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Time of concentration based infiltration under different soil density, water content, and slope during a steady rainfall

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Abstract

Time of concentration, *Tc*, is defined as time elapsed from the beginning of rainfall infiltrated into soil layer until it reaches a constant infiltration rate (*fc*) which is indicated an equilibrium subsurface flow rate. In hydrological view, time of concentration plays a significant role in elaboration of transformation of rainfall into runoff in a watershed. The aims of this research are to define influence of soil density and soil water content in determining time of concentration using infiltration concept based on water balance theory, and to find out the effect of land slope this time. Watershed laboratory experiment using rainfall simulator was employed to examine time of concentration associated with infiltration process under different slope, soil density and soil water content based on water balance concept. The steady rainfall intensity was simulated using sprinklers which produced 2 $dm^3 \cdot min^{-1}$. Rainfall, runoff and infiltration analysis were carried out at laboratory experiment on soil media with varied of soil density (*d*) and soil water content (*w*), where variation of land slopes (*s*) were designed in three land slopes 2, 3 and 4%. The results show that relationship between soil density and land slope to time of concentration showed a quadratic positive relationship where the higher the soil density address to the longer time of concentration. Moreover, time of concentration had an inverse relationship with soil water content and land slope that means time of concentration decreased when the soil water content increased.

Key words: *infiltration, runoff, slope, time of concentration, water content*

INTRODUCTION

Time of concentration *Tc* is one of the fundamental parameters in urban drainage planning which is defined as the time needed for a parcel of water to travel from the hydraulically most distant point of a watershed to a reference point downstream [ALMEIDA *et al.* 2017]. BEN-ZVI [2012], defined *Tc* as the time elapsed from the onset of rainfall until it reaches equilibrium flow rate. Some researches regarded *Tc* as the period from the commencing of effective rainfall to the period at which the flow reached 95% and 98% of equilibrium discharge such as described by SU and FANG [2004] and WONG [2005]. Time of concentration, *Tc*, plays a significant role in the explanation of the transformation of rainfall into runoff in a watershed [MICHAILIDI *et al.* 2018]. In regard with water resources engineering applications, *Tc* has been widely employed in hydrological design tools as an input variable for common methods of rainfall runoff relationship, such as the rational method and the concept of unit hydrograph. BEN-ZVI

[2013] stated that information of *Tc* is needed for problems hydrology for estimating the design flood as a basis for planning a drainage system such as storm sewer, pipe, road side ditches, detention/retention facilities, and pump system. LEE and CHANG [2005] applied Geomorphological Instantaneous Unit Hydrograph (GIUH) based on travel time probability distributions for runoff in surface flow and subsurface flow.

Many studies have been carried out to study concerning time of concentration as a function of length of watershed, surface roughness of watershed, slope of watershed, and rainfall intensity [CHEN, WONG 1993; HAN LI, CHIBBER 2008; WONG 2005]. Most of the empirical formulas to estimate *Tc* use the reciprocal of topographic slope S_o [MANOJ *et al.* 2014]. However, as far as our concern, the majority of previous studies did not consider the effect of soil characteristics, particularly soil density and water content on the time of concentration. Those previous studies only consider the effect of land surface characteristics on the time of concentration. A study conducted by LIMA [2003] showed that the concept of time of concentration was determined only by considering runoff variables. Total runoff was directly related to the duration of rainfall at a certain intensity [HORTON 1940]. The effect of rainfall intensity on runoff is highly dependent on the level of infiltration process. Therefore, runoff is always in accordance with the increasing in rainfall intensity. The concept of water balance is managed through the relationship between rainfall, runoff, and infiltration, and the balance is influenced by factors such as soil characteristics, land treatment, and rainfall intensity. The effect of soil physical characteristics on hydrological aspect is demonstrated through overland flow and absorption of water into the soil. Rainfall which affects infiltration can be observed by observing the level of water entering and leaving the catchment area. Infiltration is derived by determining reduction of rainfall to runoff depth. Infiltration capacity in $dm^3 \cdot min^{-1}$ is flow capacity which could be retained in soil layer at a particular time. Infiltration capacity occurs when the rain intensity exceeds the ability of the soil to infiltrate rainwater. The maximum infiltration capacity of the soil has a constant magnitude during the time of concentration. The maximum soil infiltration capacity was obtained by reducing rainwater with runoff [HJELMFELT 1978]. In this study, the determination of the time of concentration was carried out using the concept of water balance on land which included not only runoff variable but also took into account the variables of rainfall and infiltration that occurred. Runoff and infiltration rate are influenced by variables of rainfall, land slope, and soil characteristics. The soil characteristic variable comprises the physical properties of the soil and the condition of the land surface. The physical properties of the soil include soil grain distribution, soil porosity, void ratio, water content, degree of saturation, specific gravity (*Gs*), dry soil weight, and wet soil weight, while the condition of land surface of land use type, land cover type, soil density due to compaction from building loads above the soil. Infiltration rate was affected by the variable of slope, rain intensity, and soil properties such as infiltration rate is influenced by a number of factors such as bulk density, porosity, soil moisture, and soil texture [CZYŻYK, ŚWIERKOT 2017; HAGHNAZARI *et al.* 2015; NASSIF, WILSON 1975; SURYOPUTRO *et al.* 2018]. GREGORY *et al.* [2006] studied about the effect of various levels of soil compaction on infiltration rates of sandy urban development sites as compared to uncompacted infiltration rates and found that there could be a significant difference between the effect of compaction caused by relatively light construction equipment and very heavy equipment on infiltration rate. Soil compaction was shown to have a negative effect on infiltration rates of soils. ANDERSON *et al.* [2009] et al conducted research on infiltration at agroforestry and found that infiltration measurements in clay soils were highly influenced by antecedent soil water content. WANGEMANN *et al.* [2000] carried out rainfall simulation on bare land under varying soil water content and concluded that increasing soil water content resulted in lower infiltration rates. LIU and SINGH [2004] found that when the land slope gradient decreases to some small value, the unit discharge decreases because of the increase in infiltration rate, conversely the infiltration rate will decrease on increasingly steep lands. GHOLAMI *et al.* [2014] examined infiltration and time to drainage on sandy-loam soil using laboratory experiment.

