Study on behavior of ponding time based on characteristics of infiltration rate and rainfall intensity with varying return period

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Abstract. Runoff management is based on two main concepts: controlling runoff discharge and managing concentration (Tc). Tc is closely related to understanding ponding time (tp), which is associated with estimating the length of tp on a land surface. The present study aims to investigate the behavior of tp due to varying infiltration rates (f) and rainfall intensities (i) with different return periods (Tr). The ponding time (tp) was derived from graph analysis of infiltration rate and rainfall intensity with Tr 2, 5, and 10 years. Infiltration measurements were conducted at 8 points using a double-ring infiltrometer. Meanwhile, rainfall data were obtained from 2010 to 2019. The observed tp (tpobs) was derived through overlying between infiltration rate curve and rainfall intensity. In contrast, empirical tp (tpemp) was estimated using Horton's formula. The result confirms that the infiltration rate followed an exponential curve and varying rainfall intensities. Infiltration rates give vary in tp where the longer Tr, the faster the initial time of tp. There was fairly good consistency between tpobs and tpemp as shown by relatively high-value $R^2$ >0.6) for Tr 2, 5, and 10 years. It indicates that the Horton's formula has reliable to estimate tp in the study area.

keywords: Infiltration rates, rainfall intensities, runoff

1. Introduction
Watershed hydrology in urban areas is dominated by the study of rainfall partitioning into infiltration and surface runoff. This topic is essential in the watershed hydrology study [1]. The rapid physical development resulting from high population growth and urbanization has changed land use in urban areas [2]. Changes in land use, which are generally in the form of the development of settlements, industry, and urban facilities, have the impact of disrupting the hydrological cycle. That's because of reduced infiltration of rainwater into the soil and increased surface runoff [3,4]. Naturally, some rainwater that falls on the earth's surface infiltrated into the ground, while the remaining part flows as surface runoff [5,6]. A good understanding of the infiltration process and its influential factors is needed as a reference for implementing effective water management and land use, particularly in urban areas.
An effective surface runoff management is closely related to two things, namely the runoff volume and the time of concentration \( (T_c) \) controlling \([9]\). \(T_c\) is frequently associated with understanding the initial inundation time (ponding time, \(tp\)). Ponding time \( (tp) \) is a term used in infiltration studies to describe the transition from infiltration at a rate less than the capacity rate to infiltration at the capacity rate \([10]\). It depends partly on local soil surface micro-relief, infiltration rate, and rainfall characteristics \([11,12]\). Information about ponding time can estimate when flooding begins on the land, which is the onset of the surface runoff. Some researches discussed concerning ponding time had been conducted previously. \([13]\) develop a method for predicting ponding events in level basins, emphasizing the impact of different irrigation practices on ponding time characteristics where the result showed that land irrigation affected the maximum expected ponding time. \([14]\) focussed on factors that affect infiltration rate that influence the characteristics of ponding time. However, the study did not include the effect of varying rainfall intensity in those relationships. \([15]\) used field-measured surface water depths for an irrigation basin and an irrigation border to investigate the impact of variable-ponded depth on estimated infiltration levels. There is a lack of employing varying rainfall intensities on infiltration rate and investigating its influence in ponding time behavior. The present study has an objective to examine the behavior of ponding time based on characteristics of infiltration rate and rainfall intensity with varying return periods.

[7,8]. The volume of surface runoff could be determined by knowing the ponding time. It is helpful to design runoff management infrastructure, particularly in urban areas.

2. Material and Methods
This study was conducted on the campus of the University of Brawijaya in Malang, East Java Province, Indonesia, which is located between 7°57'6.79" to 7°57'15.74" N latitude and 112°36'43.23" to 112°36'54.51" E longitude. The campus area is 22.04 ha. The bare area is 21.00 ha, while vegetated land and 1.04 ha of building space. The research was carried out in eight measurement locations, as shown in Figure 1. The location of measurement points was determined based on the similarity of the land

![Figure 1. Location of the measurement point](image-url)
cover in the study area, where the area occupied by grassland was selected as the point of measurement. Additionally, detailed information about the altitude, longitude, and latitude of each measurement point was recorded.

