International Journal on Advanced Science Engineering Information Technology

Vol.13 (2023) No. 2
ISSN: 2088-5334

Performance Evaluation of the Urban Drainage Network Structure Using the SWMM Model

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Abstract— **The drainage channel system is an important factor in city planning. It controls runoff and prevents cities from flooding. The urban drainage design also contributed to the city planning in Padang, where the risk of flooding is very high. Belimbing Area is one of the neighborhoods in Padang that often floods because of the poor drainage channel system. This research aims to improve its drainage channel system by surveying parts of the Belimbing Area with a high risk of flooding and evaluating its drainage channels using EPA SWMM v5.1. Data such as drainage channel dimension, climate, and subbasin data are collected and simulated using the software. Rainfall data used for this research are 20 years from Koto Tuo Station and Gunung Nago Station. The distance between each station to the research area is 2.30 km for Koto Tuo Station and 3.30 km for Gunung Nago Station. The infiltration method used in the software is Horton's Method, which will provide the data by Infiltrometer. The result shows parts in Belimbing Area that cannot hold their runoff and which drainage channel overflows. Fortunately, there is no significant runoff or severe overflows, but the result does not match its existing situation. This might happen because of lots of trash and plants clogging the channel. This research will benefit the government and stakeholders to take action on the current situation by recovering Belimbing Area's drainage channel.**

Keywords— **ID modelling; flooding; drainage; infiltration; Horton.**

Manuscript received 5 Jan. 2022; revised 14 Aug. 2022; accepted 12 Feb. 2023. Date of publication 30 Apr. 2023.

I. INTRODUCTION

Padang is one of many cities in Indonesia that are often threatened by floods [1]–[3]. From the data that National Agency for Disaster Management provides, Padang has a high risk of flooding [3]. Belimbing Area is one the areas that frequently floods. The drainage channels in the area are too small, and most are damaged. Improvement to the drainage channels is needed. By evaluating the drainage system in Belimbing Area, we can check the maximum height in every drainage channel. Environmental Protection Agency Storm Water Management Model v5.1 (EPA SWMM v5.1) is a model that can analyze and evaluate drainage systems and will be used for this research [4]–[9].

This research aims to determine how much runoff happens in the Belimbing Area and the effectiveness of the drainage system. The benefit of this research is contributing thoughts and ideas to the government so the drainage system problem can be fixed. This research will be focused on certain settlement areas. Rainfall data for this research is taken from Koto Tuo Station and Gunuang Nago Station. SWMM model will analyze the area's drainage channel system and runoff [10], [11]. It will also be used to calculate infiltration value using Horton's method [12], [13]. Percentages of previous and impervious areas will use Google Earth Pro. For this research, flows outside the research station and runoff on streets are not calculated.

Drainage is a technical act to prevent too much runoff from rainfall, seepage, or excessive irrigation water from an area/land so that the area/land would not be destroyed. The drainage system is used to control and distribute runoff safely. The explanation above shows that drainage is one of the main factors for good city planning [14].

Urban drainage is a sewer network that dries parts of the city and urban area from runoff from local rain or overflowing river crossing the city [10], [15]. Urban drainage prevents city areas from runoff that causes negative impact, flows runoff to nearby water storage, controls excessive runoff that can be used for water supply, and protects facilities and infrastructure [16].

Hydrology is a study that explains water availability and flows in nature. It relates to how it changes form to liquid, solid, and gas inside the Earth's atmosphere, on and under the ground. Hydrology analysis predicts streams that enter each period [17], [18]. It is also used to determine the channel capacity by looking at the hydraulic properties that occur in an area.

II. Material and Methods

A. The Study Area and Existing Condition

Rainfall data used for this research are 20 years from Koto Tuo Station and Gunung Nago Station. The distance between each station to the research area is 2.30 km for Koto Tuo Station and 3.30 km for Gunung Nago Station.

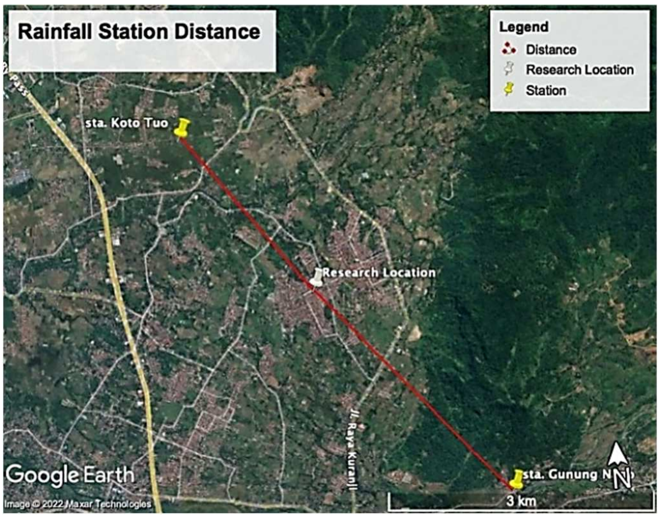


Fig. 1 Distance from the station to the research area

Socio-economic factors in developing countries make it more difficult to solve urban drainage problems than in more advanced countries. Urban drainage infrastructures are facing critical challenges due to a lack of integrated asset management and periodic maintenance. Many drainage channels in the research area function poorly. Some are caused by sedimentation; others are led by moss growth. Piles of trash also hamper many drainage channels. These problems have occurred as a result of clogged drainage streams. The lack of operation and maintenance causes the lack of operation and maintenance at the urban drainage system. It worsens since the rainwater and disposal are mixed in the same channels. Figures 2 and 3 show that the channels are filled with garbage.