However, most of the previous studies only considered the affect of soil density and soil water content on infiltration rate, did not attempt to examine their influence on time of concentration (*Tc*). Furthermore, the previous studies only discussed on time of concentration (*Tc*) that correspond to surface runoff occurrence. Yet, studies examining time of concentration (*Tc*) associated with infiltration process under different slope, soil density and soil water content are limited. In this study, the time of concentration (*Tc*) is defined as the time elapsed from the beginning of rainfall infiltrated into soil layer until it reaches a constant infiltration rate (*fc*) which is indicated an equilibrium subsurface flow rate. Thereby, the time of concentration (*Tc*) does not attribute to time correspond to surface flow rate occurrence but more refer to subsurface flow rate occurrence. Thus, the purposes of this research were to: 1) incorporate the influence of soil density and soil water content in determining the time of concentration using infiltration concept based on water balance theory, and 2) to find out the effect of land slope, water content and soil density on the time of concentration beside rainfall intensity.

METHODS

The rain simulator used in the Watershed Experimental Laboratory was utilized to observe behaviour of rainfall flowing over and through a soil surface. The equipment was employed to collect data regarding runoff and infiltration from several different types of soil, at various slopes and under widely differing rainfall intensities. This instrument was equipped with a rectangular experimental watershed tank on dimensions of 2 m long × 1.2 m wide × 0.3 m depth which was shown in Photo 1. The top of the experimental catchment tank had nozzles that regulated the diameter of the falling raindrops. The experimental watershed tank also had two pipes with pores at the

Photo 1. Rainfall simulator of hydrology system SK-III Armfield (phot. *D.N. Khaeruddin*)

bottom side. These pipes were installed into the tank to facilitate runoff measurement.

Soil testing analysis in this research was conducted on five soil parameter, namely water content, soil density, porosity, void ratio and degree of saturation as shown in Table 1. The specific gravity of soil sample showed value of 2.67, which indicated that the soil samples included in granular soil groups, non-cohesive, and high in organic matter. Furthermore, analysis of the degree of saturation in soil samples exhibited the value of 0.386, which means that the soil samples were included in the category of moist soil. Table 2 shows the composition of sand, silt and clay in the soil samples used in this research. Based on Table 2, it can be noticed that the composition of the sand grain was 19% which found the largest percentage in soil samples followed by silt and clay of 38.7% and 42.3%, respectively. This indicates that the soil samples included in the group granular soil with organic matter content that feasible to be used in different soil density.

Table 1. Soil properties of sampling media

Media	Water content, *w* (%)	Specific gravity, *Gs* (g·cm^{-3})	Void ratio, *e*	Porosity, *n*	Saturated degree, *Sr*
Soil U114	34.59	2.67	1.054	0.513	0.386

Source: own study.

Table 2. Soil grain size used in this study

Media	Granulometric composition (%)		
	sand	silt	clay
Soil U114	19.0	38.7	42.3

Source: own study.

Data sources used in the study were obtained from the direct observation in the laboratory. Variables which were considered in the study comprised of rainfall, land slope and soil characteristics. These three variables were observed and examined in the laboratory to obtain runoff data produced from the rain simulator instrument [HAN LI, CHIBBER 2008]. The soil physical characteristics observed included soil texture, water content, soil grain size, porosity, void ratio, specific gravity, and soil saturated degree. The steady rainfall intensity was simulated using sprinklers which produced 2 dm^3·min^{-1}. The rainfall runoff analysis were performed at laboratory experiment on the soil media with varied of soil density (*d*) and soil water content (*w*), where variation of land slopes were designed in three land slopes 2, 3 and 4%.

INFILTRATION RATE

Infiltration rate is the velocity at which rain water penetrates into the soil during rainfall event. The infiltration rate was measured by unit of length per time which is same unit with rainfall intensity. The relationship between the rate of infiltration and runoff was shown during rainfall with a constant intensity. Curve of infiltration rate was characterized by the maximum at the beginning of rainfall event but then decreases with prolonged rainfall until it reached a constant rate.

