable pavement. These properties are thickness, porosity, field capacity, wilting point, conductivity, conductivity slope, and suction head. For rain gardens, street planters, and other land-based bio-retention units, the standard soil layer thickness ranges from 18 to 36 inches (450 to 900 mm).

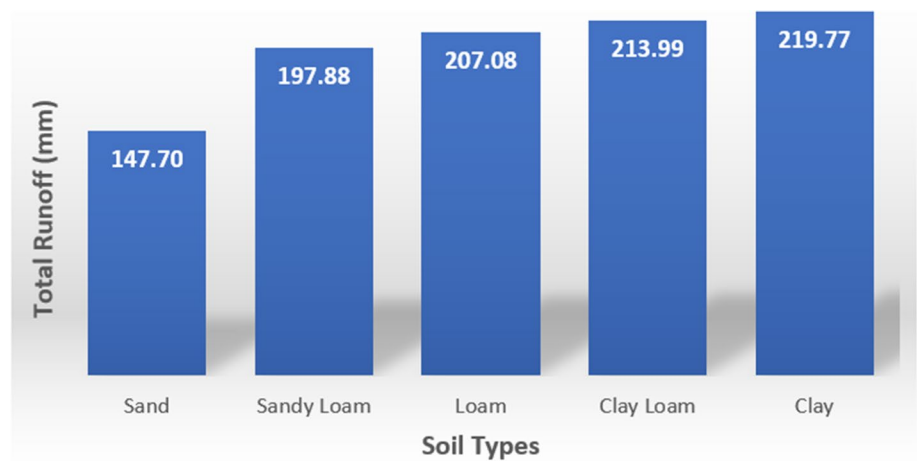
Meanwhile, the wilting point of well-dried soil is the volume of pore water relative to the total volume at which only bound water remains, and the moisture content of the soil cannot decrease below this limit. The typical conductivity slope values are in the range of 30 to 60.

Meanwhile, the features of the crushed stone or gravel layer employed in bio-retention cells are described on the storage layer. The characteristics required for the storage layer are thickness, void ratio, seepage rate, and clogging factor. The thickness refers to the gravel layer or the rain barrel's height. The thickness of crushed stone and gravel layers commonly ranges from 6 to 18 inches (150 to 450 mm). For gravel beds, the void ratio typically ranges from 0.5 to 0.75. If there is no blockage, the clogging value is 0.

The subsequent step is inputting the time series rainfall data on 5th and 6th December 2021, obtained from the Department of Irrigation and Drainage (DID) Sarawak, into the infiltration model. The rainfall data was chosen due to the heavy rainstorms during these 2 days. After all the parameters and relevant information have been entered into SWMM, the model is ready to perform the simulation. The outcomes will be calculated and saved in the report summary.

Table 4 Report summary from the sub-catchment runoff

Types of soil	Sand	Sandy loam	Loam	Clay loam	Clay
Total precipitation (mm)	264.00	264.00	264.00	264.00	264.00
Total evaporation (mm)	0.00	0.00	0.00	0.00	0.00
Total infiltration (mm)	1.64	1.48	1.48	1.48	1.48
Impervious runoff (mm)	48.19	48.19	48.19	48.19	48.19
Pervious runoff (mm)	101.65	101.65	101.65	101.65	101.65
Total runoff (mm)	147.70	197.88	207.08	213.99	219.77
Total runoff (10 ⁶ L)	59.08	79.15	82.83	85.60	87.94
Peak runoff (m ³ /s)	11.84	15.00	15.39	15.54	15.96
Runoff coefficient	0.559	0.750	0.784	0.811	0.837

Fig. 4 Total runoff versus different types of soil

4 Results and discussions

SWMM had performed a high degree of correlation of infiltration rate with the observed data using the Dynamic Wave routing method and Horton's model. These calibration results showed that infiltration rates predicted using SWMM are very close to the ones measured on the field. SWMM predicted 5% and 3% infiltrated volumes lower than the observed sandy and sandy loam data, respectively. The predicted infiltrated volume for loam is 6% lower than the observed data. Meanwhile, higher predicted infiltrated volumes of 7% and 10% were found using SWMM compared to the measured ones for clay loam and clay, respectively.

