INFILTRATION AND SURFACE RUNOFF PROCESSES ON SLOPE AND COMPACTION SOIL WITH RAINFALL SIMULATOR EXPERIMENT

by Zakki Fuadi Emzain

INFILTRATION AND SURFACE RUNOFF PROCESSES ON SLOPE AND COMPACTION SOIL WITH RAINFALL SIMULATOR EXPERIMENT

Dian Noorvy KHAERUDIN[1], Agus SUHARYANTO[2], Donny HARISUSENO[3], Lily MONTARCIH[4]
[1] Department of Civil Engineering, Thribhuwana Tunggadewi University, Malang 65144 Indonesia
Email: dianoorvykhaerudin@gmail.com
(2,3,4) Department of Water Resources Engineering, Brawijaya University, Malang 65145 Indonesia
Email: Agus.s@ub.ac.id; donnyhari@ub.ac.id; lilymont2001@gmail.com

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. This research aims to find out how the relationship of soil density, initial moisture content, and slope of lands influence the rain, runoff, and infiltration. This research was conducted in a laboratory using a rainfall simulator plot tank. The size of the plot tank was 1.17 m x 0.97 m x 0.30 m. The plot tank fills soil with the same specific gravity for different initial water content in compaction soil land slope variation. The experiment carried out on steady rain intensity and every point in the plot was assumed in uniform velocity. The method describes the compaction of urban land use prototype that influences the infiltration rate and runoff processes. Infiltration rate was calculated by reducing intensity rain and runoff as output data from a running rainfall simulator. The processes were explained in water balance concept in urban drainage. Based on the results of the study, the compaction and the slope will affect positively against the runoff, the higher the compaction, the greater the runoff will be, but will affect negatively to infiltration.

Key Word: compaction soil, infiltration rate, runoff, rainfall simulator, urban drainage

1. INTRODUCTION

Rainfall in urban areas uses drainage principle of which rainfall is contained and controlled to prevent floods and runoffs. Rainfall will be contained and let pass as described by the continuity law of the water balance concept. Water balance concept explains the hydrological process, runoff, surface puddle, evaporation and infiltration (Bedient, 2008). Surface puddle is counted as runoff while evaporation is disregarded which leaves us with infiltration as the only loss factor.

The limitation of lands in urban areas decreases environmental support. Conventional urban drainage concept expects rainwater to be conveyed away as quickly as possible to underground pipes or main drainage waterways or even to the sea. Although rainfall can also be absorbed temporarily by soil and the infiltration for water storage can be planned in urban areas.

Buildings in urban areas affect soil density (Fox, 1997). Increased soil density will make the infiltration lower. Runoffs will be much larger because water flow depends on land slope, land condition, and rain itself. Rainwater will flow for sometimes, at times, water will reach the maximum level depends on drainage conditions in lands, waterways, or pipes.

Rain process and runoffs in overland flow are influenced by rain intensities, land slope, and condition. The land condition, which includes soil texture variations, structure, and layer interface (Kodesová et al., 2009; Kulli et al., 2003; Vogel et al., 2005), among other effects, affect rain process, runoffs, and infiltration. Land slope also affects runoffs and infiltrations (Maximilian, 2011), so does land prior conditions, such as initial water content.

The problem is how those 3 parameters simultaneously affect rain process, runoff, and infiltrations which connected by time using a rain simulator tool. The purpose of this research is to understand runoff and infiltration conditions in initial water content using density and slope as variables. Another purpose includes getting the statistics between runoff and infiltration and mentioned parameters, while also gaining the time analysis, which happens in rain process, runoff, and infiltration.

2. MATERIAL AND METHOD

2.1 Overland flow Concept

Rain process, runoff, and infiltration happen in overland flow drainage. This is a concept where continuity law meets momentum law. Infiltration acts reduction factor in rain process and runoff.
Continuity equation for overland flow (Bedient, 2008, pp. 278 – 283)

$$\frac{\partial q_0}{\partial x} + \frac{\partial y_0}{\partial t} = i - f \qquad [1]$$

With i-f is the rainfall rate minus infiltration (mm/s), qo is the unit width flow rate (m^2/s/m'), yo flow depth (m).