Infiltration rate (*f*) was measured by the unit of cm·h^{-1} or mm·h^{-1}. The measurement was performed every 10 seconds and data processing was initiated after reading data for 10 seconds. If water is inundated in case of an overland flow occurrence, the infiltration is expressed as potential infiltration rate or infiltration capacity. If water supply or rainfall intensity on soil surface is smaller than the potential infiltration rate, then actual infiltration rate is smaller than the potential infiltration rate. Cumulative infiltration (*F*) is the accumulation of infiltrated depth at certain period, and the rate was similar to the integral of infiltration at that period which is shown in the following equation:

$$F(t) = \int_0^t f(t) \partial t \tag{1}$$

Where: $F(t)$ = cumulative infiltration; $f(t)$ = infiltration rate; and t = observation time.

Infiltration rate is the derivative of cumulative infiltration which could be described as follows:

$$F(t) = \frac{\partial F(t)}{\partial t} \tag{2}$$

Where: t = time, f = infiltration rate, F = cumulative infiltration.

Horton formula used in the study in order to estimate curve of infiltration rate where the Horton concept explained that infiltration rate for a given soil decreases with time from the beginning of rainfall event [BEVEN 2004] as shown in the following equation:

$$f_t = f_c + (f_o - f_c)e^{-Kt} \tag{3}$$

Where: f_t = infiltration capacity at any time t from time beginning of rainfall, f_o = initial infiltration capacity at $t = 0$, fc = final constant infiltration rate, t = duration of rainfall, K = constant depending upon the soil characteristic and land cover.

RESULTS AND DISCUSSION

The watershed laboratory experiment using rainfall simulator was employed in the present study. The observation of rainfall, runoff hydrograph, and infiltration became the main variable which was observed in the laboratory experiment. The kinematic wave law in the water balance concept was used to obtain infiltration rate which was derived by subtracting rainfall to runoff. Subsequently, the infiltration model resulted from rainfall and runoff relationship analysis was used for estimating the time of concentration (T_c). The slope of the watershed experimental tank was designed in three type of slopes, 2, 3 and 4%. Runoff measurement with rainfall simulator instrument employed the concept of water balance. Figure 1 and 2 show the relationship among rainfall, runoff, and infiltration based on laboratory observation and measurement. Figure 1 denotes the relationship of the rainfall duration with the infiltration rate which was gained from subtraction of rainfall to runoff. Based on Figure 1 it can be shown that at the beginning of time 0–30 min represented an occasion when rainfall began to infiltrate into the soil layer to a condition where rainfall will overflow on the land surface. The infiltration rate at time 0–30 min has a magnitude corresponding to the rainfall intensity which is of 2 $dm^3 \cdot min^{-1}$ which indicates that the rainfall was infiltrated entirely into the soil during those time periods. Furthermore, Figure 1 expresses that the infiltration rate declined until it reached the constant infiltration rate (*fc*) 0.35 $dm^3 \cdot min^{-1}$ in 105 min which was most likely induced by increasing in water content, soil porosity and degree of soil saturation. The association between the rainfall duration and runoff that takes place on the land surface is displayed in Figure 2. Measurement of runoff referred to the part of the rainwater that was not infiltrated into the soil. The runoff process started to begin on 30 min when the soil infiltration capacity initiated to decrease due to the occupying of the soil porosity by infiltrated rainwater.

The runoff remained to increase until the rainfall duration reached around 50 min, and subsequently, the runoff had a constant magnitude 1.40 $dm^3 \cdot min^{-1}$ when the entire soil porosity condition had been filled with infiltrated rainwater. The runoff that took place on the land surface was influenced by the slope of the land and the characteristics of the soil on the land. From Figure 2, it can be identified that the infiltration capacity of the soil attained the

