The Influence of Slope, Initial Water Content and Soil Compaction on Runoff and Infiltration in Urban Drainage

By Dian Noorvy Khaerudin

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Dian NOORVY[a], Donny HARISUSENO[b], Agus SUHARYANTO[b]

[a] Department of Civil Engineering, Tribhuwana Tunggadewi University, Malang, Indonesia

[b] Department of Water Resource Engineering, Brawijaya University , Malang, Indonesia

[b] Department of Civil Engineering, Brawijaya University , Malang, Indonesia

ABSTRACT

The hydrological processes in the urban drainage are rainfall, runoff, and infiltration. This phenomenon of water balance occurs to be the concept of urban drainage. Hydrological problems cannot be solved just by linking two variables or see the influence of one variable against another variable, so this research aims to find out how the relationship soil density, initial water content, and slope of land can influence together in the event of rainfall, runoff and infiltration. This research uses experimental methods using a rainfall simulator. Based on the results of the study, the density and the slope will affect positive against the runoff, the higher the density, the greater the runoff it will occur, but will affect negatively to infiltration. Both of these variables when added with variable initial water content, then on the third condition variable it is high, it will have a positive effect against runoff, i.e. the higher the third variable it will be the higher the runoff. However, in the process of rainfall infiltration and runoff, there were other influences, namely time. The time that occurs in the process it is time start percolating, the time is balanced between the runoff and infiltration, and time to constant.

Key word: runoff, infiltration, rainfall simulator, overland flow, urban drainage

Corresponding author: DianNoorvy, E-mail: dianoorvykhaerudin@gmail.com

INTRODUCTION

Urban drainage planning is often hindered with land limit. The limited land brings the difficulty to produce a water canal with huge capacity. Land use in urban area has been widened and converting open land into urban buildings.

Land coverage by urban buildings influences soil compaction (D.M Fox, 1997). The greater the soil compaction is the lower the infiltration. The inundation from rainfall may be faster and the timing of overland flow due to rain depends on some factors, such as slope, land condition and rain intensity.

The increase of runoff is not always comparable to the increase of rain intensity, and it happens due to overland flow. Rain intensity influences discharge or volume of runoff. Total runoff of a rain is directly associated with rain duration at certain intensity, and it is confirmed by Horton in Beven (Robert E. Horton's perceptual model of infiltration processes, 2004). The effect of rain intensity on runoff is greatly depending on infiltration rate, and therefore, runoff is always in parallel with the increase of rain intensity.

Water balance concept involves rain, discharge and infiltration. Infiltration is the only factor behind water loss. Water balance concept is different for canal and pipeline. In canal, water discharge exiting from the canal can have similar rate to that incoming to the canal. Such order is also similar for the case of pipeline. The difference between both is that the highest discharge during rain is found in the furthest point of the canal (McCuen, 1984).

Water balance is managed through the relationship between rainfall, runoff and infiltration, and the balance is influenced by factors such as soil characteristic, land treatment and rain intensity. Each soil type has different condition depending on its formation past time and its treatment in current days. Hydrology cycle process is also influenced by soil condition, respectively by the falling of rain water on soil surface. Soil has changed so much due to human treatment. The effect of soil physical characteristic on hydrology characteristic is realized through overland flow and water absorption into the ground, which in turn influences water balance in the ground and earth surface.

The problem of research is: How is the relationship between rainfall, runoff and infiltration becoming the influential factors to urban drainage land? and What parameters are used to observe the relationship between rainfall, runoff and infiltration.

The objective of research is to understand the effect of soil compaction factor on water absorption at urban drainage land if considering simultaneous effect soil treatment, slope and initial water content on soil compaction factor.

The effect of these factors above is then understood through observation at the laboratory using rainfall simulator device. Method of rainfall simulator involves considering rain as input and runoff as output. In water balance concept at urban drainage land, infiltration is the only factor of water loss.

MATERIALS AND METHODS

Preparation of electronic versions

Drainage canal design comprises of components such as planned canal discharge and flow speed. Flow speed is interpreted as rain intensity in mm/hour, whereas flow coefficient is the factor of runoff water on land-use parameters. In the case of fixed intensity, rain duration is similar with water balance time, and flow rate is also similar to rain increment rate (Fang, 2007).