Momentum Equation

Considering the steady uniform flow and free air pressure are disregarded, then the basic slope equals the energy line slope. Momentum equation was taken from second Newton law, which is:

$$F = \frac{d}{dt}(mv),$$

$$\frac{d(mv)}{dt} = m\frac{dv}{dt} + v\frac{dm}{dt} = \rho A \Delta x \frac{dv}{dt} + \rho v q \Delta x, \qquad [2]$$

$$\frac{dv}{dt} = \frac{\partial v}{\partial t} + v\frac{\partial v}{\partial x}$$

Equation becomes:

$$S_o - S_f = 0 \qquad [3]$$

Then :

$$Q = \frac{S_o^{1/2}}{n} . A^m \qquad [4]$$

The surface runoffs phenomenon is shown through the water balance theory in the continuity equation below: (Bedient, 2008)

Real rainfall rate = Puddle + evaporation + infiltration + surface runoffs. The puddle is included in surface runoffs and disregarding evaporation, then effective rainfall rate obtained equals to surface runoff as shown below:

Effective rainfall rate = Real rainfall rate – (infiltration and surface runoff). Based on that, time distribution is essential to be known in effective rainfall rate. Time distribution of effective rainfall rate, which interpreted as runoff and infiltration, is obtained and observed through uniform flow rate in constant rainfall.

Water balance in the relationship between rainfall rate and infiltration as shown in Figure 2.2.

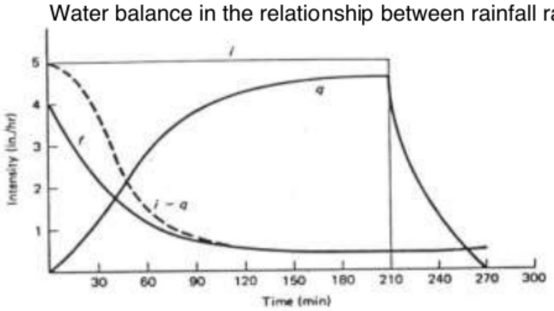


Figure 1. Water balance in overland flow
source **:** Gupta (1989, p.87)

Q = runoff (inci/hr)
I = rainfall (inci/hr)
f = infiltration (inci/hr)
t = time (minute)

2.2 Runoff

Runoff can be described as water flow from land to surface waterways. Runoff which flows to channel is dependent on time. Effective rainfall, which flows from land to waterways is called overland flow (Subramanya, 2002). Whereas overland flow which goes to smaller waterways and then joins a bigger waterway with the hydraulics flow of an open waterway is called surface runoff. Time, which differentiates between the two, depends on certain parameters on land and waterways during the water flow process.

Different processes of overland flow and surface runoff occurred from q and flow media. In overland flow, q is unit width flow rate, whereas surface runoff is Q with wetted media. Flow depth in overland flow occurred because of infiltration, whereas flow depth in surface runoff is water depth from the ground channel. Based on that, the parameters affect each flow are different. From this runoff process, the time-concentration in each case will be solved differently, although still in water balance concept.

2.3 Infiltration

A loss water factor which affects the amount of surface runoff will be different with the overland flow. In a surface runoff, water loss occurred because of waterways curves, basic material, ground roughness, and dimension. Whereas in overland flow the affecting factor of water loss is infiltration, then for overland flow is rain process and runoff.

Infiltration process is observed through the reduction of stored runoff from rainfall rate (Wilson, 1990).

Factors affecting infiltration rate are soil characteristics, land lid condition, and slope. Land lid condition can be observed through the density, which can be measured by its dry weight. The land characteristic can be observed through certain parameters, pores value, saturation degree, porosity, specific gravity, water rate, and land slope.

Infiltration rate is affected by land slope. The steeper the land, the lower the infiltration rate is (Fox, 1997). If infiltration rate is lower, then concentration time, which is the time when the soil condition reaches maximum and constant, is longer.

Infiltration rate models:

a. Kostiyakov Model

Kostiakov Model relates infiltration to time as a power function while excluding initial and final water content (constant infiltration rate). Infiltration rate and equation are shown below:

$$F = at^b, \qquad 0 < b < 1 \qquad [5]$$

$$f = \frac{dF}{dt} = abt^{b-1} \qquad [6]$$

Where *a* and *b* are constants that depend on the soil characteristics and initial water content. These constants cannot be measured before and usually obtained by pulling a straight line on a Figure paper for empirical data or by using the smallest quarter method.

b. Model Horton (1930) in Subramanya (2001, p. 87):

$$f_{ct} = f_{cf} + (f_{co} - f_{cf})e^{-K_h t} \qquad \text{for } 0 \geq t \leq t_d \qquad [7]$$