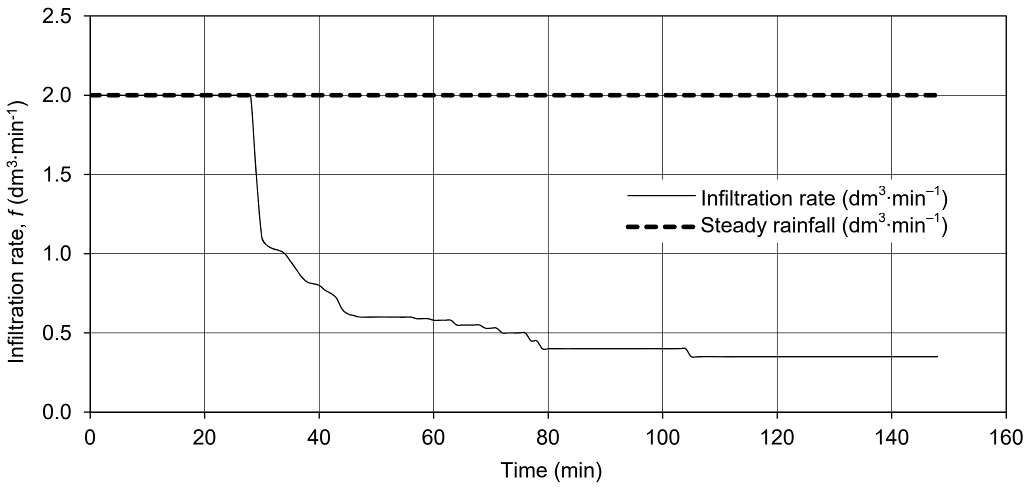

Fig. 1. Infiltration rate during observation time; source: own study

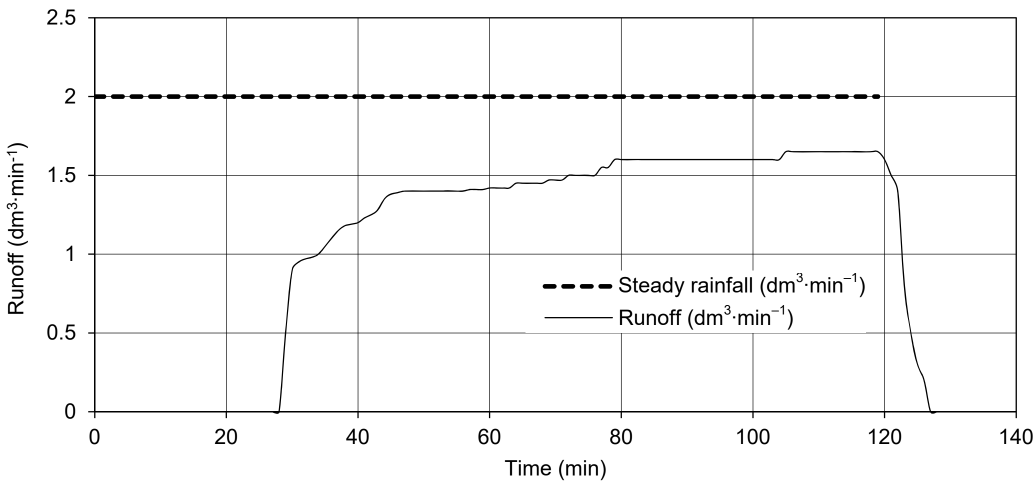

Fig. 2. Runoff during observation time; source: own study

maximum condition when the rainfall duration was 120 min of length where the constant magnitude of runoff had occurred in the land surface which was 1.65 $dm^3 \cdot min^{-1}$. This means that the infiltration process stopped at rain events with duration of more than 120 min. Photo 2 displays the constant height of piezometer which indicated the soil infiltration capacity reach maximum and the runoff shows a steady condition.

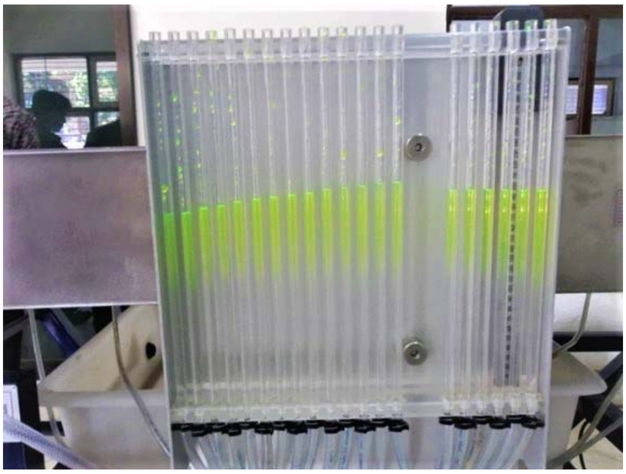

Photo 2. Piezometer height at constant infiltration capacity (phot. *D.N. Khaeruddin*)

As previously mentioned that the Horton formula employed as an approach to estimating the value of time of concentration (T_c). The initial infiltration rate f_o was analysed from laboratory measurement which subsequently used in Horton formula to obtain the infiltration rate. The result exhibited that K parameter in the Horton formula showed changes depend on soil characteristic particularly the water content and void ratio. Additionally, the study found that the high the infiltration rate (f_p) had been occurred in the soil with a low density having higher water content and void ratio.

Further, the study confirmed that the land slope and soil density had an influence in the constant infiltration rate (f_c). The constant infiltration (f_c) was smaller at the land with the steep slope and characterized by high soil density. The analysis was showed that the infiltration rate (f_p) increase with the decrease in value of K parameter and time period (t) while the infiltration rate (f_p) decrease along with decreasing of the constant infiltration rate (f_c). The time of concentration (T_c) was determined from the Horton infiltration rate model which could be explained as follows [DIJCK, ASCH 2002]:

$$f_p - f_c = (f_o - f_c)e^{-Kt} \quad (4)$$

The right and left sections of the equation (4) are elaborated in form of logarithmic which is displayed in the following equations (5), (6) and (7):

$$\log(f_p - f_c) = \log(f_o - f_c) - Kt\log e \quad (5)$$

$$t = -\frac{1}{K\log e}\log(f_p - f_c) + \frac{1}{K\log e}\log(f_o - f_c) \quad (6)$$

$$t = -\frac{1}{K\log e}[\log(f_p - f_c) + \log(f_o - f_c)] \quad (7)$$

Equation (7) has a common form $y = mx + c$ which has a straight line regression with a slope m which is equal with $m = 1/(K \log e)$. Based on Horton formula in equation (4), the estimation of time of concentration (T_c) could be performed by integrating ($f_p - f_c$) into equation (7). Figure 3 displays the relationship between observation time (t) and log ($f - f_c$). From Figure 3, it could be showed that the equation the value of $m = 1/(K \log e)$ has negative score –28.195 which indicate that the infiltration rate (f_p) decreases with the increasing of time observation (t). The value of time period will reach a maximum at the minimum of the infiltration rate (f_p) until it showed a constant value of time period which is indicated that the difference between the infiltration rate (f_p) and the constant infiltration rate (f_c) close to 0 (zero).