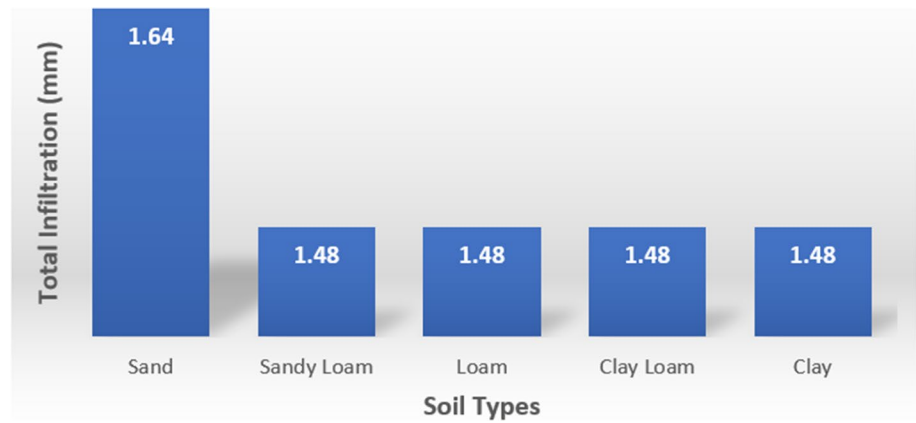
The simulation results are summarised in Table 4. For all types of examined soils, the inputs for total precipitation, impermeable runoff, and permeable runoff are the same. Figures 4 and 5 compare total runoff and total infiltration for all types of soil.

Figure 4 shows that the sand type has the lowest total runoff, at 147.70 mm. The total runoff of sandy loam, loam, and clay loam, is 197.88 mm, 207.08 mm, and 213.99 mm, respectively. Clay is well-known for having poor drainage, resulting in the highest total runoff at 219.77 mm. The result is as expected since the pore spaces, or so-called gaps between particles in clay, are relatively small, allowing water to permeate the soil very slowly. Only a small quantity of precipitation infiltrates during heavy rains. Most of precipitation was turned into surface runoff.

Figure 5 shows that the total infiltration for loam, clay loam, and clay, is only about 10 mm. Sand has a slightly higher total infiltration, with 1.64 mm. This is because sand has more significant gaps, allowing water to flow through and increasing overall infiltration. Furthermore, sand has a higher hydraulic conductivity for water transmission through the soil. These soil characteristics led to more rainwater infiltrating into the sand. Meanwhile, the total infiltration obtained for sandy loam, loam, clay loam and clay, was found to be 1.48 mm.

To further study the flow characteristics of various types of soils, 30 soil samples were simulated at depths of 0.5 m, 1 m, 1.5 m, 2 m, 2.5 m, and 3 m. Tables 5, 6, 7, 8, and 9 present the flow performance for sand, sandy loam, loam, clay loam, and clay, respectively.

Fig. 5 Total infiltration versus different types of soil



In this case study, simulation results indicated that all soil samples with different depths have infiltration loss. The infiltration losses with all soil samples were consistent with the value of 1.477 mm, except for sand with soil depths of 0.5 and 1.0 m. The infiltration for sand with a depth of 0.5 m was found to be 1.635 mm, and 1.487 mm for sand depth of 1 m. The infiltration losses for other soil types with different depths investigated in this study were found to be 1.477 mm.

Results also discovered that the storage capacity of soil is significantly affected by soil type. The soil depth has minimal impact on storage capacity. The difference between initial and final storages for sand, sandy loam, loam, clay loam, and clay at the depths of 0.5 m, 1.0 m, 1.5 m, 2.0 m, 2.5 m, and 3.0 m, were depicted in Fig. 6. Blue lines in Fig. 6 are indicating the initial storage, while the orange line is presenting the final storage of the soils at different depths. The differences between initial and final storage are reflecting the soil storage capacity. For each soil type, Fig. 6 demonstrated that the storage capacities are fairly consistent as the soil depths were increased from 0.5 to 3.0 m.