Where :

F_{ct} = the infiltration capacity or potential infiltration rate (cm/h)

f_{cf} = the final constant infiltration rate (cm/h)

f_{co} = the infiltration capacity at (cm/h) t = 0

K_h = geophysics constant which depends on soil characteristics and land lid

t_d = rainfall time

2.4 Time of Concentration

Time of concentration has two definitions based on the development of kinematic wave theory (Bedient, 2008), which are 1) time of concentration is the time required for water to travel from the most hydraulically-remote portion of a watershed to the channel, and the second definition is 2) time of concentration balance time in a watershed with constant rain intensities. Time of concentration according to Richard (1984) is the time required for water to travel from the most hydraulically-remote portion of a watershed to a location of interest.

In land, time of concentration equation is: (Richard, 1984)

$$Tc = 0{,}04690 \cdot L_f^{0{,}4450} \cdot i_2^{-0{,}7231} \cdot Ø^{0{,}5517} \cdot S_{fm}^{-0{,}2260} \qquad [8]$$

With:

L_f = overland flow path of distance

i_2 = 2 years rain intensities

S_{fm} = slope

Φ = stored flow variable

2.5 Parameter optimization

Januardin (2008) states that the higher soil density, the lower rate of infiltration. Soil density occurred because of collisions between rain and the soil surface. Vegetated soil usually has a higher infiltration rate than the open soil surface. This is caused by vegetation roots which make porosity higher which has higher rain collision energy so infiltration rate is higher.

Soil density also affects surface runoffs. Soil density occurred in urban areas because urban land is used a lot more than rural areas, such as crowded human habitation and skyscrapers (Noorvy, 2014)

Pore size and amount affect infiltration rate as well. The more and bigger pores make higher infiltration rate. In accordance with that, clay is dominated with small pores whereas sand is with big pores. So it can be concluded that infiltration in sandy soil is a lot higher than those in clay (Lipiec, 2006).

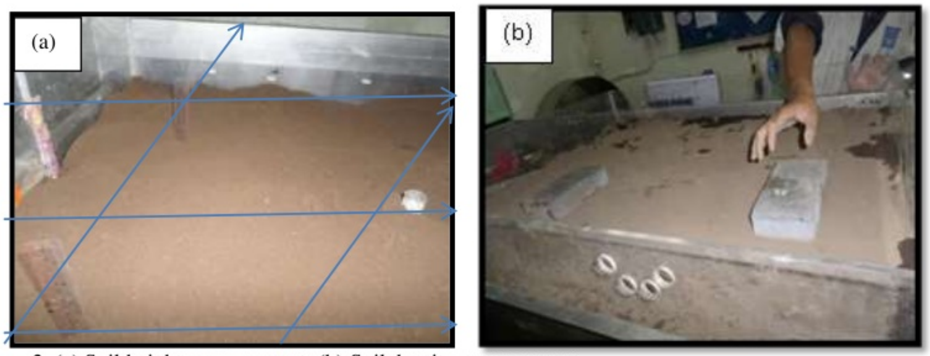


Figure 2. (a) Soil height measurement; (b) Soil density measurement

As much as 120 kg of soil is mixed with water amounts 20% of the soil used, which then divided into 3 density layers following the Proctor Test rule. Soil used in this experiment has to be dry and passed filter no. 10. Put the soil into the testing box, and compact it using a 2.9 kg pounder.

The initial water content variable is obtained by determining water mix in the experimental soil, which is 20% water from soil weight. After mixing is done, flow groundwater to the still soil for 2 hours, 2 days, and 4 days with the initial water content measured at each time. Which will result in water content for w1=

A concrete weight is dropped to soil layers from 10 cm above ground. The weight falls horizontally and vertically to make the density spread evenly. Soil heights before and after pounding are measured by dividing the soil to 3 parts horizontally and 2 parts vertically. After the first layer is pounded, the second layer is added. The same thing goes for third layer.

Soil density is measured in 2 spins (d1), 4 spins (d2), and 6 spins (d3) in order to get various densities in evenly pondered soil. Each of the three soil layers is pounded evenly. Each density gets 4 initial water content treatment, w1, w2, w3, and w4. Every density and initial water content get 3 slope treatment: S1, S2, and S3. Experiment design is shown in Table 1.