The result of Horton model of infiltration rate equation was shown in the equation (8):

$$f = 0.1846 + 1.6613\ e^{-0.0817t}. \quad (8)$$

Based on Horton formula in equation (7), the estimation of time of concentration (T_c) could be performed by integrating ($f_p - f_c$) into equation (7).

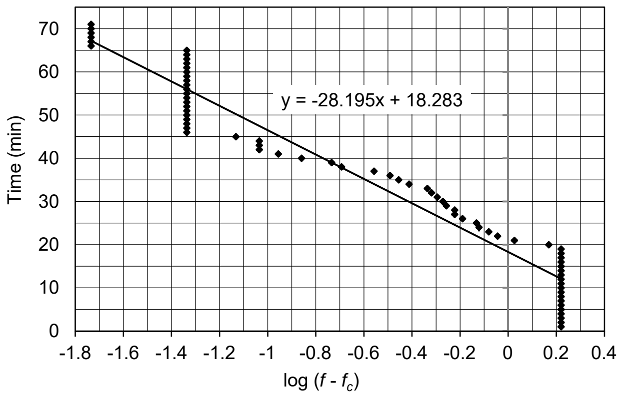

Fig. 3. Relationship between observation time (t) and log ($f - f_c$); source: own study

THE RELATIONSHIP BETWEEN SOIL DENSITY WITH TIME OF CONCENTRATION (T_c)

Table 3 denotes the characteristics of the time of concentration (T_c) on the land surface with varying slope and soil density. Graphical presentation of the relationship between the time of concentration (T_c) with the soil density variation on varies land slope appears in Figure 4. The figure described that on the land surface with an identical slope, the higher the soil density shows the longer the time of concentration (T_c). This is most likely due to the high soil density having less pore space. The limitation pore space in the soil addresses to low infiltration rates which had been confirmed by PIKUL and AASE [1995] who found that the major effect of soil density was the reduction in infiltration rate. BHARATI *et al*. [2002] affirmed that as the soil density increased, soil infiltration rate decreased. The result was also consistent with previous experimental studies carried out by DIJCK and ASCH [2002] who reveals that the soil density reduces neither steady-state infiltration rates nor total infiltration. Moreover, the result was also

Table 3. Time of concentration (T_c) with variation of soil density (d) and land slope (s)

Soil density g·cm^{-3}	Concentration time (min) at slope (%)		
	2	3	4
0.83	72.45	52.30	51.97
0.56	40.19	45.54	26.15
0.34	41.40	47.83	26.70
0.23	40.82	46.75	26.44
0.96	75.12	57.58	55.99
0.67	33.76	30.77	23.54
0.44	33.68	30.56	23.51
0.28	26.62	9.08	21.12
1.09	83.79	60.12	43.82
0.76	32.82	28.22	23.19
0.49	35.82	35.97	24.33
0.31	39.84	44.84	26.00

Source: own study.

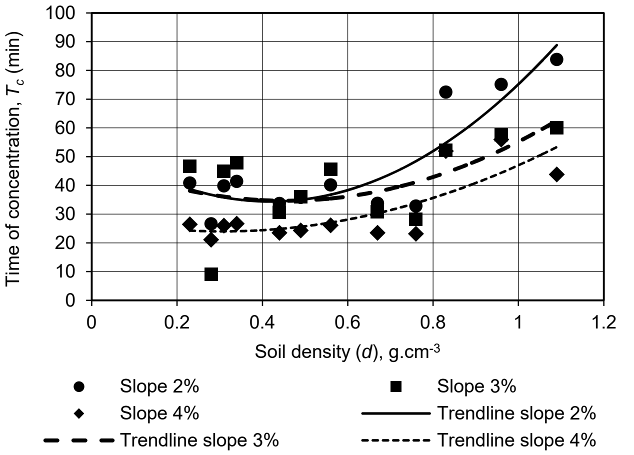

Fig. 4. Graphic representation of T_c with soil density (d) and land slope (s); source: own study