As shown by the analysis, soil condition factor excludes soil compaction condition. Infiltration in water balance concept is the only factor of water loss in kinematical wave equation.

Water balance principle

In water balance principle stated by previous reserach (Anonim, USCS, 1959), runoff is counted by the following base equation:

$$O = S - F$$

Where :

O = runoff volume

S = rainfall volume

F = infiltration volume

Because infiltration depends on time, then infiltration is described as

$$W = \frac{S-0}{T} = \frac{F}{T}$$

W = Infiltration Rate

T = Time

Infiltration is observed during runoff. Rainfall volume influential to infiltration is observed by examining the rates of water incoming to and runoff from the retention region. Both rates are measured, and the differentia is the absorbed water, or called as infiltration (Wilson, 1990).

Rainfall Simulator is a human-made rainfall simulation to understand the relationship between rainfall and runoff at different soil compaction and different slope. Rainfall Simulator is the device helping us to acknowledge hydrology cycle at small scale. However, some factors are excluded including evapo-transpiration. Term “evapo-transpiration” is defined as evaporation caused by sun and plant. This device is equipped with a trial tank at dimension 2 x 1.2 x 0.3 meter. The upper part of the tank has *nozzle* that regulates the size of the fallen rain grain. Trial tank also has two pipes with pores on the lower part. These pipes are installed to the tank to facilitate flow measurement. Both pipes connect trial tank to other tank, namely flow measuring tank, from which each flow is measured.

Figure 1. Rainfall Simulator of Hydrology System SK-III Armfield

Data source is primary data obtained from laboratory. It means that data are collected through direct observation from laboratory. *Rainfall Simulator* is used by variation of soil compaction and soil slope. From factors influencing runoff, then three variables are examined to obtain runoff data, such as soil characteristic, soil slope and soil compaction (Chibber, 2008).

Three variables above are measured by manipulating simulator and experiment condition. By manipulating the simulator, the trialed rainfall is at from 1 liter to 3 liters per minute with slope 1% to 5%. In early experiment, the relationship between rainfall and runoff is understood from the combination between rainfall volume from 1 liter to 3 liter per minute and the slope from 1 % to 5%. The best result is obtained from the experiment with 2 liter/minute rainfall with the slope from 2% to 4%. This best result on 2 liter/minute is possibly influenced by quantity and quality of experiment material.

The observed physical characteristics of the soil include texture, water content, specific weight, and load weight. Soil texture is observed with hydrometer, whereas water content and load weight are understood from soil sample. This sample is classified as "disturbed sample" because it has the distribution of various particle sizes although particle size is similar to that of the original place, and soil structure is quite damage.

Infiltration rate is the speed when water penetrates into the ground during the rain (Asdak, 2002). Infiltration is measured by unit of length per time. The unit is also used for rainfall. At water depth of 1 cm per hour, infiltration rate is not depending on water section width. It means that water section width is not directly impacting on infiltration rate. Infiltration data are usually shown in curve, as shown by Figure 2.3. This figure shows the relationship between infiltration rate and runoff that is often seen during artificial rainfall at fixed intensity. The capacity of soil infiltration is the biggest at early rain but it declines with the prolonged rain until it reaches minimum constant, as indicated by Figure 2.3.

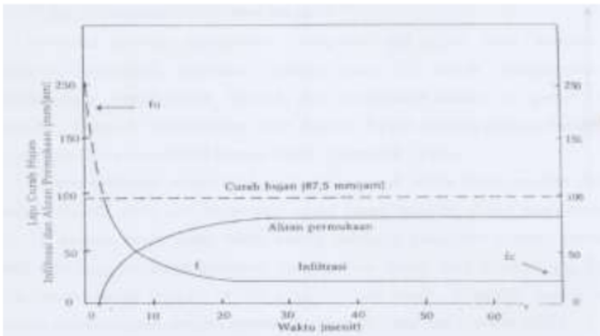


Figure 2. The curve of the relationship between infiltration rate and runoff in the artificial rainfal at fixed intensity.