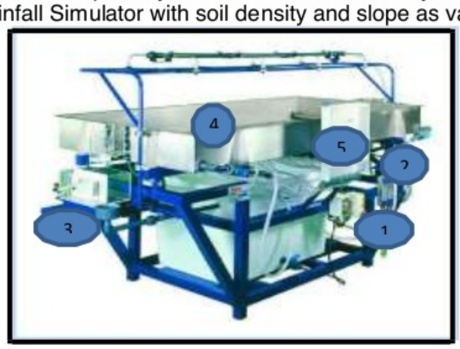
2.6 Experiment Set Up

The relationship between runoff amount and time (t) will be obtained as the result. The relationship between rain and runoff is that the higher the rainfall rate, the higher the runoff is and vice versa. When runoff is constant, the soil will be water saturated and has constant infiltration as well.

The relationship between rain and runoff is often used in hydrological design and analysis using factors that affect runoff as a parameter. Hydrography is a Figure that shows height, amount, velocity, and other characteristics of time-dependent water.

The experiment is done in a hydrological laboratory in Water Engineering of Brawijaya University using a rainfall simulator S12-MKII Hydrology System, Armfield UK. Machine specifications are shown in Figure 3. The output of the experiment is surface runoff amount.

The data achieved are primary data from the laboratory, which means, it is directly observed in a laboratory using Rainfall Simulator with soil density and slope as variables.



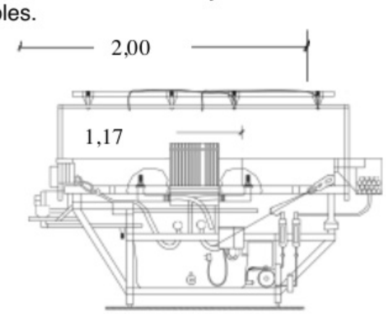


Figure 4

Figure 3. Rainfall Simulator S12-MKII Hydrology System, Armfield UK parts used in the machine are:

1. Rain intensities Control
2. Slope Control
3. Runoff Control
4. Material Tank
5. Infiltration Height Gauge (multi-tube manometer)

Rainfall Simulator shows the hydrological event in the surface land. This machine has a 2x1.2x0.3 meter plot tank. While in this experiment it has been modified to 1.17x0.97x0.30 meter as shown on Graph 4. The nozzle on the top controls rainwater size. This tank also has two porous pipes and two gauge flow tank.

Table 1 Experimental design of Relationship between rain, runoff, and infiltration

Compaction	Intial water	Slope	Compaction	Intial water	Slope	Compaction	Intial water content	Slope
d1	w1	S1	d2	w1	S1	d1	w1	S1
		S2			S2			S2
		S3			S3			S3
	w2	S1		w2	S1		w2	S1
		S2			S2			S2
		S3			S3			S3
	w3	S1		w3	S1		w3	S1
		S2			S2			S2
		S3		w4	S3			S3
	w4	S1		w4	S1		w4	S1
		S2			S2			S2
		S3			S3			S3

Keterangan:

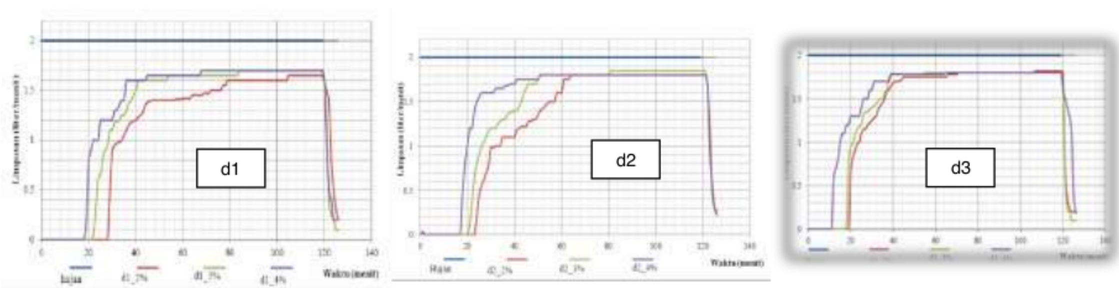
d1, d2, d3 : compaction soil
w1,w2,w3,w4 : Initial water content
S1, S2, S3 : land slope

3. RESULTS

3.1 Runoff Analysis

Runoff happens when rainfall rate is higher than the infiltration capacity of soil. In this research, surface runoff occurred on water saturated and unsaturated soils.