in line with HORTON *et al.* [1987] who confirmed that the soil pore space influenced the soil infiltration rate which subsequently affects the time of concentration. The result underlined that the estimation of time of concentration was significantly overestimated if soil pore space was not taken into account. The time of concentration (T_c) is shorter in soils with low density due to the high infiltration rate caused by available of pore space. For the soil which having similar soil density, the steeper the slope of the land surface shows the shorter the time of concentration (T_c). The results agreed with NASSIF and WILSON [1975] and GREGORY *et al.* [2006] who found that infiltration rate decreased in increasingly either soil density and land slope. Figure 4 exhibits that the slope of the land influences the ability of the soil to absorb rainwater where on the land with a mild slope the soil has a high infiltration rate compared to a steep slope. This is consistent with FOX *et al.* [1997] and SHARMA *et al.* [1983] who demonstrated that land slope contributed a significant effect on soil infiltration rate. The result of the present study showed that the low infiltration rate appeared in the steep slope whereas mild slope attribute to high infiltration rate. This was due to greater of flow velocities on land with a steep slope which lead to less chance for rainfall to be infiltrated into soil. Additionally, the infiltration process on land with sloping slopes was influenced by gravitational and soil capillary forces where the gravitational force that affected the rate of infiltration was restricted by the motion perpendicular to the ground through the soil profile. Thus, a land with the mild slope will have a high infiltration rate because of the magnitude of gravitational force which affects the rate of water infiltrated into the soil. The infiltration rate low on steep slopes due to decreasing of the effectiveness of gravitational force in influencing the rate of water infiltrated into the soil. Soil capillary forces work on soil pores that flow up, down and horizontal direction. In soils with high density, the effect of capillary forces on the rate of water infiltrated into the soil is tiny because of the lack of pore space in the soil. BHARATI *et al.* [2002] proved that the infiltration rate showed an inversely proportional relationship with soil density thus, the low infiltration rate occurs on high density soils which cause the longer time of concentration.

The results of ANOVA analysis to measure the effect of soil density variations and slope on the time of concentration (T_c) showed R^2 of 0.78 which implied that 78% of the variability of the time of concentration (T_c) had been explained by the variation of soil density and slope. The relationship of variation in the soil density to the time of concentration (T_c) on the land surfaces with slope variation of 2, 3, and 4% showed a positive relationship where the higher the soil density addressed to the longer the time of concentration (T_c).

THE RELATIONSHIP BETWEEN WATER CONTENT AND SLOPE WITH T_c

Table 4 displays the characteristics of the time of concentration (T_c) on the land surface under different slope (s) and water content (w). Figure 5 exhibits the representation of time of concentration (T_c) with land slope (s) and soil water content (w). For the land with relatively similar slope, the figure showed that the time of concentration (T_c) had an inverse relationship with the soil water content (w) where the time of concentration (T_c) declined when the soil water content (w) increase. This condition most probably caused by the high degree of soil saturation due to increasing in the soil water content (w) which directly affect the

Table 4. Time of concentration (T_c) with variation of water content (w) and land slope (s)

Water content, w (%)	Concentration time (min) at slope (%)		
	2	3	4
19.93	72.45	52.30	51.98
31.89	40.19	45.54	26.16
31.44	41.40	47.83	26.70
31.66	40.82	46.75	26.44
18.94	75.12	47.82	56.00
34.27	33.77	30.77	23.54
34.30	33.69	30.56	23.51
36.92	26.62	9.09	21.12
22.40	65.79	60.12	43.82
34.62	32.82	28.22	23.20
33.51	35.82	35.97	24.33
32.02	39.84	44.85	26.00

Source: own study.

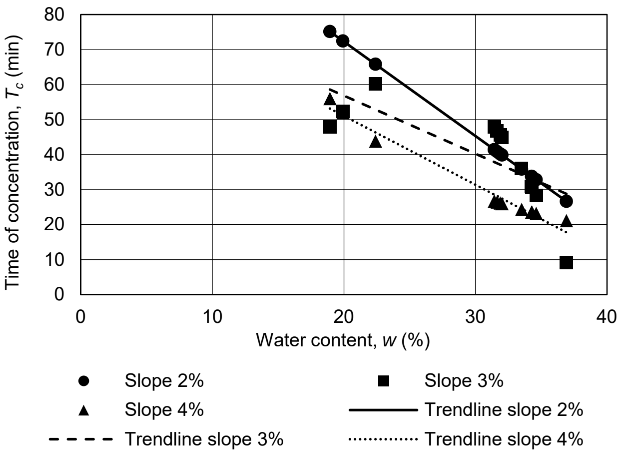

Fig. 5. Graphic representation of *Tc* with land slope (*s*) and water content (*w*); source: own study

soil infiltration rate as stated by ANDERSON *et al.* [2009] revealed that the soil water content highly influences soil infiltration rate. The result of the analysis demonstrated that the soil water content (*w*) significantly affects the time of concentration (T_c) when the soil water content was less than 25%. Thus, from Figure 5, it could be identify that the pattern of time of concentration (T_c) for the soil water content higher than 25% showed disorder pattern. The soil water content closely associated with soil degree of saturation, hence the high the soil water content indicated the high soil degree of saturation. Thus, the high soil degree of saturation caused increasing on the time of concentration (T_c). The result was consistent with YEN and AKAN [2010] who found that increasing in the degree of saturation at soil layer was followed by a decline in infiltration rate. Accordingly, the decline in the infiltration rate address to the longer of time of concentration to be developed, conversely, the increment of infiltration rate leads to the shorter of time of concentration. The influence of soil water content (*w*) and slope on the time of concentration (T_c) using ANOVA showed R^2 of 0.61 which denoted that 61% of the variability of the time of concentration (T_c) had been described by the variation of soil water content (*w*) and slope. The relationship of variation in the soil water content (*w*) to the time of concentration (T_c) on the land surfaces with slope variation of 2, 3, and 4% showed a negative relationship where the higher the water content attributed to the longer the time of concentration (T_c).