Field measurements were conducted from May 2019 to September 2019, consisting of infiltration measurements and soil sampling at each measurement point. The rainfall data for 2010 – 2019 were obtained from Automatic Rainfall Recorder (ARR) managed by the Laboratory of Hydrology, Water Resources Engineering Department, Universitas Brawijaya. The period of rainfall data collected consists of hourly rainfall data and annual maximum daily rainfall data. Hourly rainfall data is used to estimate the distribution of hourly rainfall. In contrast, annual maximum daily rainfall data obtain design rainfall with various considered return periods. The infiltration rate was measured using a Turf-tec Infiltrometer Model of the IN2-W. This tools consists of two concentric metal cylindrical rings, inner ring (D = 6.03 cm; H = 17.78 cm) and outer ring (D = 10.79 cm; H = 15.24 cm). The equipment was designed with a timer and water level indicator of water level scale in inches and millimetres. Figure 2 displays the Turf-tec Infiltrometer Model of the IN2-W used in this study [16].

![Double ring turftec-infiltrometer](image)

**Figure 2.** Double ring turftec-infiltrometer

### 2.1. Rainfall analysis

The Rainfall analyses consist of rainfall intensity and design rainfall analyses. In this study, the rainfall intensity was derived from the recorded rainfall depth divided by the duration of the collection period. Hourly rainfall data collected from Automatic Rainfall Recorder used for obtaining rainfall intensity and hourly rainfall distribution. Further, the hourly rainfall distribution was employed to compute hourly design rainfall intensity and subsequently analyze ponding time. In the present study, the rainfall intensity was approached by using the Mononobe equation developed by Dr. Mononobe as shown in equation (1) as follows [17,18]:

\[
I = \frac{R_e}{T} \left[ \frac{T}{t} \right]^{\frac{3}{5}}
\]  

(1)
Where $I$ is rainfall intensity (mm.hr$^{-1}$), $R_t$ is design rainfall with $T$ years return period (mm), $T$ is the total duration of daily rainfall (hr) and $t$ is rainfall duration (hr). The rainfall duration $(t)$ employed in this study was determined by corresponding to the time interval of infiltration measurement derived during field measurement. The hyetograph of rainfall intensity was utilized along with the infiltration rate curve to determine ponding time. The design rainfall analysis was obtained using Log Pearson Type III distribution which is commonly used to design rainfall analysis [19]. The design rainfall analysis was obtained using Log Pearson Type III distribution which is commonly used to design rainfall analysis. Henceforth, the design rainfall was applied to gain the rainfall intensity with varying return periods, that later used to derive ponding time characteristics for each return period.

2.2. Horton infiltration model
The Horton model is one of the well-known infiltration models in hydrology. Horton admits that the infiltration capacity decreases with time until it approaches a constant value. Horton expressed his view that the decrease in infiltration capacity is controlled by factors operating at the soil surface rather than the flow process in the soil. Horton’s model can be expressed in the following equation (18):

$$f = f_i + (f_0 - f_i) e^{-kt} ; t \geq t_c$$

(2)

Where $f$ is infiltration rate (mm.hr$^{-1}$); $f_i$ is constant infiltration rate (mm.hr$^{-1}$); $f_0$ is initial infiltration rate (mm.hr$^{-1}$), and $k$ is constant depend on soil characteristics. The infiltration curve is obtained from the Horton equation. Inundation time with varying return times is obtained from the infiltration curve and rainfall intensity.

2.3. Ponding time
The time to ponding is that moment when surface runoff occurs initially at the soil surface during constant-flux infiltration. This is essential because environmental concerns like erosion, pollutant transport across the soil surface, and peaks in streamflow can only emerge when surface ponding and surface storage capacity have been surpassed and runoff has begun. Conceptually, the ponding time is determined when the rainfall intensity exceeds the soil infiltration rate [20]. The value of ponding time ($tp$) is very important in estimating the duration of inundation on land, surface runoff volume, and the time of concentration of surface runoff. In this study, the observed ponding time ($tp_{obs}$) was calculated from the relationship between infiltration rate ($f$) dan rainfall intensity ($i$) curves. Where $tp_{obs}$ theoretically initiated at a period when rainfall intensity is higher than infiltration rate ($i > f$). In addition, the empirical ponding time ($tp_{emp}$) was computed using the cumulative infiltration with Horton’s formula, as shown in the following equation (20):

$$F_{f+\Delta t} = F_i + f_i \Delta t + (f_i - f_0) \left( \frac{1-e^{-k\Delta t}}{k} \right)$$