1. The first kind of flow occurred on the unsaturated soil. In this case, soil can be dry by adding 20% water (of soil weight) into *Rainfall Simulator*.
2. The second kind of flow occurred when soil has become saturated and there are no empty pores left to be infiltrated. This soil layer condition happens because the soil has become saturated of prior rainfall, so infiltration stops.
   Below are the results of runoff observation before and after saturation with rain is stopped in every minute:



Graph 5. Runoff curve in density 2, 4, 6 spin (d1, d2, d3) and slope 2,3,4%

Curves on the Graph 5 above show rainfall and runoff in 120 minutes of soil sample with density 2, 4, 6, and slope spins 2%, 3%, 4%. In d (1), the curve shows times when runoff starts, increase, summit, constant start, and constant. It also shows that the steeper the land, runoff starting time is faster and time to reach constant is also faster.

For runoff starting time, the steeper the land, runoff starting time is faster. In density 4 spin, the steeper the land, the faster it is to reach constant. It can be seen in 4% curve that runoff process is steeper than 4% in 2 spins (d1). This shows that alongside slope, density also the affect runoff process rate. Graph 5 curves (d3) show that runoff starting time and constant starting time in density 6 spin slopes is 2%, 3%, and 4 %. Curve below shows that the denser the soil, the faster the runoff starting time. The curve goes up in 6 spin (d3) and is tighter than d2. This shows that rain process and runoff are affected by slope and density.

Curve tightness in the highest density shows that runoff and infiltration will reach rain value depends on the soil treatment. The denser the closer. This water content variable is observed for runoff process and infiltration. Below are the Figures for this condition, Figure 6:

dari kondisi ini:

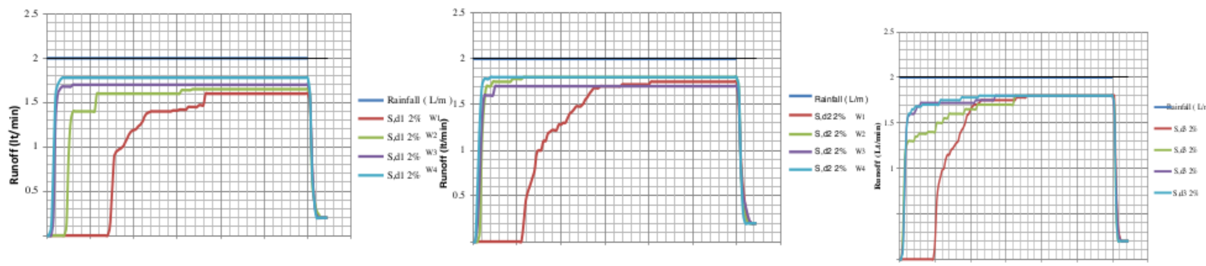


Figure 6. Runoff and time at d1, d2, d3_S 2% different water content.

Initial water content at the same slope and density means a faster constant time. This shows that soil in same density and slope has pores that are fully filled with water. Runoff is higher at same density and slope, but high water content. This is because the soil is filled with water. So does the runoff starting time, the higher water content means faster runoff starting time, as shown in Figure 6.

3.2 Infiltration Analysis

During rainfall water infiltrates the soil from the surface and redistributes in the unsaturated zone. The distribution process depends upon the soil moisture conditions, water pressure, and unsaturated permeability (Gavin, 2008).

According to Pratama (2012), the relationship between infiltration and rain intensities variables, density and slope, are directly proportional. Infiltration will increase when rain intensity is increased. The relationship between infiltration and the density is inverted. Infiltration will increase if the density is decreased. Relationship between infiltration and slope variable is inverted; infiltration will decrease if the slope is increased.

Based on Figure 7 a), b), and c), it can be seen that infiltration rate is the same in density d2, and d3 at slope 2%, 3%, 4%, but density d1 have a higher result. Density d1 at slope 2%, 3%, 4% has an approximately same result for those of d2 and d3. So it can be concluded that maximum infiltration capacity will be same at a uniform density, slopes will affect the runoff rate to reach constant infiltration capacity.

From Figure 8 (a, b, c), it can be seen that at same slope, the higher density, the lesser infiltration. Density soil will decrease the infiltration rate up to 70% to 90% (Gregory, 2006). At a denser soil, the infiltration capacity rate has similar value and tighter, this shows that infiltration rate is similar in different density at uniform slopes.

