

Enhancing Infiltration Capacity in Urban Residential Land Using Artificial Infiltration Device

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Abstract Land use change from catchment area to residential can reduce infiltration volume, decrease infiltration capacity, and increase surface runoff. This research develops an artificial infiltration device focused on micro-scale stormwater management in residential areas that is modular, economical, and can be integrated with urban drainage systems to be applied on narrow lots. Artificial infiltration device is in the form of a shallow well measuring 50cm × 50cm × 100cm, with geotextile-covered walls and a palm fibre-covered base. In the centre of the well, a perforated PVC pipe with a diameter of 4 inches and a split of 2×3 cm is installed to facilitate the flow of water and prevent the wall of the well from collapsing. The first stage of the research involves collecting and testing soil samples from 10 residential properties to determine soil characteristics and infiltration. The second stage measures the performance of the artificial infiltration device using data on the roof area, rainfall, inflow, and outflow volumes. The final stage evaluates the performance of the device by determining the infiltration capacity using Horton's equation and the relationship between rainfall intensity, surface runoff, and infiltration. The results show that using 1 unit of artificial infiltration device with an average rainfall intensity of violent category and an average roof area of 30 m² can increase the infiltration capacity 11 times, from 72.3 mm/hour to 798 mm/hour. This result shows a significant increase in the device's water absorption capacity. The device slowed the onset of surface runoff to an average of 12.5 minutes, potentially reducing the flood peak. The device also increased the critical point from the 3rd to the 48th minute, increasing infiltration volume and

reducing surface runoff. The infiltration device can reduce the risk of flooding and inundation in urban residential land.

Keywords Infiltration Capacity, Artificial Infiltration Device, Urban Residential Land

1. Introduction

Most rainwater that falls on the ground is naturally absorbed into the soil through a process known as infiltration [1], [2]. This infiltration is influenced by several factors, including rainfall intensity, land slope, existing vegetation, soil moisture, and levels of soil permeability [3], [4]. Land conversion often occurs as urban areas experience population growth and increased development. This transition leads to a reduction in vegetation and an increase in surfaces covered by impermeable materials, thereby hindering natural infiltration [5], [6].

Land use change from stormwater catchment areas to residential areas can disrupt the water cycle in the area [7], [8], [9]. This change reduces the amount of water infiltrating, reduces infiltration capacity, and increases surface runoff [10], [11], [12]. These changes are caused by construction activities where the original soil is replaced with selected fill soil to achieve high soil-bearing capacity, heavy equipment traffic during construction, and compaction activities [13], [14], [15], [16]. These conditions change soil parameters such as density, structure, and porosity so that more rainwater becomes surface runoff

[17], [18]. Surface runoff enters drainage channels and rivers, causing the capacity of rivers to be unable to accommodate excess runoff, resulting in flooding. Delaying surface flow and reducing flood peak flows can be achieved by reducing the volume of surface flow through artificial infiltration [19], [20], [21], [22], [23].

Artificial infiltration is a solution to reduce surface runoff by increasing the infiltration capacity of the soil [24], [25], [26], [27]. Various types of engineered infiltration are widely used, such as leaky wells, retention trenches, infiltration basins, infiltration cells, and infiltration pipes or galleries. An infiltration gallery is a cell or pipe filled with a permeable material that facilitates water infiltration into the ground [28], [29]. Infiltration galleries are often used in urban and residential areas to manage stormwater runoff [30], [31], [32].

In this study, an artificial infiltration device has been developed that combines various functions of previous types of artificial infiltration, such as infiltration galleries, infiltration wells, porous troughs, and infiltration trenches, so that they can be applied according to the characteristics of urban residential areas. This research offers novelty by developing artificial infiltration devices that use materials that are easy to obtain, can be applied to narrow plots, are modular, economical, and integrated with urban drainage systems. The tool focuses on micro-scale stormwater management in residential areas, providing effective and sustainable local solutions. This innovation will contribute to the development of artificial infiltration methods and water resource management in urban areas, helping to reduce flood risk and improve groundwater conservation in line with the Sustainable Development Goals (SDGs).