Infiltration rate (f) is measured by the unit of centimeter/hour or mili-meter per hour. If water is inundated in the case overland flow, the occurred infiltration is potential infiltration. If water supply on soil surface is smaller than potential infiltration, then actual infiltration is smaller than potential infiltration. Cumulative infiltration (F) is the accumulation of infiltrated depths at certain period, and the rate is similar to the integral of infiltration at that period, which:

$$F(t)=\int_0^t f(t)\,\partial t \quad (1)$$

Infiltration rate is the derivative of cumulative infiltration, which:

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

Where:
t = time
f = infiltration rate
F = Cumulative Infiltration
The following is infiltration models that use empirical approach.

Horton Model

It is a famous infiltration model in hydrology. Horton asserts that infiltration capacity decreases with the increase of time until it reaches a constant. Horton adds that the decrease of infiltration capacity can be controlled by factors that operate on soil surface, not by underground flow.

(1) Kostiyakov Model

Kostiyakov Model uses the function of infiltration rate as model approach. It excludes early and final water contents (during fixed infiltration) from the function. The function of infiltration rate in this model is written as following:

$$F = at^{b}, 0 < b < 1 \quad (3)$$

$$f = \frac{dF}{dt} = abt^{b-1} \quad (4)$$

Both a and b are constant. Constants a and b depend on soil characteristic and initial water content. Both constants are not previously determined and often established by making a straight line on graphic paper based on empirical data, or by using the smallest square method.

Model Horton can also be presented mathematically by following the equation:

$$f = fc + (fo - fc)e^{-kt} \; ; i \geq fc \text{ and } k = \text{constant} \quad (5)$$

Note:

f : actual infiltration rate (cm/h)

fc : fixed infiltration rate (cm/h)

fo : early infiltration rate (cm/h)

k : geophysical constant

This model is very simple and quite proper for experiment data. Main weakness of this model is that it must determine exactly the parameters of fo, fc and k, and this determination is made through data fitting.

Green-Ampt Model

Green – Ampt method is emphasized on the approach to soil physical rather than the approach to solution/liquid. Green-Ampt Equation for total infiltration is :

$$K.t = F(t) - \varphi.\Delta\theta.\ln\left(1 + \frac{F(t)}{\varphi.\Delta\theta}\right) \quad (6)$$

Infiltration rate can be understood by Green-Ampt Equation as following:

$$f(t) = K.\frac{\varphi.\Delta\theta}{F(t)} + 1 \quad (7)$$

Note:

K : hydraulic conductivity (cm/hour)

Θe : effective porosity = η – θr (θr is the remaining water content after water drainage)

Δθ = (1 – Se) . Θe

Se = (θ – θr) / (η – θr) : effective water saturation

Ψ : wet boundary surface (cm)

Ƞ : ground water content

RESULTS AND DISCUSSION

Runoff measurement with rainfall simulator device is using the concept of runoff with water balance theory. The rain fallen onto soil surface will flow at two speed conditions depending soil surface condition. Speed condition in every point of land width can be similar or different.

Infiltration and runoff occurrences from the relationship between rainfall, runoff and infiltration under laboratory experiment can be described as follows:

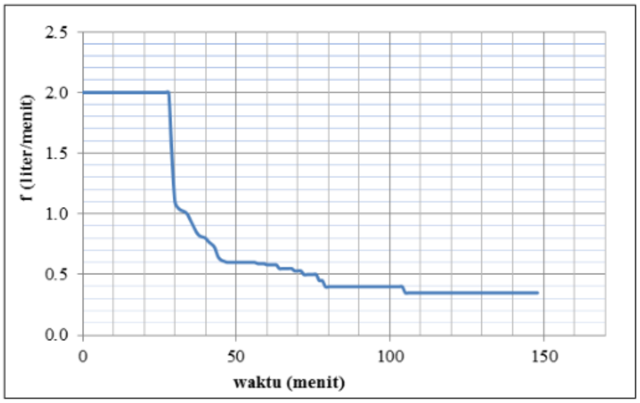


Figure 3. Concentration Time during Infiltration Process.