But in density d1, there are spaces between each density. This means that there are other effects in rain process, runoff, and infiltration. The factor is initial water content. Initial water content affects the process of filling pores in soil density process. The soil density process is stated as SG (Specific Gravity) and pore value inverse. A higher SG means higher soil density (dry soil volume), whereas a higher pore value (e) means lesser soil density. Which means high density will make a decline rate of infiltration.

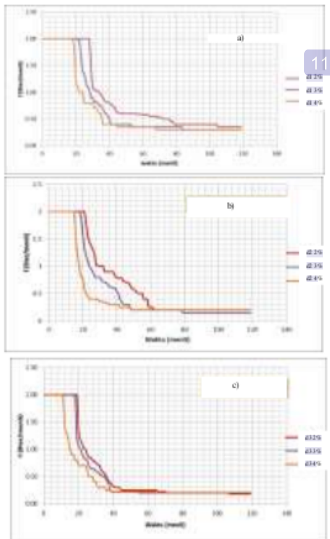


Figure 7 infiltration rate from rain and runoff relationship at (a), (b), and (c).

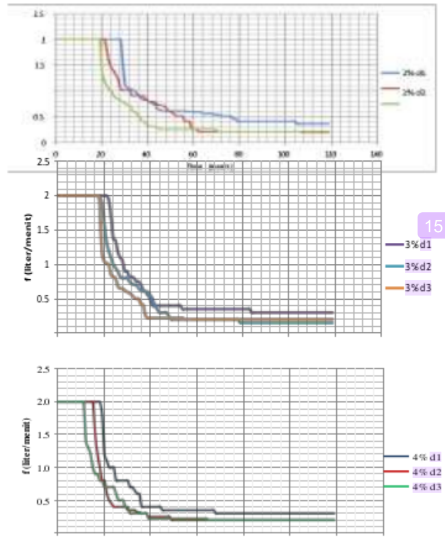


Figure 8. Infiltration rate on rain and runoff relationship S2%, S3%, S4%_d1, d2, d3

3.3 Rainfall, Runoff and Infiltration Processes Analysis

Rain and runoff process use the concept of water balance with infiltration as the only loss factor in overland flow. Rain, runoff, and infiltration curve show three moments of rain, runoff, and infiltration processes. Those are rainfall and infiltration moment, runoff moment when infiltration is lower than rainfall until the meeting point of runoff and infiltration curves, the last is when infiltration and runoff have reach constant.

In this curve, runoff starting time and constant infiltration will be shown at the same time. This explanation is part of water balance concept. Figure 9 shows result from relationship data of runoff and rain. Runoff and infiltration relationship also show a meeting point at certain times when runoff and infiltration have the same amount. Because the rainfall rate is 2 Liter/minute, it shows that runoff and infiltration are in balance which is 1 Liter/minute. The steeper the slope, the faster meeting point happens. Figure 9 shows water balance time of which meeting point between runoff and infiltration on a denser soil means the faster balance between rain, runoff, and infiltration occurred. This time shows runoff starting point after infiltration process. This time balance occurs in density with same initial water content and slope .

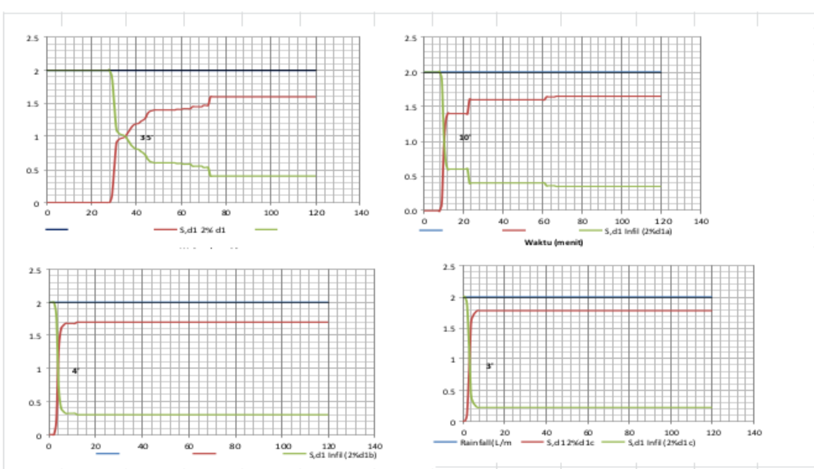


Figure *9* relationship between rain, runoff, and infiltration for d1_2%_w1,w2,w3,w4
Infiltration happens on a denser soil, steeper slope, and higher initial water content is faster.

