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by Dr Andung

Design of Sustainable Road Drainage System Model

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Abstract. The existing drainage system of roads proposed to manage the quantity of runoff from the road only, while the quality remains uncontrolled. In fact the pollutants and waste originated from the road surface contains hazardous substances. Sustainable drainage system (SUDS) concept offers various structures to solve both quantity and quality problems of surface runoff from roads. One of the potential drainage structure is filter drain or infiltration trench develope along the right side and left side of road. It could be developed by retrofitting the existing drainage channel of the road. The objective of this paper proposes the design model of road drainage based on the concept of a sustainable urban drainage system.
The model consists of U-ditch channel, reservoir, an infiltration well. The bottom of U-ditch channel completed with a number of holes to make it porous. The channel filled with aggregate to filter the runoff from the road before flow down into the reservoir beneath. The water is then discharged to infiltration well. The model was developed based on rainfall data and other physical characteristics in Ambarawa City, Semarang Regency, Central Java.
The channel dimensions and the depth of aggregate filter were designed base on runoff volume. The relationship among rainfall, runoff volume, area ratio, and drainage dimension are obtained. The results concept of sustainable road drainage is obtained in addressing the quality and quantity of rainwater.

1. Introduction

The function of the road drainage is to drain runoff water through the channel and flow into the river so that a drainage channel with sufficient dimensions and capacity is needed to convey runoff water discharge. If that is not fulfilled, it will result in water flooding on the road and damage to road pavement. Rain falling on the road and its surroundings generate runoff which must be considered also the level of quantity and quality. In quantity, high rainfall will increase the volume of surface flow and result in puddles if the drainage system is not functioning properly. Waterlogging has the greatest effect on the aggregate surface layer and acts as an anti-adhesion where water causes the aggregate to be released from aggregate asphalt bonds on the surface layer (Chairuddin, Tdaronge, Ramli, & Patanduk, 2013). Rainwater quality on the road has decreased with the existence of vehicle operations, namely, rainwater has contained exhaust emissions from motor vehicles. The results of measurements of heavy metal concentrations on runoff stormwater consist of cadmium, copper, and zinc (Almaditya, and Zevi, 2013). The sustainable drainage system is a drainage system which, in addition to aiming to reduce problems caused by surface runoff, also aims to reduce the problem of water pollution (aquatic), convert water resources and increase the value of water use, especially in urban environments. Drainage ecology

(Ecological drainage or Ecodrainage) is a thought intended to support a sustainable drainage system in urban areas, especially in developing countries (Parkinson & Mark, 2005).

2. Concept of Sustainable Road Drainage

The sustainable drainage system is one of the uses of the drainage system in urban areas that functions to manage surface water so that it does not cause problems of inundation, flooding, and drought for the community, as well as beneficial for environmental sustainability. There is a change in the paradigm of a conventional drainage system from a drainage system that directly drains water towards eco-drain. The principle of eco-drain is to improve the quality of water in the drainage system, reduce drainage load and involve community participation in the management of drainage infrastructure (Suripin, 2004).
The concept of environmental-friendly or sustainable road drainage system in which the surface water run-off is infiltrated through an integrated artificial facility consisted of side channels, filter layers and infiltration wells, instead of discharging it through side channel into water body ((Yunianta, Setiadji, & Suripin, 2018).
Thus a sustainable urban drainage system (SUDS) developed to create a drainage system model that absorbs runoff water into the soil or is often referred to as infiltration. This infiltration system continues the runoff water into the drainage channel and is processed with a filter to filter pollutants or waste that is involved in runoff water. The filtration system uses geotextiles or other media as a pollutant or garbage filter (Golio, 2001).
Drains / Infiltration Trenches Filter Drains / Infiltration Trenches use drainage systems on the right and left sides of the road as permeable media that can run runoff water on the road and carry out temporary water treatment before water is drained into the ground, such as Figure 1.
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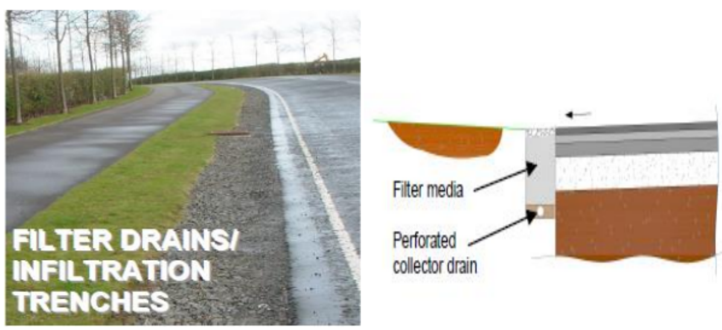