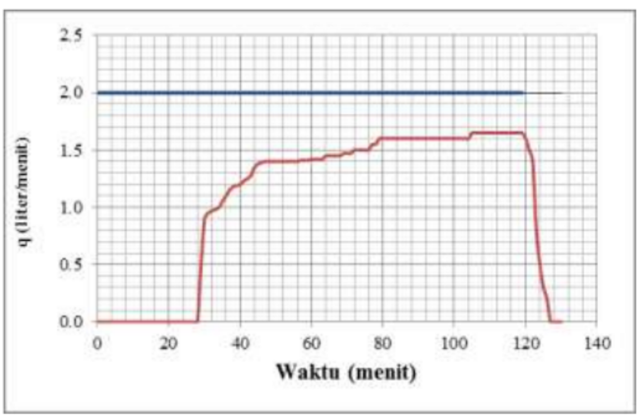


Figure 4. The curve of runoff at rain duration longer than concentration time.

Rain is stopped when runoff is constant, and runoff is ceased at similar cumulative time, precisely at 120 minutes. Reading is done every 10 seconds. Data processing begins after reading the data for 10 seconds.

Research utilizes the experimental relationship between rainfall and runoff (*storm hydrograph*). Rain fallen on the ground is subjected to a process depending on land treatment.

Experiment land is empty and free of treatment. Treatment is only given to the compaction. In land experiment (Figure 3 and 4), water flows in similar line, meaning that flow moves at similar speed in any places. The observation involves the compaction of 2 periods at slope 2 % (Figure 5.12). Runoff of the rain begins at minute 30. In duration more less 50 minutes, runoff increases until rain water satiates the pores of solidified soil, and thus, runoff achieves its maximum discharge.

The following is the result of observation on runoff discharge starting from less-saturated to saturated conditions, while rain is stopped at certain time per minute.

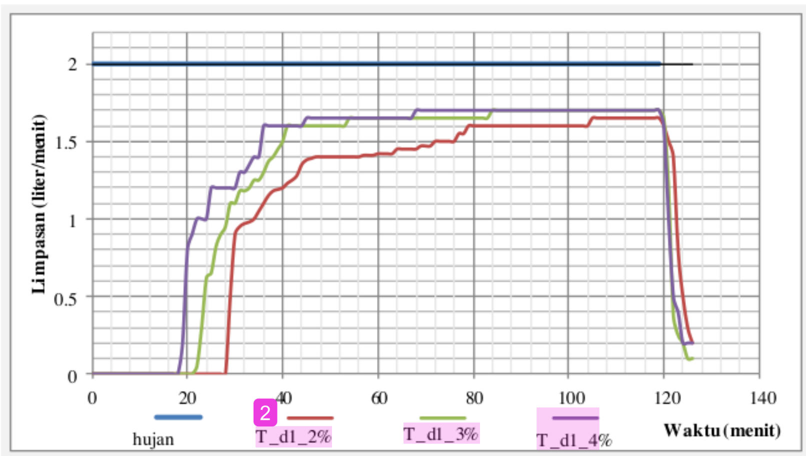


Figure 5. The curves of runoff at the compaction of 2 periods (d1) and the slopes of 2, 3, and 4%

Above curve (Figure 5.12) shows the process of rainfall and runoff for 120 minutes in Tlogomas Soil at the compaction of 2 periods and the slopes of 2, 3, and 4%.

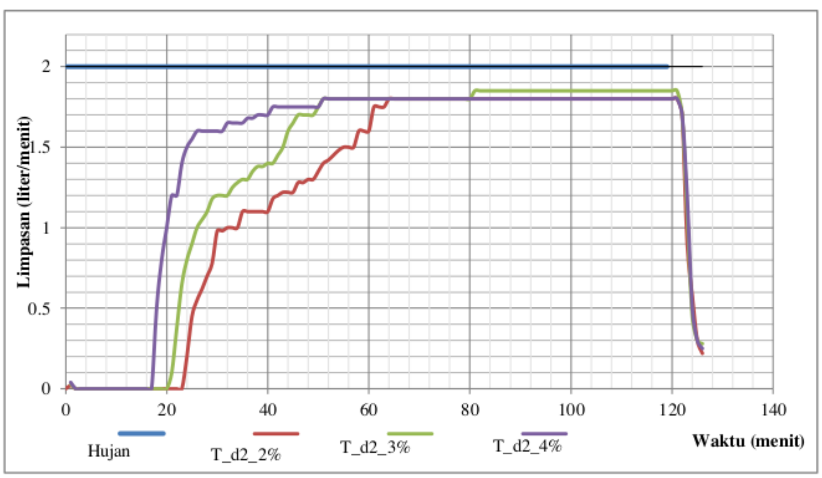


Figure 6. The curves of runoff at the compaction of 4 periods (d2) and the slopes of 2,3,4%