2. Materials and Methods

2.1. Study Area

The location for sampling and testing using artificial infiltration tools was carried out in urban residential areas in Padang City, West Sumatra Province, Indonesia. The location selection is based on the function of the land as residential land and the performance factor of the infiltration gallery, which can function as artificial infiltration. It has a water surface elevation greater than 2 meters. Determining research location points for data collection and testing was carried out using a grid system, where the Padang City - Indonesia area was divided into 16 grids. Figure 1 presents the results of mapping the location point of the research site.

2.2. Research Stages

The first stage of the research is the manufacture and installation of an artificial infiltration device. The device is a shallow 50cm × 50cm × 100cm well. The walls and top of the well are lined with non-woven geotextiles ($K = 8 \times 10^{-4}$ cm/sec) [33] to act as a partition between the original soil and the infill crush aggregate. The bottom of the well is lined with a 10 cm thick layer of palm oil to prevent sediment jumping due to uplift. A vertical 4" PVC pipe is installed in the centre of the well. The pipe is drilled first. The diameter of the holes is 12 mm, with 5 cm between each hole. At the top end of the pipe (still in the ground), a 4-inch horizontal pipe is connected, which drains excess water from the artificial infiltration system to the municipal drainage system (Figure 2). The space between the pipe, the box wall, and the palm oil layer is filled with 2×3 cm splits, which act as a smooth downward flow of water and also serve to prevent the well wall from collapsing. The split should be larger than the vertical hole in the pipe so that the split does not go into the hole.

The second stage is to determine the soil characteristics and infiltration in the residential areas of the study area. The soil characteristics are known by taking samples in the residential land of the study area (10 residential locations). The samples consisted of disturbed and undisturbed soil samples. The soil samples were tested in the laboratory to determine soil physical properties, soil texture, bulk density, and permeability. Infiltration of the surface layer of the soil was also carried out at the ten residential sites using a double-ring infiltrometer to determine the infiltration rate.

Data regarding the infiltration rate was obtained by conducting measurements on the infiltration gallery prototype, specifically focusing on the roof area that collects rainwater (A), the duration of the rainfall (t), the depth of the rainfall (d), the volume of water entering the artificial infiltration device, the measurement time (t), and the volume of inflow to the artificial infiltration device. The infiltration rate can be determined using the following formula:

$$f = \frac{\Delta h}{\Delta t} \quad (1)$$

Δh is the change in water level (mm) obtained by dividing the volume of incoming water by the cross-sectional area of the infiltration gallery. The inflow volume is calculated using the formula $A \times d$. Δt is the time interval (minutes).

The final stage of the research is the performance of the artificial infiltration device. The performance is known by analysing the measured data to obtain the infiltration capacity. The infiltration capacity is calculated using Horton's equation:

$$f = f_c + (f_o - f_c)e^{-k.t} \quad (2)$$

Where f is the infiltration capacity in cm/s, f_o is the initial infiltration rate (cm/s), f_c is the final infiltration rate (cm/s), t is the time since the onset of rain (sec), and k is a constant value that depends on soil type and vegetation.

The relationship between rainfall intensity, surface runoff, and infiltration capacity was also determined. The results of this analysis were used to determine the increased infiltration capacity and reduced surface flow levels that occur when artificial infiltration devices are used.