Figure 1: Model Drainase Filter Drains – Infiltration Trenches (SCOTS and SUDS Working Party, 2007)

2.1. Road Drainage Planning

One of the guidelines for planning a road drainage system issued by the Research and Development Agency, Ministry of Public Works Republic of Indonesia number Pd. T-02-2006-B. The things that need to be considered in surface drainage planning are as follows:

1. Area of Service (A), calculation of service area based on the length of the road segment. The area of service area consists of an area of half the road body (A1), the area of the road shoulder (A2), and the area of the surrounding area (A3). The length of the drainage area that is calculated consists of half the width of the road body (I1), the width of the road shoulder (I2), and the surrounding area (I3) which is divided into urban areas which are ± 10 m.
2. Flow coefficient (C), flow coefficient is influenced by land surface conditions in the service area and possible changes in land use. This number will affect the flowing flow so that it can be

estimated channel capacity. In this case, a topographic map and the type of soil erosion are needed. Flow coefficient value (C) is found in Table 1.

Table 1: Value of Runoff Coefficient (C) (Department of Public Works, 2006)

No.	Land Cover	Runoff Coefficient (C)
	Materials	
1.	Concrete road & asphalt road	0,70 – 0,95
2.	Gravel road & dirt road	0,40 – 0,70
3.	Roadside:	
-	Fine-grained soil	0,40 – 0,65
-	Coarse-grained soil	0,10 – 0,20
-	Hard massive rock	0,70 – 0,85
-	Soft massive rock	0,60 – 0,75

1. Concentration-time (Tc), the longest time needed for all service areas to channel water flow simultaneously (runoff) after passing certain points. The concentration-time for open channels is calculated by Equation (1), up to Eq. (3).

$$T_c = t_o + t_d \quad (1)$$

$$t_o = \left(\frac{2}{3} \times 3{,}28 \times l_o \times \frac{nd}{\sqrt{i_s}}\right)^{0{,}167} \quad (2)$$

$$t_d = \frac{L}{60 \times V} \quad (3)$$

Note:
Tc = concentration-time (minutes)
to = time to reach the start of the channel from the farthest point (minutes)
td = flow time in channels along from the end of the channel (minutes)
lo = the farthest distance to the drainage facility (m)
L = channel length (m)
nd = coefficient of resistance (see Table 2.)
is = slope of the longitudinal channel
V = average water velocity in the drainage channel (m/sec)

Table 2: Coefficient of Obstacles (nd) Based on Surface Conditions (Department of Public Works, 2006)

No.	Land Surface Condition	nd
1.	Cement and concrete asphalt layer	0,013
2.	The surface is slippery and waterproof	0,020
3.	Slippery and sturdy surface	0,100
4.	Land with thin and bald grass with a slightly rough surface	0,200
5.	Grassland and grass	0,400
6.	Barren forest	0,600
7.	Lush forests and dense forests are dense with a stretch of grass rarely meeting	0,800

2. Rainfall data for several of years expressed in mm/day. If the service area does not have rainfall data, then data can be used from stations outside the service area that are considered to still be able to represent, the amount of rainfall data required at least 10 years. The characteristics of the rain return period indicate that certain large rains have a certain return period, the return period for the construction of the drainage channel is determined to be 5 years, adjusted for its intended

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use. In the use of distribution person log III, the calculation step of the available rainfall data is given as in equation (4) to (7).