There is an effect of compaction and slope that accelerates the runoff. The curves at 6 periods (d3) are more proximate than that in d2. It means that the process of rain and runoff is influenced by compaction and slope. It is also meant that compaction and slope are influencing the acceleration of runoff.

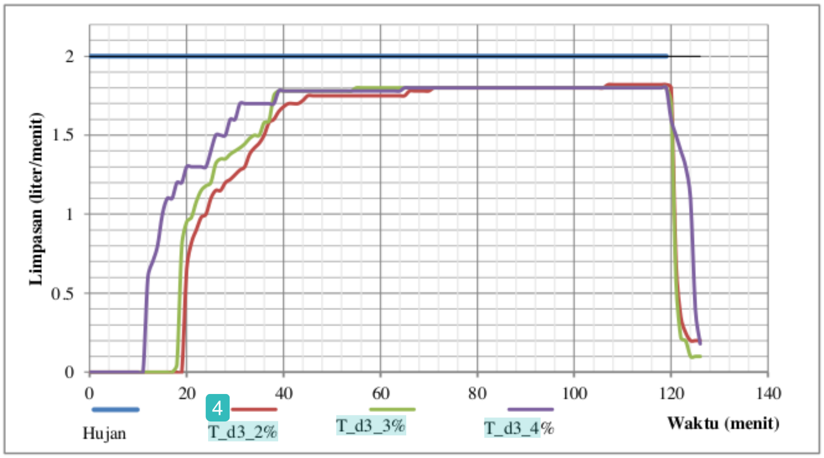


Figure 7.. The curve of runoff at the compaction of 6 periods (d3) and the slope of 2, 3, and 4%

Greater proximity of curves at the higher compaction means that runoff and infiltration rates that approximate rainfall rate will depend on land treatment. The greater is the soil compaction, the greater is its proximity to rainfall rate. Initial water content is observed in the process of runoff and infiltration. The following is the description:

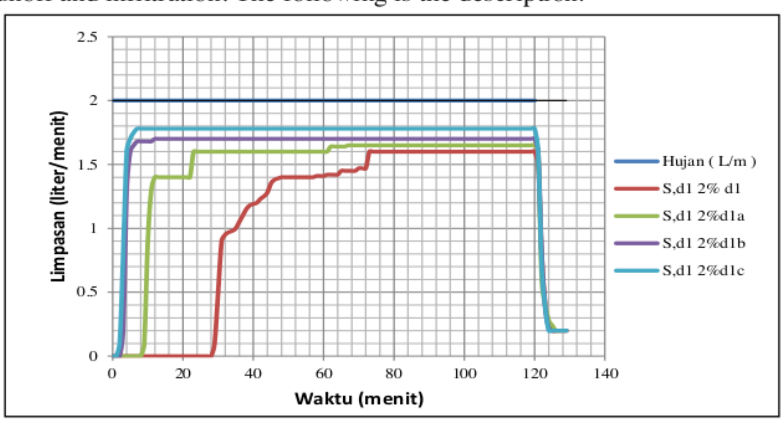


Figure 8. Runoff and time at T_d1_ with the slope of 2% and different water content.

Initial water content at similar compaction and similar slope can lead to faster time for achieving the constant. It means that in similar compaction and slope, soil pores are saturated faster because it is filled by water from water content.

Runoff at similar compaction and slope, but in greater water content, can be excessive. It is said so because the soil has been saturated with water. When runoff begins at certain time, then the higher water content is the shorter time to take for runoff.