(3)

Where $F_{f+\Delta t}$ is cumulative infiltration (mm.hr$^{-1}$), $f(t)$ is infiltration rate at time $t$ (mm.hr$^{-1}$), $k$ is constant of decay, $f_i$ is constant infiltration rate (mm.hr$^{-1}$), $f_0$ is initial infiltration rate (mm.hr$^{-1}$), and $t$ is ponding time (hr). The ponding time ($tp$), henceforth computed using the technique of successive approximation approach which is a procedure for estimating the value of an unknown quantity by comparing it to a sequence of known quantities repeatedly [21]. Further, the result of $tp_{emp}$ was compared with $tp_{obs}$ to examine the reliability of Horton’s formula in estimating ponding time. The determination coefficient ($R^2$) was employed to assess the consistency result between $tp_{emp}$ and $tp_{obs}$.

3. Results and Discussion
The field measurement of infiltration rate was conducted using the turf-tec double-ring infiltrometer at eight (8) locations in the study area. The infiltration rate measurement was carried out based on a constant time interval, a 5-minutes interval of observation. From the field measurements, the infiltration
rate for each time interval \((f_t)\), the initial infiltration rate \((f_0)\), and the constant infiltration rate \((f_c)\) were obtained, and which were subsequently employed for computing the Horton's parameter. Figure 3 displays the results of infiltration rate measurement at each point in the study area. From figure 3, it was demonstrated that the infiltration rate is high at the beginning of the measurement \((f_0)\) due to the dry condition of the soil and has an exponential decay as time elapsed. The infiltration curve has typical characteristics high in the beginning and ultimately shows curve flattens out and becomes nearly constant \((f_c)\). Among the measurement points, it was revealed that point G shows the highest infiltration rate compared with others. It is probably due to point G's soil condition, which contains coarse-grained and friable soil that allows water to drain freely, preventing waterlogged soil. Accordingly, the initial infiltration seems high at the beginning of the soil infiltration process. However, the content of clay minerals in the soil results in a low constant infiltration rate at point G.

![Figure 3. Infiltration rate measurement at each point](image)

The results of infiltration rate measurement, further yield the main parameter needed for the Horton's model at each measurement point namely the initial infiltration rate \((f_0)\) and the constant infiltration \((f_c)\). The Horton's decay constant \((k)\) is determined by drawing a semi-log plot of \(t\) vs \((f_0 - f_c)\) with \(t\) to linear scale which is in the form of a straight line. After that, the Horton's decay constant \((k)\) can be derived from the straight-line slope. Table 1 presents the value of Horton's parameters \(f_0, f_c,\) and \(k\) at each measurement location.

Those Horton's parameters presented in Table 1 were employed to compute the cumulative infiltration \((F_t)\), the main input to calculate the empirical ponding time \((t_{p, emp})\) using the successive approximation technique.

**Rainfall intensity analysis**

In this study, rainfall data were used along with infiltration rate to estimate the observed ponding time \((t_{p, cal})\), where theoretically ponding time initiated when the rainfall intensity \((i)\) was higher than infiltration rate \((f)\). The rainfall analyses comprise design rainfall and rainfall intensity analyses with varying return periods where 2, 5, and 10 years return periods were employed in this study. Log Pearson Type III distribution was employed to calculate the design rainfall with varying return periods.
Table 1. The value of Horton’s parameters $f_0$, $f_c$, and $k$ at each location of measurement

| Point | Initial infiltration rate ($f_0$), mm.min$^{-1}$ | Constant infiltration rate ($f_c$), mm.min$^{-1}$ | Decay constant ($k$), min$^{-1}$ |
|-------|-----------------------------------------------|-----------------------------------------------|-------------------------------|
| A     | 3.65                                         | 0.75                                         | 0.17                           |
| B     | 2.6                                          | 1                                            | 0.35                           |
| C     | 6.8                                          | 1                                            | 0.19                           |
| D     | 5.26                                         | 1                                            | 0.29                           |
| E     | 3.93                                         | 0.88                                         | 0.16                           |
| F     | 2                                            | 1.1                                          | 0.27                           |
| G     | 4.33                                         | 0.33                                         | 0.14                           |
| H     | 4.8                                          | 1                                            | 0.12                           |