Data is changed in logarithmic form: X = log X ....(4)

Average value: $log\bar{X} = \frac{\sum_{i=1}^{n} \log X_i}{n}$..(5)

The standard deviation value with $s = \left[\frac{\sum_{i=1}^{n}(\log X_i - log\bar{X})^2}{n-1}\right]^{0,5}$ ....(6)

Value of coefficient of inclination: $G = \frac{\sum_{i=1}^{n}(\log X_i - log\bar{X})^3}{(n-1)(n-2)s^3}$..(7)

Furthermore, to determine the intensity of the rain, the Mononobe formula is used, namely the equation (8).

$$I = \frac{R_{24}}{24}\left(\frac{24}{t}\right)^{2/3} \quad \text{......(8)}$$

Note:

I = rain intensity(mm/jam)

t = the duration of rain

R_{24} = maximum daily rainfall (for 24 hours) (mm)

To calculate the water flow discharge (Q) using the Rational Method equation (9).

$$Q = 0{,}002778\ C\ x\ I\ x\ A \quad \text{......(9)}$$

Note:

Q = water flow discharge (m^3 / sec)

C = average flow coefficient of C1, C2, C3

I = rainfall intensity (mm / hour)

A = Service area (ha) consists of A1, A2, A3

3. The placement of the aggregate position as a filter in the drainage channel uses an assumption on the permeable pavement structure with partial exfiltration as shown in Figure 2.

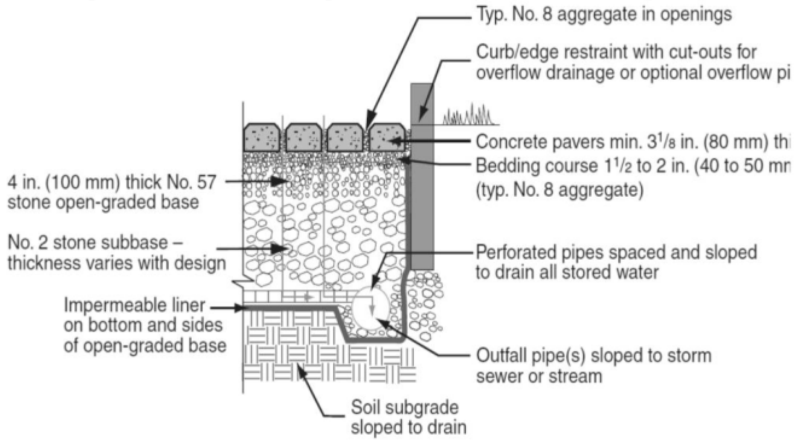

Figure 2: Typical Partial Exfiltration Structure at Permeable Pavement (Smith, 2005)

For the aggregate filter layer which consists of a layer of fine aggregate with a thickness of at least 5 cm with a diameter of type No. granules. 8 and coarse aggregate layers with a minimum thickness of 10 cm with a granular diameter of type No 57. These layers usually consist of granular material that provides a high degree of porosity to receive and drain water to the outlet pipe and then flow to the receiving water body or water reservoir. The calculation of the aggregate filter depth is assumed by following the procedure for calculating permeable pavement with Equation (10) (Smith, 2005).

$$d_p = \frac{\Delta Q_C R + P - fT}{V_r} \quad \text{...(10)}$$

Note:

dp	= aggregate depth (m)
ΔQc	= total runoff from area coverage contribution (m / hr)
R	= (Ac / Ap) the comparison value of the area coverage contribution with the permeable area
P	= rainfall design (m)
f	= infiltration rate design (m / hr)
T	= effective infiltration time (hr)
Vr	= void ratio for aggregate

2.2. Calculation of Road Drainage System

The calculation process is started by determining the rainfall according to the location of the planning, in this study the location determined is Ambarawa City, Semarang Regency, Central Java and the determination of runoff volume from the road and the surrounding area. The results of runoff volume calculation is used to design channel dimensions and aggregate filter depth, and continued to determine the volume of reservoirs that will enter the infiltration well. For determining the dimensions of infiltration wells and infiltration capacity is determined from the runoff volume and the rate of infiltration of the soil according to the location. The process of numerical analysis of sustainable road planning is as follows:

1. Determination of the extent of a service area.
    a. The channel length segment (L), the road drainage structure is made with precast concrete and is made per segment with a length (L) = 1 meter, with a channel length of 10 meters with 2 infiltration wells.
    b. Area of the service area (A), calculation of service area based on the length of the road segment. Planning location with road width = 7 meters and shoulder width = 1.5 meters, as shown in Figure 3. The area of service consists of:
        i. the area of the half body road (A1) = 3.5m x 10m = 35 m²
        ii. shoulder area (A2) = 1.5m x 10m = 15 m²
        iii. the area around (A3) = 10m x 10m = 100 m².
        iv. The length of the drainage area is calculated consists of:
        v. half the width of the road body (I1) = 3.5 m
        vi. shoulder width (I2) = 1.5m
        vii. the area around (I3) = 10 m
2. Calculation of maximum daily rainfall using Log-Person III Distribution in Table 3. Rainfall data for the Ambarawa City area is secondary data sourced from the Center for Disaster Studies Studies, Institute of Research and Community Service (LPPM) Diponegoro University.

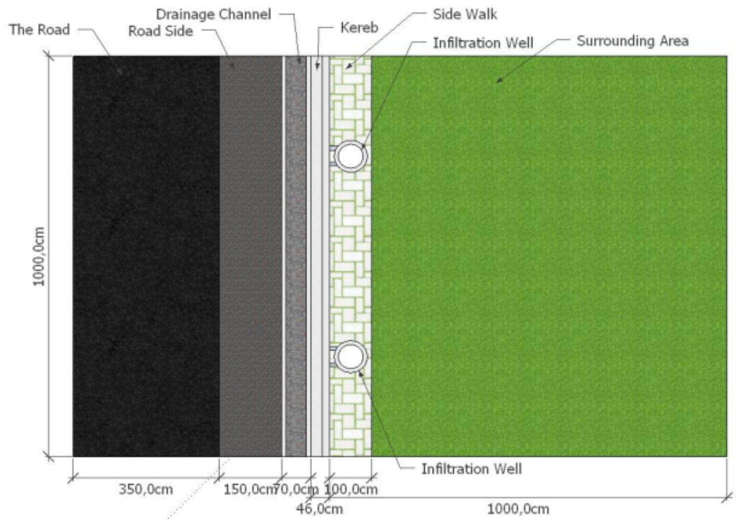

Figure 3: Area of Road Drainage Services

Table 3: Maximum Daily Probability Analysis of Rain in Ambarawa District, Semarang Regency with Distribution Log of Person III.

No.	Year	R (mm) (X)	Log X	$\log X_i - log\bar{X}$	$(\log X_i - log\bar{X})^2$	$(\log X_i - log\bar{X})^3$
1	2005	108	2,033423755	0,10122734	0,010246975	0,001037274
2	2006	71	1,851258349	-0,0809381	0,00655097	-0,000530223
3	2007	99	1,995635195	0,06343878	0,004024479	0,000255308
4	2008	80	1,903089987	-0,0291064	0,000847184	-0,000024658
5	2009	87	1,939519253	0,00732284	0,000053624	0,00000039268
6	2010	94	1,973127854	0,04093144	0,001675383	0,0000685758
7	2011	80	1,903089987	-0,0291064	0,000847184	-0,000024658
8	2012	61	1,785329835	-0,1468666	0,021569791	-0,003167881
9	2013	83	1,919078092	-0,0131183	0,00017209	-0,00000225754
10	2014	105	2,021189299	0,08899289	0,007919734	0,0007048
11	2015	85	1,929418926	-0,0027775	0,0000077144	-0,00000002143
	Average		1,932196412	Total	0,053915129	-0,00168335

The value of rainfall with Distribution Log Person III is 98.6278 mm

a. Hydrological analysis, then the Mononobe formula is used to determine the rainfall intensity. I = 86,1595 mm/hour
b. Flow coefficient (C) = 0.70
c. To calculate the flow rate of water (Q) using the Rational Method formula
   Q = 0,002778 x 0,7 x 86,1595 x 0,0150
   Q = 0,00251 m³/detik
d. Time of concentration (Tc), the concentration time for open channels is calculated as follows:
   l_o= 10 m
   L= 10 m

nd = 0,013
is = 0,075
v = 1,5 m/sec

$$t_o = (\frac{2}{3} \, x \, 3{,}28 \, x \, 10 \, x \, \frac{0{,}013}{\sqrt{0{,}075}})^{0{,}167}$$

$$t_o = 1{,}0 \text{ minute}$$

$$t_d = \frac{10}{60 \, x \, 1{,}5}$$

$$t_2 = 0{,}11 \text{ minute}$$

tc = 1,0 + 0,11 = 1,11 minute = 0,018 hour.