CONCLUSIONS

The water balance concept on land which involved rainfall, runoff, and infiltration employed to estimate the time of concentration through the watershed laboratory experiment using the rainfall simulator under different slope, soil density, and soil water content. The time of concentration discussed here has an important role in estimating subsurface flow rate rather than surface runoff. Determining the estimated time of concentration in subsurface flow rate could be addressed to estimate amount of rainwater volume infiltrated into soil and become subsurface flow rate which subsequently could be used for designing volume of groundwater conservation structure. Variation in soil density and land slope to time of concentration showed a quadratic positive relationship where the higher the soil density address to the longer time of concentration. On the other hand, time of concentration had an inverse relationship with soil water content and land slope that means time of concentration decreased when the soil water content increased. The future research work could be carried out to develop a mathematical relationship to describe the influence of land slope, soil water content, and soil density on time of concentration. There will be a possibility to introduce other soil and land surface characteristics in order to obtain behaviour of time of concentration more realistic.

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REFERENCES

ALMEIDA I.K., ALMEIDA A.K., GABAS S.G., SOBRINHO T.A. 2017. Performance of methods for estimating the time of concentration in a watershed of a tropical region. Hydrological Sciences Journal. Vol. 62. Iss. 14 p. 2406–2414. DOI 10.1080/02626667.2017.1384549.

ANDERSON S.H., RANJITH P.U., SEOBI T., GARRET H.E. 2009. Soil water content and infiltration in agroforestry buffer strips. Agroforestry System. Vol. 75 p. 5–16.

BEN-ZVI A. 2012. Detention storage over 2D laboratory watersheds at concentration time. Journal of Hydrologic Engineering. Vol. 17 (9) p. 1053–1057.

BEN-ZVI A. 2013. Bypassing determination of time of concentration. Journal of Hydrologic Engineering. Vol. 18 (12) p. 1674–1683.

BEVEN K. 2004. Robert E. Horton's perceptual model of infiltration processes. Hydrological Process. Vol. 18 p. 3447–3460.

BHARATI L., LEE K.H., ISENHART T.M., SCHULTZ R.C. 2002. Soil-water infiltration under crops, pasture, and established riparian buffer in Midwestern USA. Agroforestry Systems Vol. 56 p. 249–257.

CHEN C.N., WONG S.W. 1993. Critical rainfall duration for maximum discharge from overland plane. Journal of Hydraulic Engineering. Vol. 119 p. 1040–1045.

CZYŻYK F., ŚWIERKOT Z. 2017. Recharging infiltration of precipitation water through the light soil, in the absence of surface runoff. Journal of Water and Land Development. No. 32 p. 25–30. DOI 10.1515/jwld-2017-0003.

DIJCKA S.J.E., ASCH T.W.J. 2002. Compaction of loamy soils due to tractor traffic in vineyards and orchards and its effect on infiltration in southern France. Soil and Tillage Research. Vol. 63. Iss. 3–4 p. 141–153. DOI 10.1016/S0167-1987(01)00237-9

FOX D.M., BRYAN R.B., PRICE A.G. 1997. The influence of slope angle on final infiltration rate for interrill conditions. Geoderma. Vol. 80 p. 181–194.

GHOLAMI L., BANASIK K., SADEGHI S.H., DARVISHAN A.K., HEJDUK L. 2014. Effectiveness of straw mulch on infiltration, splash erosion, runoff and sediment in laboratory conditions. Journal of Water and Land Development. Vol. 22 p. 51–60. DOI 10.2478/jwld-2014-0022.

GREGORY J.H., DUKES M.D., JONES P.H., MILLER G.L. 2006. Effect of urban soil compaction on infiltration rate. Journal of Soil and Water Conservation. Vol. 61. No. 3 p. 117–124.

HAGHNAZARI F., SHAHGHOLI H., FEIZI M. 2015. Factors affecting the infiltration of agricultural soils. International Journal of Agronomy and Agricultural Research. Vol. 6. No. 5 p. 21–35.

HAN LI M., CHIBBER P. 2008. Overland flow time of concentration on very flat terrains. Transportation Research Record: Journal of the Transportation Research Board. No. 2060 p. 133–140. DOI 10.3141/2060-15.

HJELMFELT A.T. 1978. Influence of infiltration on overland flow. Journal of Hydrology. Vol. 36 p. 179–185.

HORTON R., THOMPSON M.L., MCBRIDE J.F. 1987. Method of estimating the travel time of noninteracting solutes through compacted soil material. Soil Science Society of America Journal. Vol. 51 p. 48–53. DOI 10.2136/sssaj1987. 03615995005100010009x

HORTON R.E. 1940. An approach toward a physical interpretation of infiltration-capacity. Soil Science Society of America Proceedings. Vol. 5 p. 399–417.

LEE K.T., CHANG C.H. 2005. Incorporating subsurface-flow mechanism into geomorphology-based IUH modeling. Journal of Hydrology. Vol. 311 p. 91–105. DOI 10.1016/j.jhydrol. 2005.01.008.