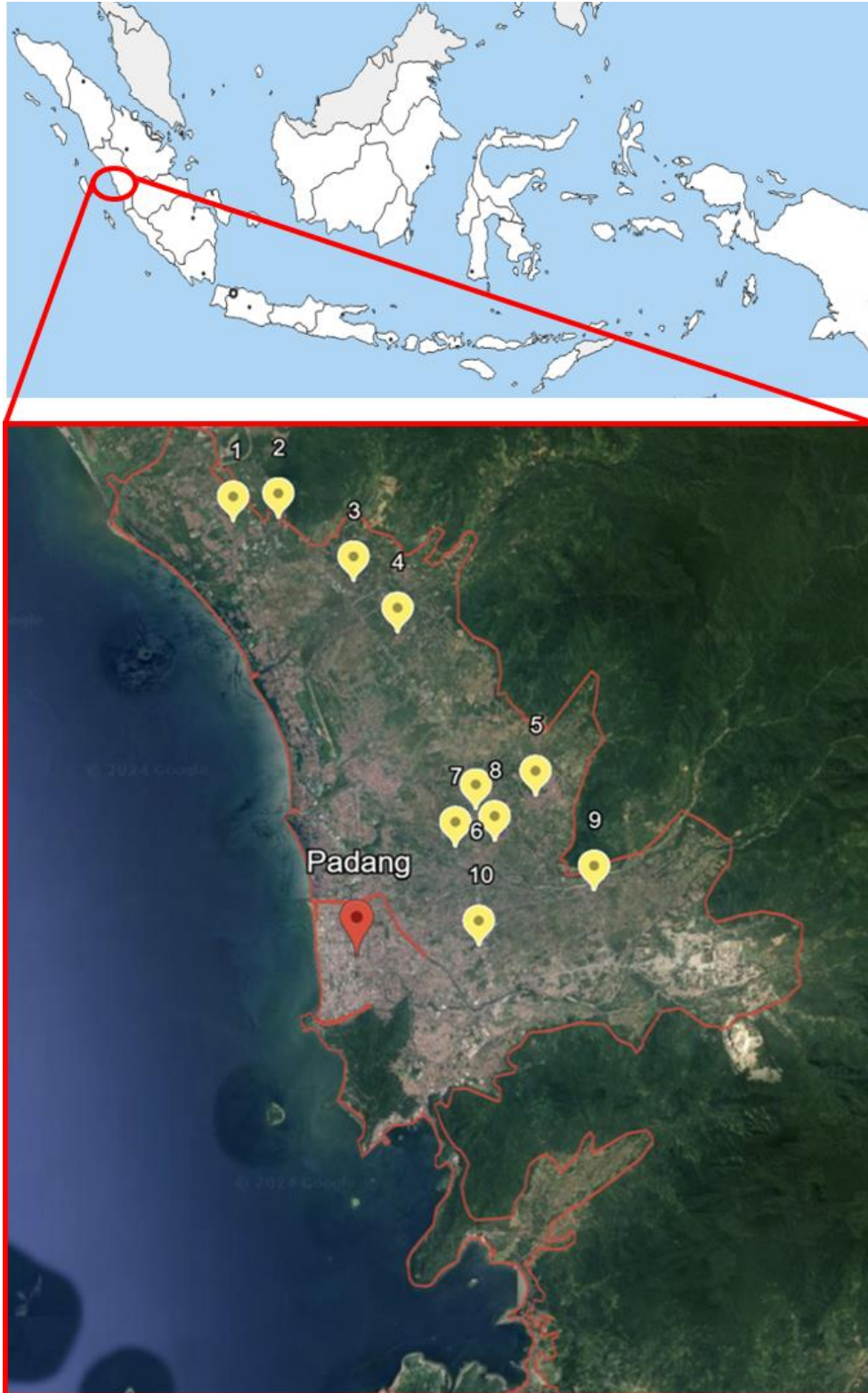


Figure 1. Research location

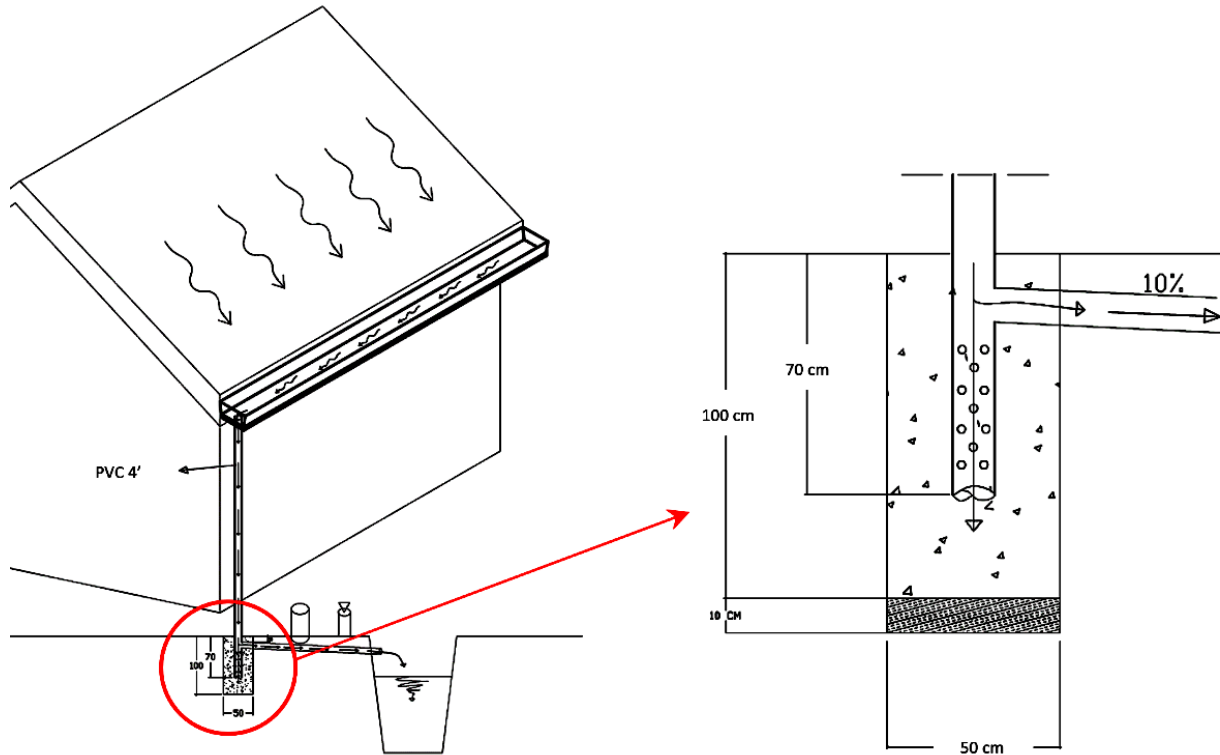


Figure 2. Installation of artificial infiltration device

2.3. Collecting Data Technique

The research data collection was divided into two groups. The first group is data obtained by measuring directly in the field, such as rain depth (d), roof area (A), the thickness of the backfill soil layer, the ratio of yard area to house building area, *inflow volume*, *outflow volume*, and infiltration rate using a *double ring infiltrometer*. The second group is data obtained through testing soil samples in the laboratory, including water content (ω), bulk density (γ), specific gravity (G_s), porosity (n), soil texture, dry density (γ_D), relative density (D_r), permeability (K), and split permeability.

2.4. Infiltration Testing Using Artificial Infiltration Device

The test mechanism is that rainwater falling from the roof of the house flows into the gutters, and then the rainwater flows through the PVC pipe to the artificial infiltration device. A rain gauge is also installed at the site of the infiltration device.

Infiltration data is collected from the time it starts to rain until it stops. The measured parameters are rainfall duration (t), rainfall depth (d), and outflow volume (V). Rainfall depth is measured with a rain gauge, which is read at every predetermined time interval, and the outflow volume is collected with a measuring cup, which is measured at every time interval equal to the time interval of the rainfall depth reading.