The highest difference between initial and final storage for sand is roughly 115.54 mm, followed by sandy loam with 66.96 mm, loam with 58.01 mm, clay loam with 51.20 mm, and clay with 48.42 mm. The findings illustrated that sand has the highest storage capacity, followed by sandy loam, loam, and clay loam. Clay had the lowest variation in

Table 5 Summary result of sand performance

SAND depth (m)	0.5	1.0	1.5	2.0	2.5	3.0
Total precipitation (mm)	264.00	264.00	264.00	264.00	264.00	264.00
Evaporation loss (mm)	0.00	0.00	0.00	0.00	0.00	0.00
Infiltration loss (mm)	1.635	1.487	1.477	1.477	1.477	1.477
Surface runoff (mm)	147.70	147.70	147.70	147.70	147.70	147.70
Initial storage (mm)	3.00	6.00	9.00	12.00	15.00	18.00
Final storage (mm)	118.40	121.54	124.54	127.54	130.54	133.54
Continuity error (%)	-0.274	-0.269	-0.265	-0.262	-0.259	-0.256
Difference between initial and final storage (mm)	115.40	115.54	115.54	115.54	115.54	115.54

Table 6 Summary result of sandy loam performance

Sandy loam depth (m)	0.5	1.0	1.5	2.0	2.5	3.0
Total precipitation (mm)	264.00	264.00	264.00	264.00	264.00	264.00
Evaporation loss (mm)	0.00	0.00	0.00	0.00	0.00	0.00
Infiltration loss (mm)	1.477	1.477	1.477	1.477	1.477	1.477
Surface runoff (mm)	197.89	197.89	197.89	197.89	197.89	197.89
Initial storage (mm)	3.56	7.13	10.69	14.25	17.81	21.38
Final storage (mm)	70.53	74.09	77.65	81.21	84.78	88.34
Continuity error (%)	-0.869	-0.857	-0.846	-0.835	-0.825	-0.815
Difference between initial and final storage (mm)	66.96	66.96	66.96	66.96	66.96	66.96

Table 7 The summary result of loam performance

Loam depth (m)	0.5	1.0	1.5	2.0	2.5	3.0
Total precipitation (mm)	264.00	264.00	264.00	264.00	264.00	264.00
Evaporation loss (mm)	0.00	0.00	0.00	0.00	0.00	0.00
Infiltration loss (mm)	1.477	1.477	1.477	1.477	1.477	1.477
Surface runoff (mm)	207.08	207.08	207.08	207.08	207.08	207.08
Initial storage (mm)	14.50	29.00	43.50	58.00	72.50	87.00
Final storage (mm)	72.51	87.01	101.51	116.01	130.51	145.01
Continuity error (%)	-0.923	-0.878	-0.836	-0.799	-0.764	-0.733
Difference between initial and final storage (mm)	58.01	58.01	58.01	58.01	58.01	58.01

Table 8 Summary result of clay loam performance

Clay loam depth (m)	0.5	1.0	1.5	2.0	2.5	3.0
Total precipitation (mm)	264.00	264.00	264.00	264.00	264.00	264.00
Evaporation loss (mm)	0.00	0.00	0.00	0.00	0.00	0.00
Infiltration loss (mm)	1.477	1.477	1.477	1.477	1.477	1.477
Surface runoff (mm)	213.99	213.99	213.99	213.99	213.99	213.99
Initial storage (mm)	23.38	46.75	70.13	93.50	116.88	140.25
Final storage (mm)	74.58	97.95	121.33	144.70	168.08	191.45
Continuity error (%)	-0.930	-0.860	-0.800	-0.748	-0.702	-0.661
Difference between initial and final storage (mm)	51.20	51.20	51.20	51.20	51.20	51.20

Table 9 Summary result of clay performance

Clay depth (m)	0.5	1.0	1.5	2.0	2.5	3.0
Total precipitation (mm)	264.00	264.00	264.00	264.00	264.00	264.00
Evaporation loss (mm)	0.00	0.00	0.00	0.00	0.00	0.00
Infiltration loss (mm)	1.477	1.477	1.477	1.477	1.477	1.477
Surface runoff (mm)	222.77	222.77	222.77	222.77	222.77	222.77
Initial storage (mm)	33.13	66.25	99.38	132.50	165.63	198.75
Final storage (mm)	81.55	114.67	147.80	180.92	214.05	247.17
Continuity error (%)	-0.898	-0.808	-0.734	-0.673	-0.621	-0.576
Difference between initial and final storage (mm)	48.42	48.42	48.42	48.42	48.42	48.42

water storage among all the soil types studied. Figure 7 depicts the relationship between soil types and their storage capacities.