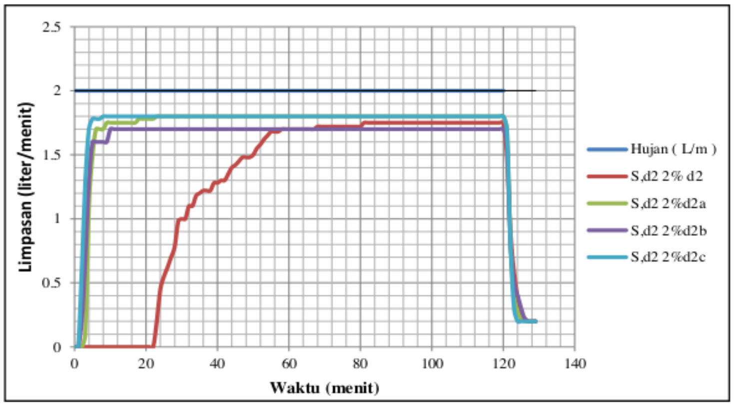


Figure 9. Runoff and time at T_d2_ with the slope of 2% and different water content.

Water content at the compaction of 2 periods (d2) has almost similar in every slope treatment. Runoff time may be seen at d2_2%_w1, whereas for w2,w3,w4, the curves are more proximate. It means that initial water content influences runoff time, especially when it is lower than 20%.

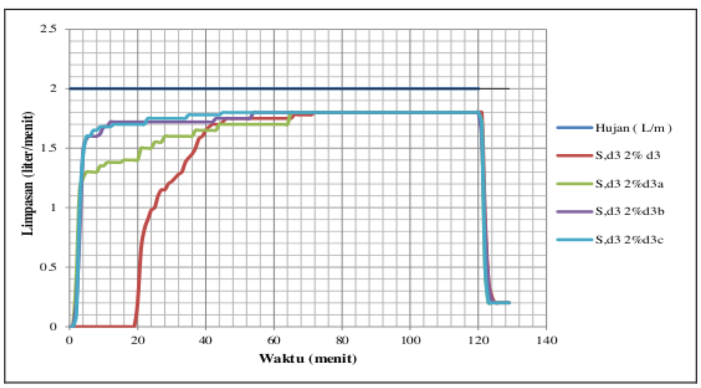
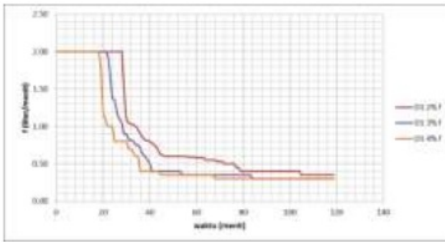
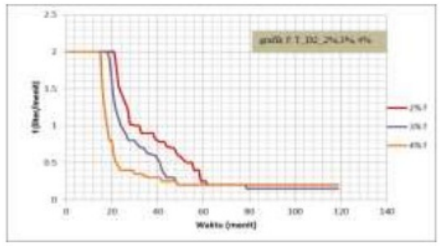


Figure 10. Runoff and time at T_d3_ with slope of 2% and different water content.





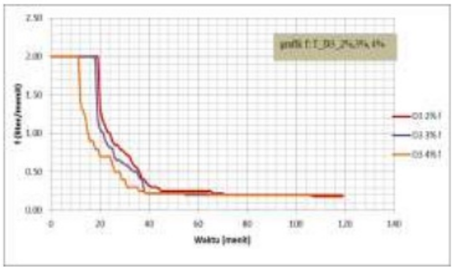


Figure 11 . Infiltration rate from the relationship between rain and runoff at (a), (b), and (c)

(a) T_d1_2%, 3%, 4%
(b) T_d2_2%_3%_4%
(c) T_d3_2%_3%_4%

Infiltration capacity in liter/minute is flow capacity in soil at certain time. Soil maximum infiltration capacity to retain rain water is constant during concentration time. Soil maximum infiltration capacity is obtained from subtracting rain water with runoff discharge (Hjelmfelt, 1978).

As shown by Figure 5.22 a), b), and c), infiltration capacity has similar value at compaction d2 and d3 with slope of 2%,3%,4%, but at compaction d1, the rate is different, or bigger than those at d2 and d3. Compaction d1 at slope of 2%, 3%, and 4% has almost similar infiltration capacity in every slope. It can be concluded that soil maximum infiltration capacity has similar rate at similar compaction, while the slope influences the speed of overland flow until it reaches constant infiltration capacity.