During the research, measurements were conducted under three different rain conditions: violent, heavy, and moderate. An artificial infiltration tool was set up at ten residential sites, and ten measurements were recorded at each site, resulting in 100 sets of measurements. All measurement results were recorded on the measurement form. A double-ring infiltrometer was used to compare the performance of the artificial infiltration device. Measurements were taken by inserting the ring into the soil to a depth of 10 to 20 cm. Measurements were taken three times for one settlement site, resulting in 30 measurements.

The interval between rain measurements and the next rain measurement is a minimum of 3 days after the previous rain measurement and a maximum of 10 days. This ensures that the results are not influenced by the previous rainfall. This is so that the previous rain does not influence the measurement.

3. Result and Discussion

3.1. Artificial Infiltration Device Performance

The infiltration rate and capacity values are derived from assessments using an artificial infiltration tool with several key characteristics. This tool features a box measuring 50x50x100 cm, serving as the primary container to direct water into the soil. The depth of 100 cm allows the tool to penetrate the surface layer and reach a deeper percolation zone. PVC pipes are integral components that facilitate water infiltration. Holes with a diameter of 12 mm enable

water to enter uniformly along the pipe at greater depths, thereby expanding the area for water seepage into the soil. The space between the pipe and the walls is also filled with split materials, which act as a percolation medium that enhances water flow from the box to the soil. This configuration helps maintain stable water flow while preventing the surrounding soil from becoming overly dense.