LIMA J.L.M.P. 2003. Laboratory experiments on the influence of storm movement on overland flow. Physics and Chemistry of the Earth. Vol. 28. Iss. 6–7 p. 277–282. DOI 10.1016/S1474-7065(03)00038-X.

LIU Q.Q., SINGH V.P. 2004. Effect of microtopography, slope length and gradient, and vegetative cover on overland flow through simulation. Journal of Hydrologic Engineering. Vol. 9. No. 5 p. 375–382. DOI 10.1061/(ASCE)1084-0699(2004) 9:5(375).

MANOJ K.C., FANG X., YI Y.J., HAN LI M., THOMPSON D.B., CLEVELAND T.G. 2014. Improved time of concentration estimation on overland flow surfaces including low-sloped planes. Journal of Hydrologic Engineering. Vol. 19. No. 3 p. 495–508. DOI 10.3141/2060-15.

MICHAILIDI E.M., ANTONIADI S., KOUKOUVINOS A., BACCHI B., EFSTRATIADIS A. 2018. Timing the time of concentration: shedding light on a paradox. Hydrological Sciences Journal. Vol. 63. Iss. 5 p. 721–740. DOI 10.1080/02626667.2018. 1450985.

NASSIF S.H., WILSON E.M 1975. The influence of slope and rain intensity on runoff and infiltration. Hydrological Sciences Journal. Vol. 20. Iss. 4 p. 539–553. DOI 10.1080/ 02626667509491586.

PIKUL J.L., AASE J.K. 1995. Infiltration and soil properties as affected by annual cropping in the Northern Great Plains. Agronomy Journal. Vol. 87. Iss. 4 p. 656–662. DOI 10.2134/ agronj1995.00021962008700040009x.

SHARMA K.D., SINGH H.P., PAREEK O.P. 1983. Rainwater infiltration into a bare loamy sand. Hydrological Sciences Journal. Vol. 28. Iss. 3 p. 417–424.

SU D., FANG X. 2004. Numerical modeling and turbulence closure techniques for shallow flows. In: Estimating traveling time of flat terrain by 2-dimensional overland flow model. Eds. H.J. Gerhard, S.J.U. Wim. The Netherland. A.A. Balkema, Member of Taylor and Francis Group p. 629–635.

SURYOPUTRO N., SUHARDJONO, SOETOPO W., SUHARTANTO E., LIMANTARA L.M. 2018. Evaluation of infiltration models for mineral soils with different land uses in the tropics. Journal of Water and Land Development. Vol. 37 (IV–VI) p. 153–160. DOI 10.2478/jwld-2018-0034.

WANGEMANN S.G., KOHL R.A., MOLUMELI P.A. 2000. Infiltration and percolation influenced by antecedent soil water content and air entrapment. American Society of Agricultural Engineers. Vol. 43. No. 6 p. 1517–1523. DOI 10.13031/2013. 3051.

WONG S.W. 2005. Assessment of time of concentration formulas for overland flow. Journal of Irrigation and Drainage Engineering. Vol. 131. Iss. 4 p. 383–387. DOI 10.1061/(ASCE) 0733-9437(2005)131:4(383).

YEN B.C., OKAN A.O. 1983. Effects of soil properties on overland flow and infiltration. Journal of Hydraulic Research. Vol. 21 (2) p. 153–173. DOI 10.1080/00221688309499442.

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Czas infiltracji w warunkach różnej gęstości gleby, zawartości wody i nachylenia terenu podczas stałego opadu

STRESZCZENIE

Czas koncentracji *Tc* definiuje się jako czas, który upływa od początku opadu infiltrującego glebę do osiągnięcia stałej prędkości infiltracji (*fc*), co oznacza zrównoważone tempo przepływu podpowierzchniowego. W hydrologii czas koncentracji odgrywa znaczącą rolę w ocenie transformacji opadu w odpływ w zlewni. Celem badań było określenie wpływu gęstości gleby i zawartości wody w glebie na czas koncentracji z wykorzystaniem koncepcji infiltracji bazującej na teorii bilansu wodnego oraz określenie wpływu nachylenia terenu na ten czas. Przeprowadzono laboratoryjny eksperyment z użyciem symulatora opadu w celu zbadania czasu koncentracji związanego z procesem infiltracji w warunkach różnego nachylenia gruntu, gęstości gleby i zawartości wody w glebie w oparciu o koncepcję bilansu wodnego. Stałą intensywność opadu symulowano używając zraszaczy o wydajności 2 $dm^3 \cdot min^{-1}$. Analizę opadu, odpływu i infiltracji prowadzono w eksperymencie laboratoryjnym na glebach o różnej gęstości (*d*) i zawartości wody (*w*) w warunkach nachylenia gruntu (*s*) równego 2, 3 i 4%. Wyniki wskazują, że zależność między gęstością gleby i nachyleniem a czasem koncentracji wyraża się dodatnim równaniem kwadratowym, gdzie większej gęstości gleby odpowiada dłuższy czas koncentracji. Ponadto czas koncentracji wykazywał odwrotną zależność od zawartości wody w glebie i od nachylenia, co oznacza, że czas koncentracji maleje wraz ze zwiększeniem zawartości wody w glebie.

Słowa kluczowe: *czas koncentracji, infiltracja, nachylenie, spływ, zawartość wody*