In this study, the rainfall data obtained from the ARR station is only available in the hourly period. Considering that the infiltration rate measurement was carried out on a 5-minutes interval, the rainfall intensity was adjusted into the same time interval using the Mononobe formula as shown in equation (1). Furthermore, the infiltration rate and rainfall intensity must be described in the same scale and units (mm.min$^{-1}$) to ease the computation of ponding time. The rainfall duration was established for 120 minutes, referring to the occurrence of rainfall events in the study area and the duration of infiltration rate measurement. Figure 4 shows the rainfall intensity with varying return periods (2, 5, and 10 years) obtained from the Mononobe formula. The 5-minutes distribution of rainfall intensity as displayed in figure 4 was established based on the pattern of rainfall data collected at ARR Station.

![Figure 4. Rainfall hyetograph at varying return periods](image)

From figure 4, it can be shown that the temporal distribution of rainfall intensity at the study area is an advanced type. That is, the rainfall peak concentrated at the beginning of the rainfall event (22).

**Ponding time analysis**

The behavior of ponding time ($t_p$) was investigated relating to the rainfall intensity with varying return periods (2, 5, and 10 years) and infiltration rate characteristics. This study used Horton’s formula as shown in equation (3) to calculate the empirical ponding time ($t_{p,emp}$). Then, it was compared with observed ponding time ($t_{p,obs}$) derived from graph analysis of rainfall intensity with varying return periods and infiltration rate relationships. The observed ponding time ($t_{p,obs}$) was initiated at the time (minute) when rainfall intensity was higher than infiltration rate ($i > f$). Figure 5a, 5b, and 5c demonstrate...
the result of observed ponding time ($t_{p \text{obs}}$) for varying return periods of rainfall intensity at the measurement point C (point C). Based on Figure 5a, it can be seen that the ponding time ($t_p$) starts at the 15th minute of the duration of the rainfall event with 2 years return period, which is indicated by the magnitude of the rainfall intensity ($i$) exceeding the infiltration rate ($f$). It means that during the first 10 minutes of the rainfall event, inundation has not occurred on the land in the study area. The inundation event ended in the 55th minute, meaning that the ponding time lasted 35 minutes at measurement point C. While Figures 5b and 5c present graphs of the infiltration rate and rainfall intensity for the 5-year and 10-year return periods, respectively. From the figures, it can be seen that the initial time of ponding occurrence took place faster for the 5 and 10 years return periods, namely 10 minutes (for a 5 year return period) and 5 minutes (for a 10 year return period), respectively. It demonstrates that the rainfall intensity with varying return periods affects the behavior of ponding time occurrence in the study area. These results indicate that the greater the return period of the rainfall intensity, the faster the initial time of ponding takes place in the land. Figures 6 – 8 present the ponding characteristics and infiltration rate for 2, 5, and 10 years return periods, respectively, for other measurement points in the study area.

![Diagram of ponding characteristics and infiltration rate](image)

**Figure 5.** Infiltration rate vs rainfall intensity for obtaining $t_{p \text{obs}}$ at point C: (a) return period 2 years; (b) return period 5 years; (c) return period 10 years

Refer to figure 6 – 8, it could be known that the varying rainfall intensities and infiltration rates give vary in the value of ponding characteristics. From the figures, it can be known that the initial time of ponding time tends to start in a long time for the soil with a high initial infiltration rate ($f_0$) and constant infiltration rate ($f_c$). Conversely, the low infiltration rate causes the initial time of ponding to occur in a shorter in its occurrence. The high infiltration rate implies good soil porosity and soil texture which
greatly influence the absorbing force of soil during rainfall events, thus the high rainfall intensity tends to be lower than the infiltration rate. Accordingly, there is no ponding at the beginning of rainfall events since all rainfall will be infiltrated into the soil. The ponding occurs when the soil reaches its field capacity, indicating the maximum storage capacity of soil to hold infiltrated rainwater, consequently decreasing the infiltration rate. Likewise, the length and ending time of ponding decrease along with the increasing of constant infiltration rate \( f_c \). Higher \( f_c \) indicates that the soil remains controlling the infiltrating water though it is less dominant. Accordingly, the ponding tends to end in a short period that affects the length of ponding in consequence. In addition, through Figures 6 – 8, the present study yielded the ponding time length, which corresponds to the length of inundation time. However, the present study has no further analysis to investigate the accuracy of the length of ponding time yielded considering the limitation of data of observed inundation time in the study area.