In this instance study, the infiltration rate for sand was found to be 2.541 mm/h, while sandy loam has an infiltration rate of 2.183 mm/h (refer to Fig. 8). Meanwhile, the loam has a lower infiltration rate of 1.432 mm/h, subsequently followed with clay loam 1.039 mm/h. Clay has the lowest infiltration rate of 0.852 mm/h. The results revealed that sand has the highest infiltration rate, followed by sandy loam, loam, clay loam, and lastly, clay soil.

5 Conclusions

This study successfully assessed the performance of various soil features in Kuching area regarding infiltration and storage capacities. The results demonstrate that sand has the maximum porosity and hydraulic conductivity, allowing water to flow freely and increasing total infiltration. The infiltration of sandy loam is the second most remarkable, followed by loam, clay loam, and clay. Total runoff is inversely proportional to infiltration. The more water penetrates, then less

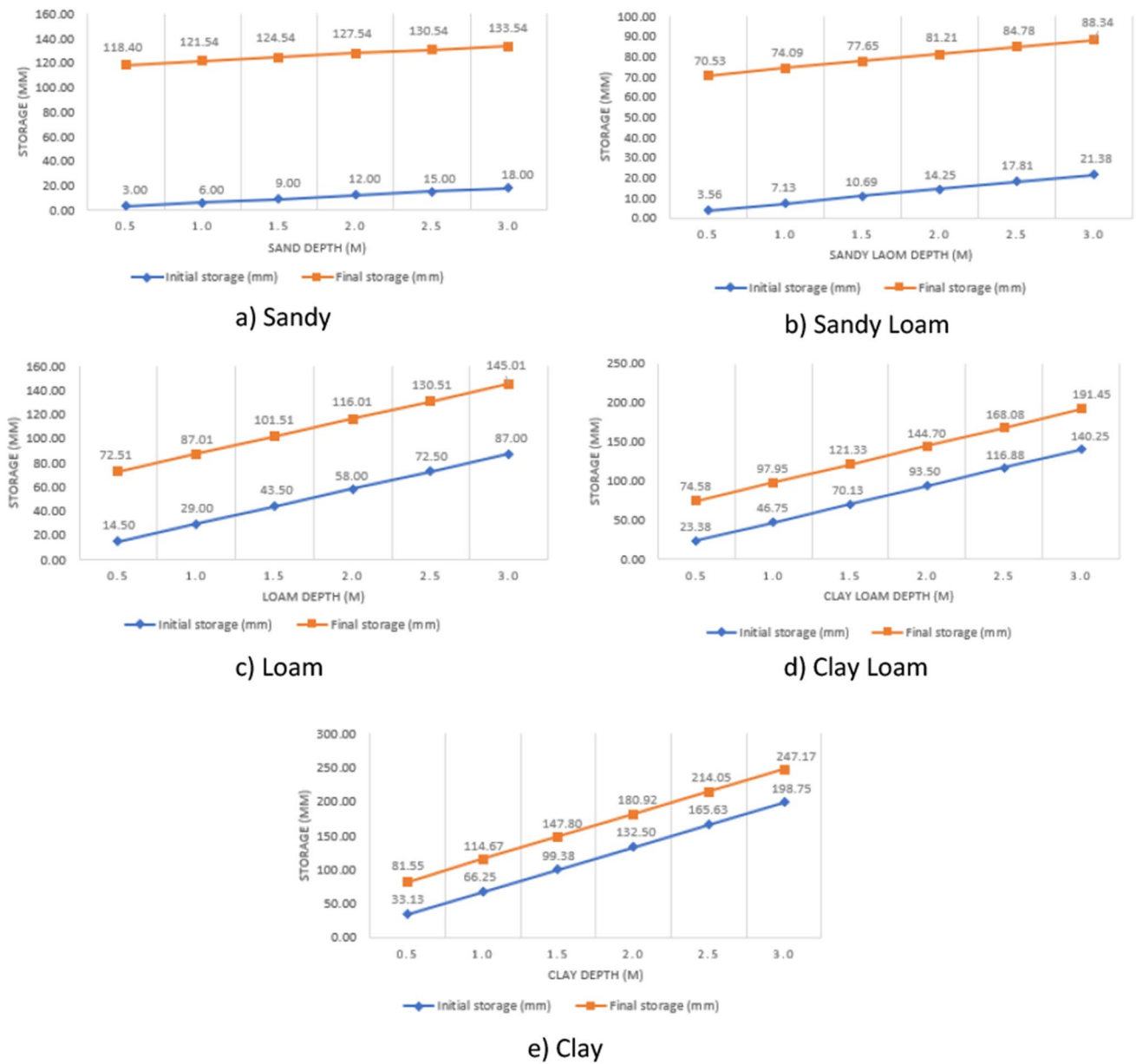


Fig. 6 Initial and final storage for various types of soil

Fig. 7 Storage capacity for different soil types

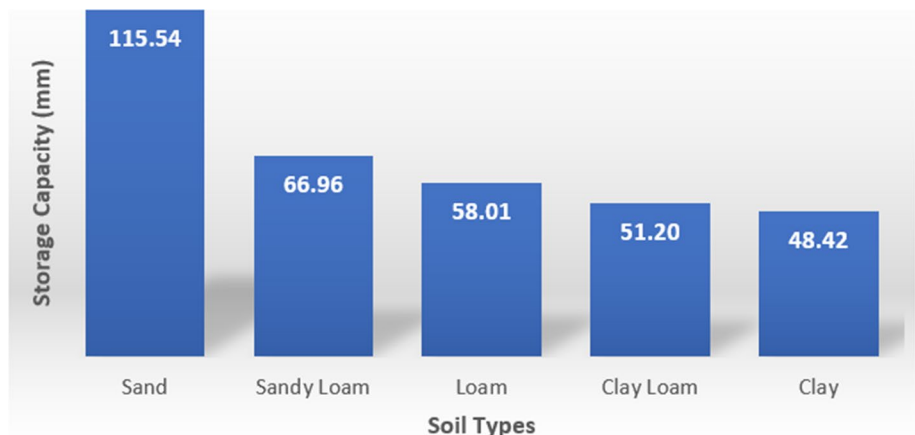
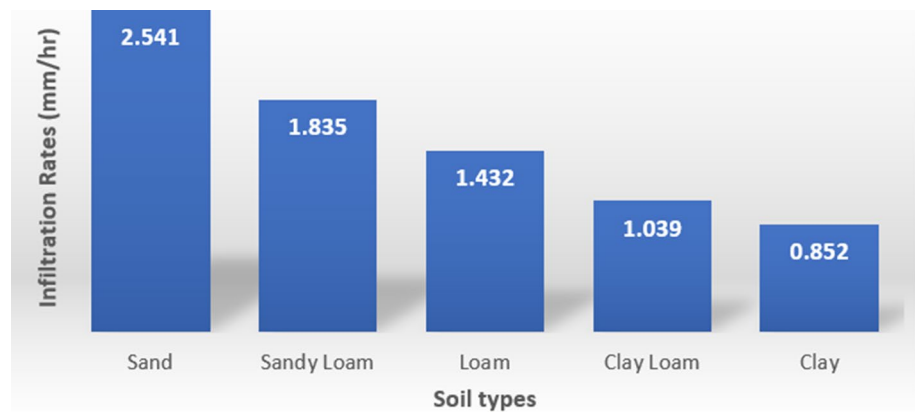


Fig. 8 Infiltration rates of different types of soil



water will be converted into surface runoff. Conversely, as the infiltration rate is poor, more runoff is generated. The low infiltration rate may cause a flash flood when most rainwater is turned into surface runoff. The difference between initial and ultimate storage capacity revealed that sand has the most significant water storage capacity, followed by sandy loam, loam, clay loam, and clay.

This study is significant since it is the pioneer study of the infiltration for different soil types in Sarawak. Results revealed that sand has performed remarkably with the ability to reduce surface runoff through infiltration compared to other investigated soil types. Hence, it is suggested that the relevant authority develop a detailed chart relating the total infiltration with different catchment sizes and rainfall intensities. The precise amount of infiltrating water for sand in new development areas is important for developing a sustainable and cost-effective drainage system. Meanwhile, the infiltration capacities of sandy loam, loam, clay loam, and clay are negligible and can be disregarded when designing a drainage system.

Author contributions KKK: planning, contribute original idea, modelling and writing the manuscript. PCC: modeling and writing the manuscript. MRR: writing and editing the manuscript. KAbMS: editing the manuscript. MYC: proof read the manuscript.

Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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