3.1.1. Infiltration Rate

An infiltration curve represents the infiltration rate using an artificial infiltration device. Infiltration rate curves were constructed using data from measurements taken in each residential area. First is the curve for one measurement, then ten at one site. Ten different locations had similar curves plotted, which led to the creation of an average

infiltration rate curve for each location on a logarithmic scale.

Figure 3.a presents the average infiltration rate curve for each location, with each location measured ten times. Subsequently, an overall average infiltration rate curve was created, encompassing all locations (1 to 10). The trend curve of the infiltration rate depicted in Figure 3.a was then utilized to establish the infiltration rate value using an artificial infiltration tool at any specified time (Figure 3.b).

The curve showed that the average constant infiltration rate (f_c) was 15.2 mm/min or 912 mm/hour. This value falls within class 7 (very fast). In terms of infiltration area classification, it is in zone 1 (very high). Thus, this artificial infiltration device can infiltrate an average volume of water of 1,050,000 m³/h/km²

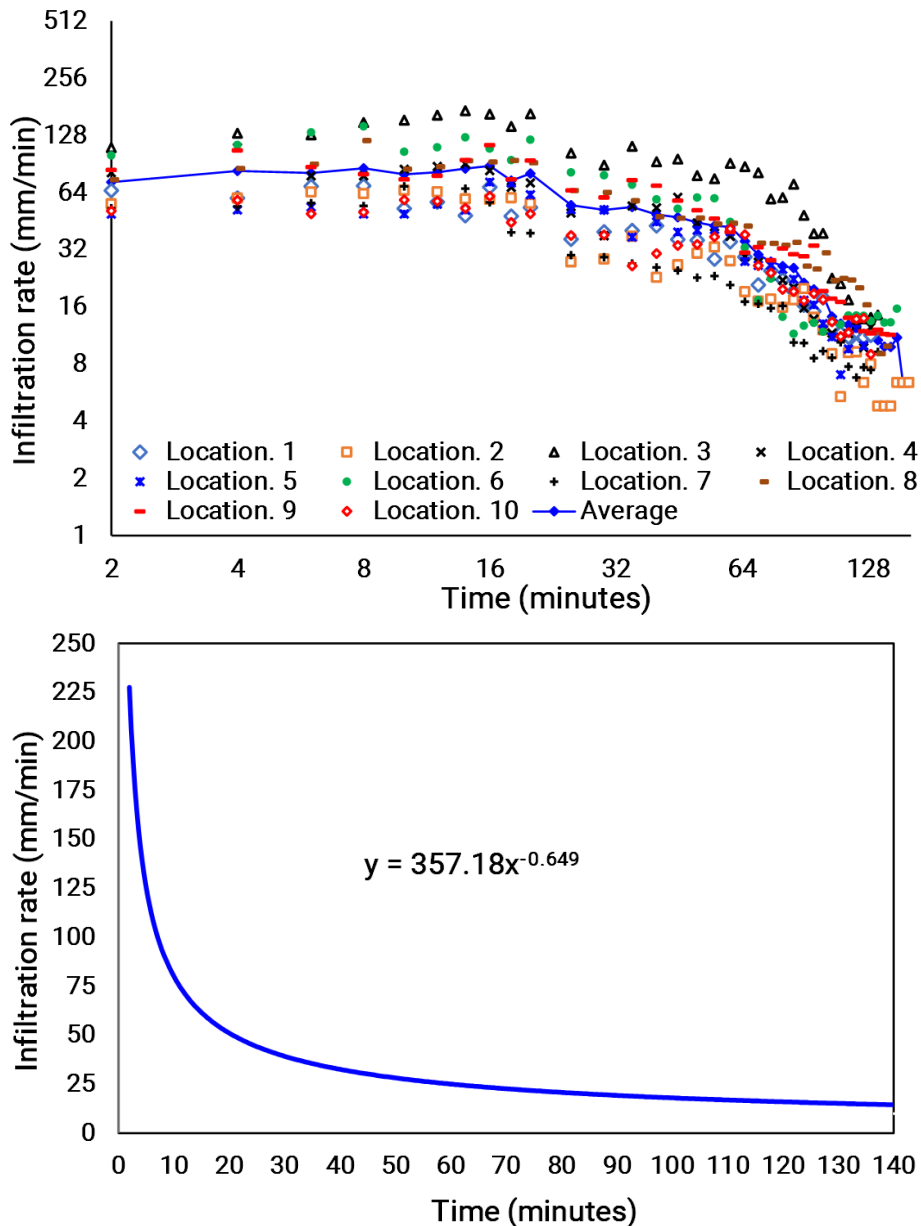


Figure 3. Infiltration rate using the artificial infiltration device

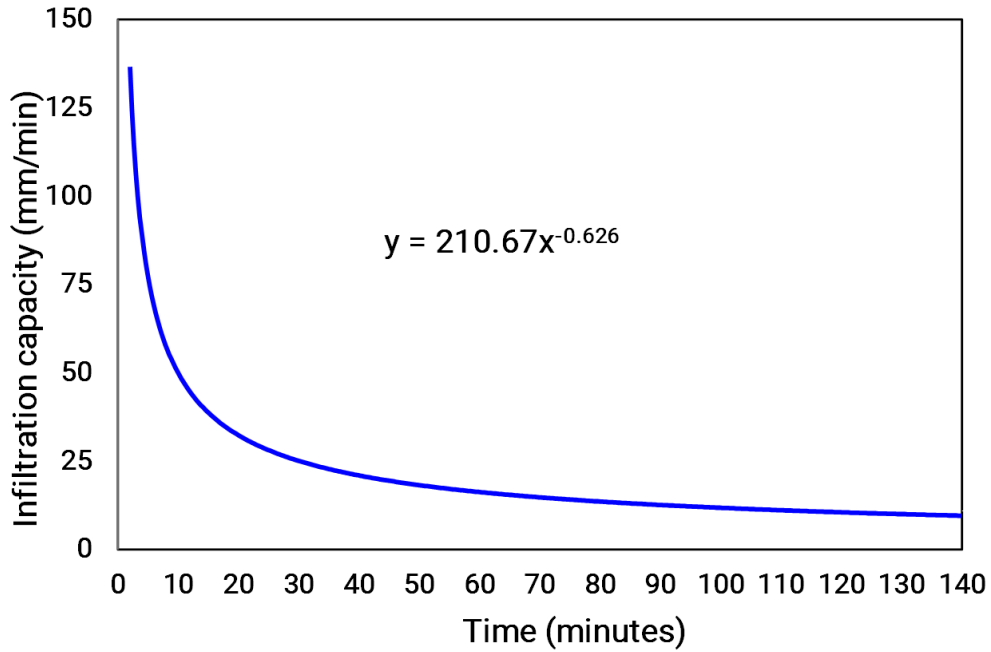


Figure 4. Infiltration capacity using the artificial infiltration device

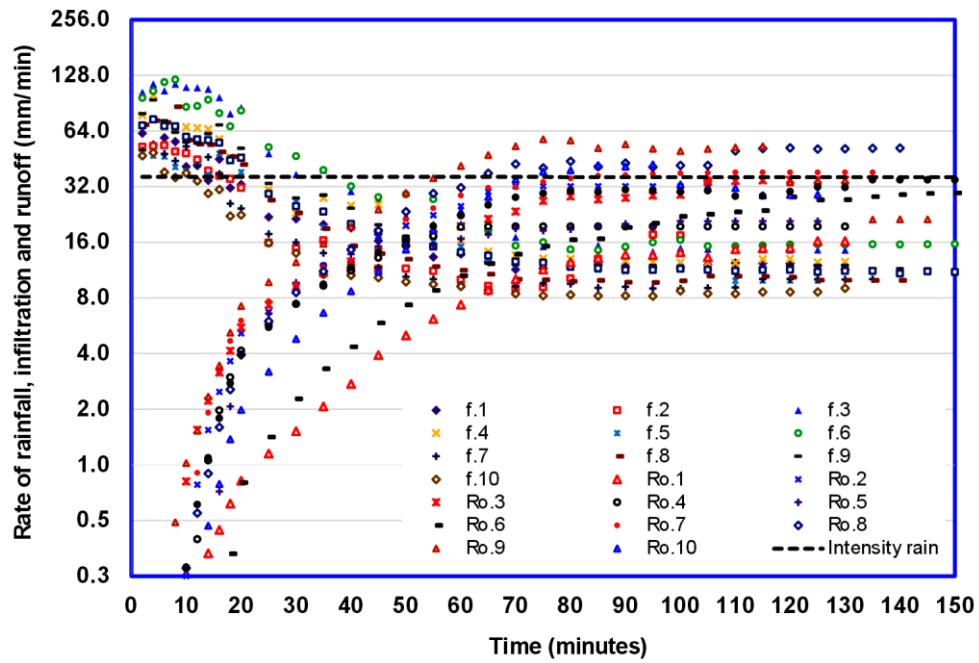


Figure 5. Relationship of infiltration capacity, surface runoff, and rainfall intensity

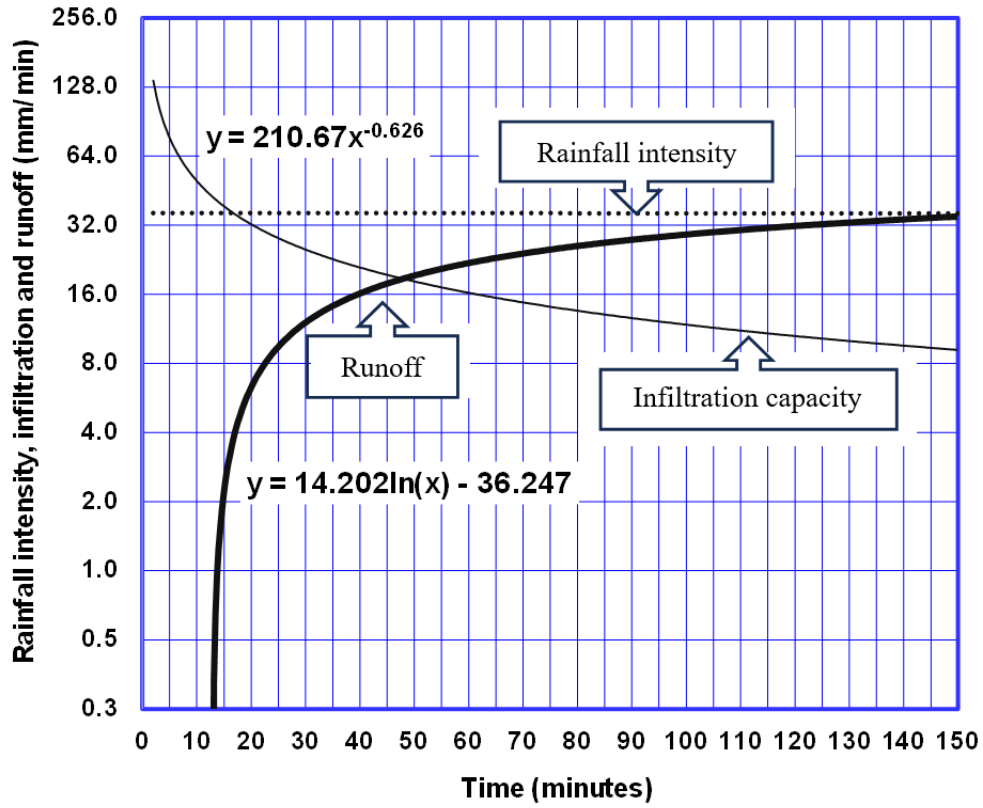


Figure 6. Relationship of infiltration, surface runoff, and rainfall intensity by using artificial infiltration device