The effect of compaction of infiltration capacity is shown in the following figure:

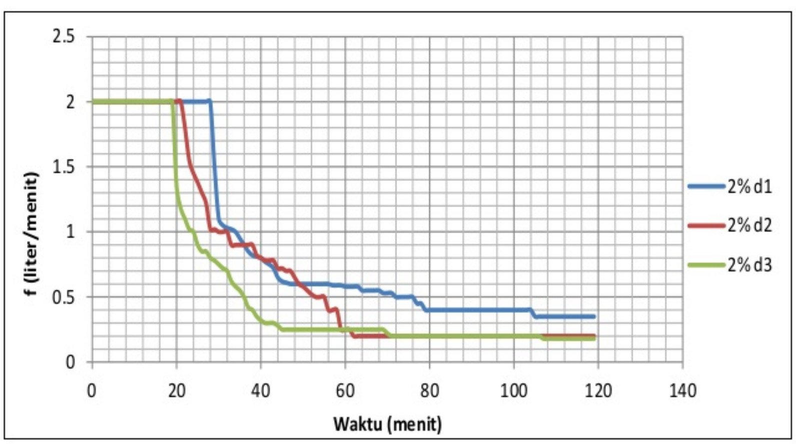


Figure 11 . Infiltration rate in the relationship between rainfall and runoff at T_2%_d1, d2, d3

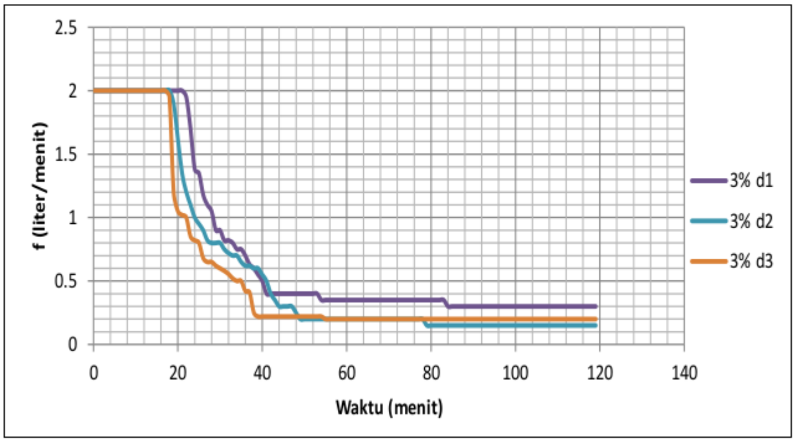


Figure 12. Infiltration capacity in the relationship between rainfall and runoff at T_3%_d1, d2,d3.

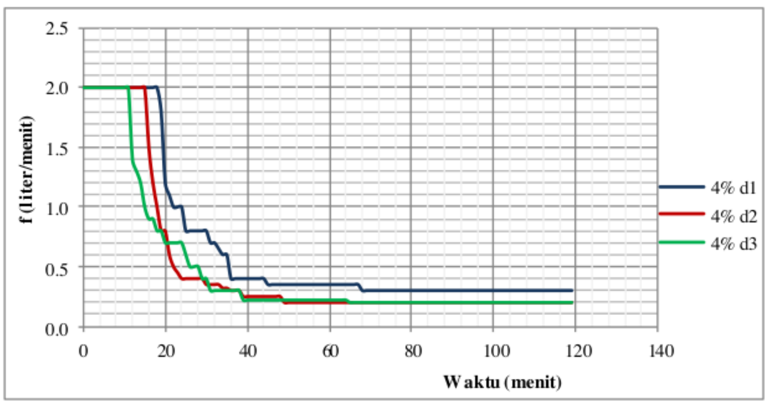


Figure 13. Infiltration capacity in the relationship between rainfall and runoff at T_4%_d1, d2,d3.

As shown by above figures, it is noted that at similar slope, but in greater compaction, infiltration is smaller. Land compaction may reduce infiltration rate by 70% to 90% (JH. Gregory, 2006). In greater compaction but at similar slope, infiltration capacity has almost similar rate with great proximity, meaning that infiltration has almost similar process in different compaction at similar slope. However, in compaction d1, infiltration is loosening. It means that other factor is influencing the process of rainfall, runoff and infiltration, which is initial water content.