e. Runoff volume:

$$Volume = \left((Q \, x \, Tc) + \left(Q(D - Tc)\right)\right) x3600$$

$$Volume = \left((0{,}00251 \, x \, 0{,}018) + \left(0{,}00251(0{,}25 - 0{,}018)\right)\right) x3600$$

$$Volume = 2{,}259 \, m^3$$

f. Aggregate depth

$$d_p = \frac{(\frac{2{,}259}{150}) \, x \, \left(\frac{150}{0{,}7x10}\right) + 0{,}098627}{0{,}4} = 1{,}05 \, m$$

So with the upper width of the 70 cm channel, 105 cm channel depth will be obtained, for more details the detailed calculation of the relationship between the width and depth of the aggregate is given in Table 4:

Table 4: Calculation of Width and Aggregate Depth

Width (m)	0,10	0,20	0,30	0,40	0,50	0,60	0,70	0,80	0,90	1,00
Depth (m)	5,89	3,02	2,13	1,66	1,37	1,19	1,05	0,95	0,87	0,81

g. Calculation of infiltration wells, review of drainage planning with a channel length of 10 meters and 2 infiltration wells.

The volume of Infiltration Wells

$$Vrsp = \frac{Tc}{24} x \, Atot \, x \, K$$

Atot = area infiltration wells (m^2)
= (0,25 x 3,14 x 0,8^2) x 2 = 1,0053 m^2
K = permeability coefficient (m / day)
= for fast sand soil 10 cm / hour

Flow time is planned for 24 hours so that the permeability rate becomes 10 cm / hour = 2.4 m / day.

$$Vrsp = \frac{0{,}25}{24} x \, 1{,}0053 \, x \, 2{,}4$$

= 0,025 m^3

3. Daily minimum rainfall calculation using Log-Person III Distribution, in Table 5.

Table 5: Minimum Daily Rain Probability Analysis of the location of the District of Ambarawa Semarang Regency with a Distribution Log of Person III.

No.	Year	R (mm) (X)	Log X	$\log X_i - log\bar{X}$	$(\log X_i - log\bar{X})^2$	$(\log X_i - log\bar{X})^3$
1	2005	14	1,146128036	0,01769797	0,000313218	0,00000554333
2	2006	3	0,477121255	-0,651308811	0,424203167	-0,27627261
3	2007	9	0,954242509	-0,174187556	0,030341305	-0,005285078
4	2008	11	1,041392685	-0,087037381	0,007575506	-0,000659352
5	2009	6	0,77815125	-0,350278815	0,122695249	-0,042977546
6	2010	30	1,477121255	0,348691189	0,121585545	0,042395808
7	2011	24	1,380211242	0,251781176	0,063393761	0,015961356
8	2012	20	1,301029996	0,17259993	0,029790736	0,005141879
9	2013	25	1,397940009	0,269509943	0,072635609	0,019576019
10	2014	9	0,954242509	-0,174187556	0,030341305	-0,005285078
11	2015	32	1,505149978	0,376719913	0,141917892	0,053463296
		Average	1,12843006	Total	1,044793293	-0,193950414

The value of rainfall with Distribution Log Person III is 98,6278 mm

a. Hydrological analysis, then the Mononobe formula is used to determine the rainfall intensity.
   I = 21,9718 mm/jam

b. Flow coefficient (C) = 0.70

c. To calculate the flow rate of water (Q) using the Rational Method formula
   Q = 0,002778 x 0,7 x 21,9718 x 0,0150
   Q = 0,000641 m^3/sec

d. Time of concentration (Tc), the concentration time for open channels is calculated as follows:
   l_o = 10 m
   L = 10 m
   nd = 0,013
   is = 0,075
   v = 1,5 m/sec

$$t_o = (\frac{2}{3} \, x \, 3{,}28 \, x \, 10 \, x \, \frac{0{,}013}{\sqrt{0{,}075}})^{0{,}167}$$

$$t_0 = 1{,}0 \text{ minute}$$

$$t_d = \frac{10}{60 \, x \, 1{,}5}$$

$$t_2 = 0{,}11 \text{ minute}$$

   tc = 1,0 + 0,11 = 1,11 minute = 0,018 hour.