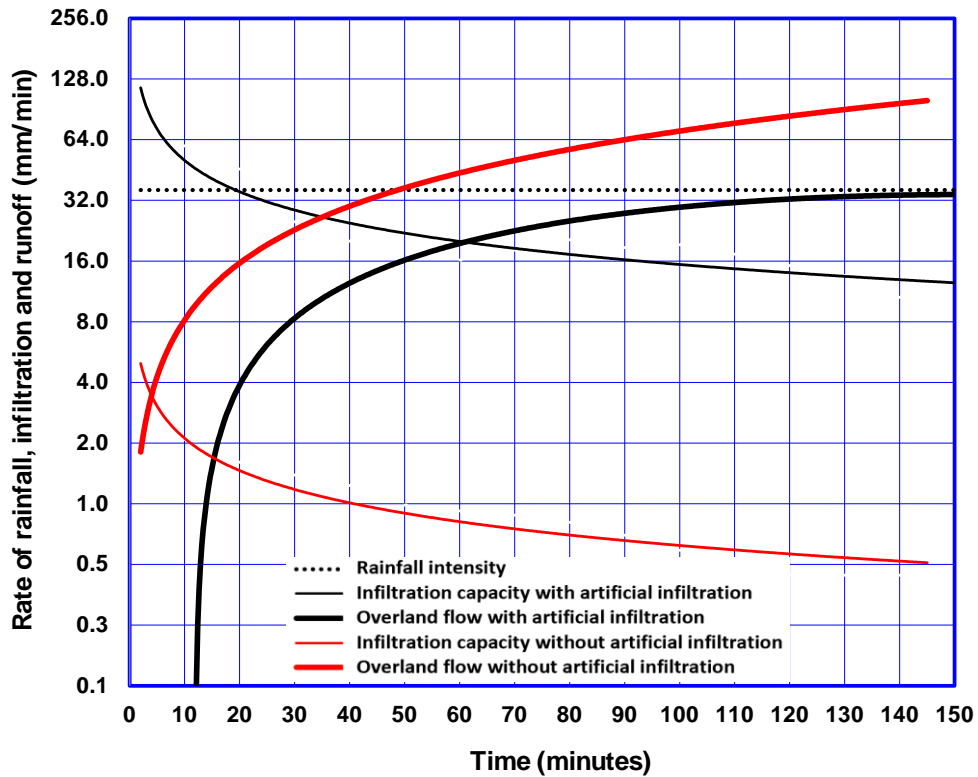


Figure 7. Comparison of infiltration capacity and surface flow with and without using artificial infiltration device

3.3. Enhance Infiltration Capacity and Reduce Surface Runoff

The increase in infiltration capacity and the reduction in surface runoff can be seen by comparing the value of infiltration capacity and the value of surface runoff on land with and without artificial infiltration devices (Figure 7).

Artificial infiltration devices showed a significant increase in soil infiltration capacity and a reduction in surface runoff rates. On land without an infiltration prototype, infiltration capacity was measured using a double-ring infiltrometer, which showed an initial infiltration capacity of 216 mm/h and a constant infiltration capacity of 39 mm/h. After the artificial infiltration device was implemented, the initial infiltration capacity increased significantly to 12,6 mm/h, while the constant infiltration capacity increased to 573 mm/h. These results show that artificial infiltration devices can significantly increase water absorption.

The infiltration capacity calculated using the Horton method increased by about 11 times, from 72.3 mm/h to 798 mm/h, for each catchment with an average area of 30 m². Additionally, the use of artificial infiltration devices resulted in a noticeable delay in the start of surface runoff, from instantaneously to 12.5 minutes. This delay has a significant impact on reducing flood peaks, which is beneficial for urban flood management.

This developed artificial infiltration tool provides a much higher increase in infiltration capacity compared to other infiltration tools such as infiltration galleries, infiltration wells, and infiltration trenches. The effectiveness of this increase is especially for limited land, such as urban settlements, to reduce the risk of flooding.

4. Conclusions

The use of 1 unit of artificial infiltration device with an average rainfall intensity of 36.2mm/hour (violent category) and an average house roof area (catchment area) of 30 m²:

- It can increase the infiltration capacity 11 times, from 72.3 mm/hour to 798 mm/hour. This shows that this artificial infiltration device can increase the water absorption capacity.
- It significantly slowed down the onset of surface runoff from the beginning to the 12th minute. The flood peak could be significantly reduced if artificial infiltration devices were used in all residential areas.
- It can increase the critical point from the 4th to the 62nd minute. This shift can increase the infiltration volume and reduce the surface flow, reducing the risk of flooding and inundation in urban residential areas.

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