Initial water content plays important role in filling soil pores during soil compaction process. Soil compaction is stated by factor Gs (specific gravity) and pore rate inverse. The greater Gs will increase soil compaction rate (dry weight of soil volume), but the greater soil pore rate (e) will decrease soil compaction rate. Therefore, the soil with high compaction will reduce infiltration capacity.

The relationship between rainfall, runoff and infiltration is understood in 3 soil samples. Measurement of each sample involves treatments and conditions. In greater slope, infiltration rate declines. This measurement is done by treating the soil sample with initial water content by averagely 20.04%. Dry soil from Tlogomas is treated with water content of 20 %, and so is for the soil from Joyogrand and Kedungkandang. All these three samples have different infiltration rate. At different water content, the result of treatment against experiment soil is similar. The dry weight of the soil is similar to the weight after 20 % water increment. Infiltration rate is also similar. The difference is only found in time needed to achieve the constants.

CONCLUSIONS

The laboratory research uses Rainfall Simulator to produce a model of infiltration in the relationship between rainfall and runoff. By using water balance concept in *kinematical wave law*, then infiltration rate is obtained by reduction between rainfall and runoff. Result of research is elaborated as following:

1. Various compactions at d1, d2, and d3 influence infiltration rate. Greater compaction of the soil causes water in the tank to runoff faster. Water absorbed is quite few. At various slopes but still in similar compaction, runoff becomes faster with the greater slope height. Runoff rate of each treatment is approximated to each other. Initial water content influences infiltration rate by affecting the process of the filling into soil pores. The quantity of water entering into the soil may be low with the increase of initial water content. Such condition is also influential at different soil specific weight and soil pore rate.
2. At similar compaction and higher slope, infiltration rate is smaller when the flow is constant. At similar slope and higher compaction, infiltration rate is also smaller when the flow is constant.
3. Based on the concept of the relationship between rainfall and runoff in water balance concept of *kinematical wave law*, then time for concentration is read during runoff occurrence. What is meant by runoff occurrence is when the curve of runoff ascends until runoff stays constant. Infiltration as the reduction of rainfall also has simlar condition.

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REFERENCES

Asdak, C. (2002). *Hidrologi dan Pengelolaan Daerah Aliran Sungai*. Yogyakarta: Gajah Mada University Press.

Beven, K. (2004). Robert E. Horton's perceptual model of Infiltration processes. *HYDROLOGICAL PROCESSES*, 3447 - 3460.

Bauer, S. W. (1974). A Modified Horton Equation For Infiltration. *Hydrological Sciences-Bulletin-des Sciences Hydrologiques*, 219-225.

Bedient, W. C. (2008). *Hydrology and Floodlpain Analysis*. Canada: Prentice Hall, Pearson Education Intenational.

Cahoon, J. (1999). Kotiyacov Infiltration Parameter from Kinematic Wave Model. *Journal Irrigation and Drainage Enggineering*, 127 - 130.

Chibber, M.-H. L. (2008). Overland Flow Time of Concentration. *Journal of the Transportation Research Board*, 133-140.

D.M Fox, R. B. (1997). The Influence of Slope Angle on Final Infiltration Rate for Interill Conditions. *Geoderma, Elsevier*, 181-194.

Hamlett, J., Melvin, S., & Horton, R. (1990). Traffic and Soil Amendment effects on infiltratio and compaction. *Transactions of ASAE* , 821-826.

Hjelmfelt, A. (1978). Influence Of Infiltration On Overland Flow. *Journal of Hydrology*, 179-185.

JH. Gregory, M. D. (2006). Effect of Urban Soil Compaction on Infiltration Rate . *Journal of Soil and Water Conservation*, 117-124.

McCuen, R. H. (1984). ESTIMATING URBAN TIME OF CONCENTRATION. *Journal of Hydraulic Engineering, Vol. 110, No. 7*, 887-904.

Richard H, M. S. (1984). Estimating Urban Time of Concentration. *Journal Hydraulic Engineering*, 887-904.

Wilson, E. M. (1990). *Engineering of Hydrology*. UK: Macmillan Education UK.

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