4. CONCLUSION

Density variation of d1, d2, d3 will affect infiltration rate. The denser the soil, water in the tank will runoff faster and infiltrated less. While at a variation of slopes but same density, runoff water will be faster with steeper soil. Runoff amount will be uniform at last. Initial water content also affects infiltration, initial water content affect pores fill so water infiltrate less when initial water content is increased. The same thing applies to soil with different kind and different pore value.

When density is same and the slope is steeper, infiltration rate at constant will be less. When the slope is same and density is higher, infiltration rate at constant will be less. Based on the relationship of rain and runoff in water balance in wave kinematic law, time of concentration will be read in runoff process. Runoff happens when runoff curve goes up until it becomes constant. Infiltration as rain absorption also has the same condition.

ACKNOWLEDGMENTS

This research is funded by Kemenristek DIKTI as a doctoral scholarship program at Brawijaya University. The author appreciates the help from Hydrological Laboratory in Brawijaya University.

REFFERENCE

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

Ben-Zvi, A. (2013). *Bypassing Determination Of Time Of Concentration*. Journal Of Hydrologic Engineering, 1674-1683.

Beven*, K. (2004). *Robert E. Horton's Perceptual Model Of Infiltration Processes*. Hydrological Processes, 3447–3460.

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

Gregory, M. D. (2006). *Effect Of Urban Soil Compaction On Infiltration Rate*. Journal Of Soil And Water Conservation, 117-124.

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 Overoverland flow*. Journal Of Hydrology, 179-185.

Keith, B. (2004). *Robert E. Horton's Perceptual Model Of Infiltration Processes*. Hydrological Processes, 3447-3460.

Lipiec, J. (2006). *Soil Porosity And Water Infiltration As Influenced By Tillage* Methods. Soil And Tillage Research, 210 - 220.

Mccuen, R. H. (1984). *Estimating Urban Time Of Concentration*. Journal Of Hydraulic Engineering, Vol. 110, No. 7, 887-904.

Meyer, G. A. (2010, Juni 28). *Runoff-Factors-Affecting*.Html. Retrieved December 14, 2015, From Www.Waterencyclopedia.Com.

INFILTRATION AND SURFACE RUNOFF PROCESSES ON SLOPE AND COMPACTION SOIL WITH RAINFALL SIMULATOR EXPERIMENT

ORIGINALITY REPORT

11%	6%	8%	8%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

1	Submitted to Universiti Teknologi Petronas Student Paper	2%
2	docshare.tips Internet Source	1%
3	gairana.lt Internet Source	1%
4	Kenneth Gavin, Jianfeng Xue. "A simple method to analyze infiltration into unsaturated soil slopes", Computers and Geotechnics, 2008 Publication	1%
5	engineerscanada.ca Internet Source	1%
6	Submitted to Indian Institute of Technology Roorkee Student Paper	1%
7	Submitted to Queensland University of Technology Student Paper	1%

8	www.innovyze.com Internet Source	1%
9	Kohne, J.M.. "Coupled simulation of surface runoff and soil water flow using multi-objective parameter estimation", Journal of Hydrology, 20110606 Publication	1%
10	Submitted to Bridgepoint Education Student Paper	<1%
11	Submitted to University College London Student Paper	<1%
12	Submitted to Cranfield University Student Paper	<1%
13	Submitted to Royal Holloway and Bedford New College Student Paper	<1%
14	www.tandfonline.com Internet Source	<1%
15	Faruqi, F.A.. "On the algebraic structure of quadratic and bilinear dynamical systems", Applied Mathematics and Computation, 20050315 Publication	<1%
16	Submitted to National Institute of Technology, Hamirpur	<1%

Student Paper

17	Submitted to Curtin University of Technology Student Paper	<1%
18	ijsr.net Internet Source	<1%
19	Isabel Kaufmann de Almeida, Aleska Kaufmann Almeida, Sandra Garcia Gabas, Teodorico Alves Sobrinho. "Performance of methods for estimating the time of concentration in a watershed of a tropical region", Hydrological Sciences Journal, 2017 Publication	<1%
20	Submitted to University of KwaZulu-Natal Student Paper	<1%

Exclude quotes	Off	Exclude matches	Off
Exclude bibliography	Off		