**Figure 6.** Ponding characteristics and infiltration rate for \( T_r = 2 \) years

**Figure 7.** Ponding characteristics and infiltration rate for \( T_r = 5 \) years
Figure 8. Ponding characteristics and infiltration rate for $Tr = 10$ years

The empirical ponding time ($t_{p\text{emp}}$)

The study employed Horton’s formula to derive the empirical ponding time ($t_{p\text{emp}}$) using the cumulative infiltration with Horton’s formula, as shown in the following equation (3). The technique of successive approximation approach was used as a procedure to compute the empirical ponding time ($t_{p\text{emp}}$). Table 2 demonstrates the results of empirical ponding time ($t_{p\text{emp}}$) along with observed ponding time ($t_{p\text{obs}}$) for varying return periods.

| Return period ($Tr$) | $t_p$ (min) | Measurement point, $t_p$ (min) |
|----------------------|-------------|---------------------------------|
|                      | $t_{p\text{obs}}$ | G  A  C  F  B  D  E  H        |
| 2 years              | 10          | 5  20  5  10  5  15            |
|                      | 13.4        | 7.8 16.4 6.3 6.6 11.4 8.9 18   |
| 5 years              | 10          | 5  10  5  5  5  20             |
|                      | 8.6         | 5  11.5 4.7 5.4 7.8 6.7 12.2   |
| 10 years             | 5           | 5  5  5  5  5  20              |
|                      | 4.2         | 3.9 7.8 4.0 4.2 5.4 5.5 9.6    |

As displayed in table 2, the magnitude of observed ponding time ($t_{p\text{obs}}$) relatively shows no fluctuation, conversely more varying values were shown in $t_{p\text{emp}}$. It is probably due to the determination of the observed ponding time ($t_{p\text{obs}}$) that was manually obtained from visual graph analysis of infiltration rate and rainfall intensity graph. Further, the consistency analysis between the empirical ponding time ($t_{p\text{emp}}$) and the observed ponding time ($t_{p\text{obs}}$) for varying return periods was investigated statistically through the determination coefficient ($R^2$). The result of the determination coefficient ($R^2$) is shown in figure 9.

As shown in figure 9, the magnitude of $R^2$ tends to decrease for the high return period, which was indicated with the value of $R^2$ 0.61 for 10 years return period. As previously explained that it was tough to gain visually $t_{p\text{obs}}$ adequately for a high return period of a rainfall event. It is because less fluctuation of $t_{p\text{obs}}$ yielded in the visual graph analysis. It induces the quality of consistency value between $t_{p\text{obs}}$ and $t_{p\text{emp}}$ in consequence. In addition, the coefficient of determination ($R^2$) shows a relatively high value ($R^2 > 0.6$) for the return period of 2 years, 5 years, and 10 years. It indicates that there is a fairly good consistency value between $t_{p\text{obs}}$ and $t_{p\text{emp}}$. Hence, it can be denoted that Horton’s formula has good reliability to estimate the ponding time ($t_p$) in the study area.
Figure 9. The determination coefficient ($R^2$) between $t_{p_{obs}}$ and $t_{p_{emp}}$

4. Conclusion

The present study investigates the ponding time characteristic due to varying infiltration rates and rainfall intensities with varying return periods. The result confirms that the infiltration rate is high at the initial time of the infiltration measurement due to the soil's dry condition and decays exponentially with time. The infiltration curve showed typical characteristics of being high initially and eventually flattening out and becoming nearly constant. The study results revealed that rainfall intensity with varying return periods affects ponding time in the study area. Additionally, it was known that the longer the return period of rainfall, the faster the initial time of ponding occurs in the land. Furthermore, the study verified that the varying rainfall intensities and infiltration rates vary in the value of ponding characteristics. The result found that there was a fairly good consistency value between $t_{p_{obs}}$ and $t_{p_{emp}}$. It is indicated by the magnitude of the coefficient of determination ($R^2$) shows a relatively high value ($R^2 >0.6$) for the return period of 2 years, 5 years, and 10 years. It indicates that Horton's formula has reliable to estimate the ponding time ($t_p$) in the study area.

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