e. Runoff volume:

$$Volume = \left((Q \, x \, Tc) + \left(Q(D - Tc)\right)\right) x3600$$

$$Volume = \left((0{,}000641x \, 0{,}018) + \left(0{,}00064151(0{,}25 - 0{,}018)\right)\right) x3600$$

$$Volume = 0{,}5769 \, m^3$$

f. Aggregate depth

$$d_p = \frac{(\frac{0{,}5769}{150}) \, x \, \left(\frac{150}{0{,}7x10}\right) + 0{,}0251515}{0{,}4} = 0{,}26 \, m$$

So with the upper width of the 70 cm channel, 26 cm channel depth will be obtained, for more details the detailed calculation of the relationship between the width and depth of the aggregate is given in Table 6:

Table 6: Calculation of Width and Aggregate Depth

Width (m)	0,10	0,20	0,30	0,40	0,50	0,60	0,70	0,80	0,90	1,00
Depth (m)	1,51	0,78	0,54	0,42	0,35	0,30	0,26	0,24	0,22	0,20

g. Calculation of infiltration wells, review of drainage planning with a channel length of 10 meters and 2 infiltration wells.

The volume of Infiltration Wells:

$$Vrsp = \frac{Tc}{24} x\ Atot\ x\ K$$

Atot = area infiltration wells (m^2)
= ($0,25 \times 3,14 \times 0,8^2$) x 2 = 1,0053 m^2

K = permeability coefficient (m / day)
= for fast sand soil 10 cm / hour

Flow time is planned for 24 hours so that the permeability rate becomes 10 cm / hour = 2.4 m / day.

$$Vrsp = \frac{0,25}{24} x\ 1,0053\ x\ 2,4$$

= 0,025 m^3

From the results of the above calculations if the graph of the relationship between width and depth for different rainfall is the maximum and minimum rainfall, the graph is obtained as shown in Figure 4:

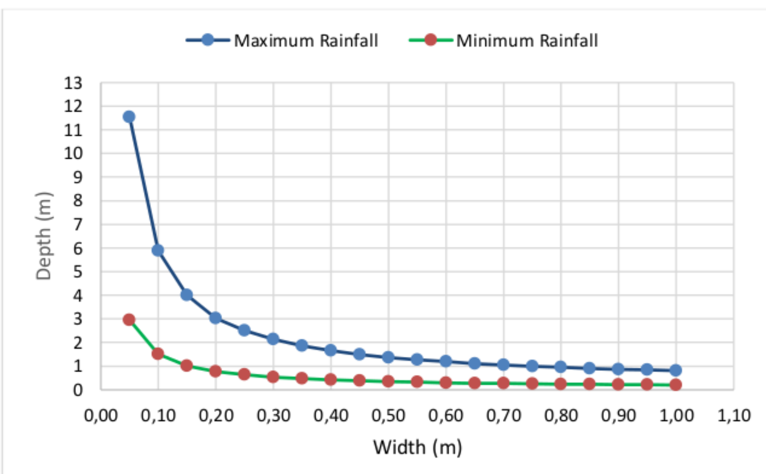

Figure 4: Graph of the Relationship of Width and Aggregate Depth for Maximum and Minimum Rainfall.

2.3. Model Design

The design of the designed model is a rectangular Drainage Channel (U-ditch) with a structure made of precast concrete with a width of 90 cm, height of 140 cm, and a length of 100 cm, with a wall thickness of 10 cm. At the bottom of the channel is a water storage room with a height of 20 cm and a width of 70 cm, as well as a 10 cm thick channel bed. The infiltration well structure is made of circular shape buis concrete with a diameter of 0.8 meters, a depth of 1 meter and a wall thickness of 0.1 meters. The depth of infiltration wells is 3 meters or 3 concrete buis, as shown in Figure 5 to Figure 7.

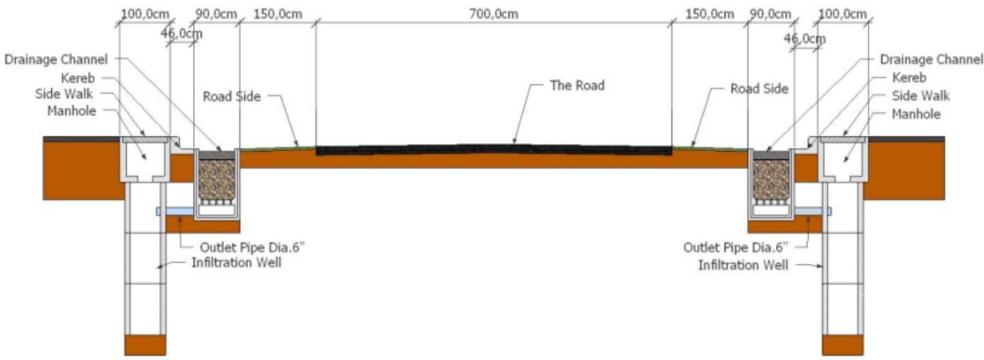

Figure 5: Typical Cross Section of the Road

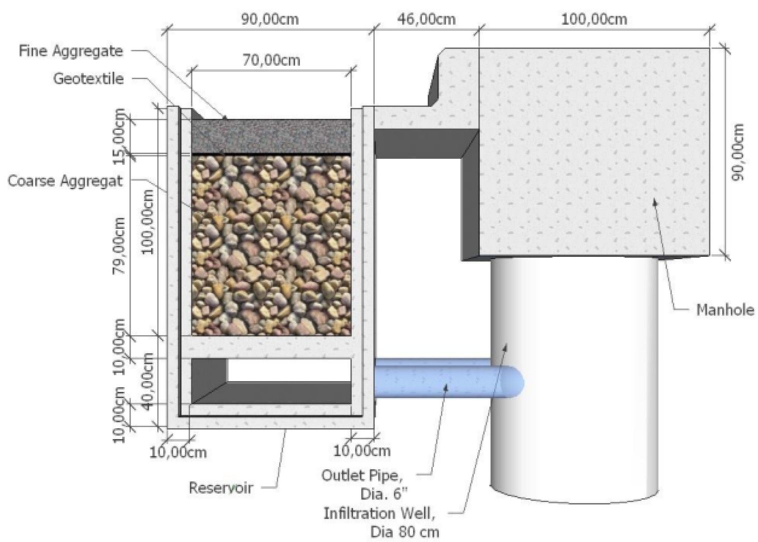

Figure 6: Typical Details of Channels and Infiltration Wells

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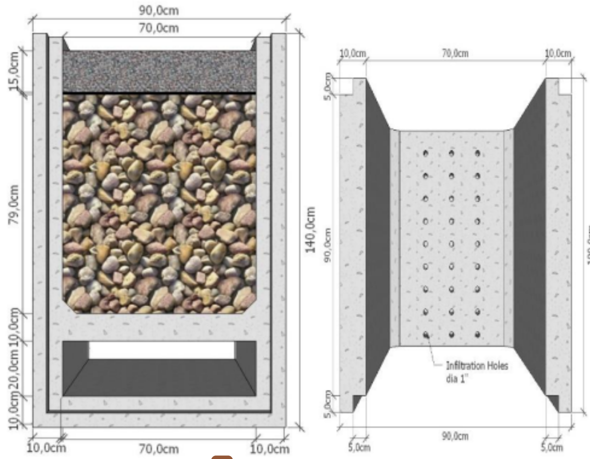

Figure 7: Details of the Drainage Channel Model

3. Conclusion

The results indicated that the concept of sustainable road drainage is potential to be developed in addressing the quality and quantity of rainwater. The relationship among rainfall, runoff volume, area ratio, and drainage dimension.

Acknowledgments

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