Fig. 2 Piles of trash on the drainage channel.

Fig. 3 Plants growing on the drainage channel

B. Hydrological Analysis

The rainfall data needed to design a drainage channel is the mean of maximum precipitation used in each station [19]. The followings are methods how for calculating regional rainfall data for two or more stations:

1) Arithmetic method:

$$P = \frac{P = P_1 + P_2 + P_3 + \ldots + P_n}{n} = \frac{\sum_{i=1}^{n} P_n}{n} \quad (1)$$

P_n: precipitation in station-n; n: number of the station used.

2) Thiessen polygon method:

$$P = \frac{P_1A_1 + P_2A_2 + \ldots + P_nA_n}{A_1 + A_1 + \ldots + A_n} = \frac{\sum_{i=1}^{n} P_iA_i}{\sum_{i=1}^{n} A_i} \quad (2)$$

P_n: precipitation in station-n; n: number of the station used.
A: area of a polygon

$$P = \frac{A_1\left(\frac{P_1+P_2}{2}\right) + A_2\left(\frac{P_2+P_3}{2}\right) + \ldots + A_{n-1}\left(\frac{P_{n-1}+P_n}{2}\right)}{A_1 + A_2 + A_{n-1}} = \frac{\sum\left[A\left(\frac{P_1+P_2}{2}\right)\right]}{\sum A} \quad (3)$$

P_n: precipitation in station-n; n: number of the station used.
A: area

Frequency analysis is the chance of the quantity of rainfall matched or exceeded. On the contrary, the return period is the hypothetical time when rainfall with a certain quantity is matched or exceeded [18], [20]–[22]. On frequency analysis, there is some distribution method that is used according to the following parameters:

- Mean

$$\bar{X} = \frac{1}{n} = \sum_{i=1}^{n} X_i \quad (4)$$

- Standard deviation (S)

$$S = \left[\frac{1}{n-1} \sum_{i=1}^{n} (X_i - \bar{X})^2\right]^{0.5} \quad (5)$$

- Coefficient of variation (Cv)

$$Cv = \frac{S}{\bar{X}} \quad (6)$$

- Coefficient of Kurtosis (Ck)

$$Ck = \frac{\frac{1}{n}\sum(X_i - \bar{X})^4}{S^4} \quad (7)$$

- Coefficient of Skewness (Cs)

$$a = \frac{n}{(n-1)(n-2)}\sum|X_i - \bar{X}|^3;\ Cs = \frac{a}{S^3} \quad (8)$$

$\bar{X}$: mean value; X_i: value in variance I; n: number of variances

TABLE I
DISTRIBUTION METHOD AND SPECIFICATION

Method	Specification
Normal	Ck ~ 3 Cs ~ 0
Log-Normal	Cv ~ 0.06 Cs ~ 3Cv
Gumbel	Cs ~ 1.1396 Ck ~ 5.4002
Log Pearson Type III	Cs ≠ 0

The goodness of fit is used to test the suitability of the sample data's frequency distribution against the probability estimated to represent the use of the distribution function. One method used in the goodness of fit is the Chi-Square method. The formula is:

$$X_h^{\ 2} = \sum_{i=1}^{G}\frac{(O_i - E_i)^2}{E_i} \quad (9)$$

X_h^2: chi-square value; G: the value of subgroup; O_i: number of observation values in sub-group-I; E_i: number of theoretical values in subgroup-i

Rainfall intensity is the height or depth of rain in each period. The relation between rainfall intensity, duration, and frequency could be determined with the Intensity-Duration-Frequency curve (IDF curve). IDF curve can be calculated using the Mononobe formula as follows:

$$I = \frac{R_{24}}{24}\left(\frac{24}{t_c}\right)^{2/3} \quad (10)$$

I: rainfall intensity (mm/hr)
R_{24}: maximum daily rainfall (mm/hr)
tc: time of concentration (hr)

3) *Return period:* The return period is an estimated average interval time for an event to occur for an event in a certain magnitude [23]. The typology of the city can determine the return period according to the following table [24]:

TABLE II
RETURN PERIOD ACCORDING TO TYPOLOGY.

City Typology	Catchment area			
	<10	10-100	101-500	>500
Metropolitan	2 years	2-5 years	5-10 years	10-25 years
Big City	2 years	2-5 years	2-5 years	5-20 years
Medium City	2 years	2-5 years	2-5 years	5-10 years
Small City	2 years	2 years	2 years	2-5 years

4) *Alternating Block Method:* The alternating Block Method is simple to create a hyetograph [25]. This method makes the rain that occurs in successive time intervals with a duration of t during the time Td = nΔt [26]

5) *Velocity:* The stream's velocity should not be too low or too high. The allowed minimum velocity is the lowest speed of flow that would not cause deposition and growing plants on the channel. The minimum speed allowed ranged from ±0.60 – 0.90 m/s [27]. This limit bears moss growth because of the small flow. Allowed maximum velocity is the highest speed flow that would not cause erosion to the drainage channel [24].

6) *Channel slope:* Channel slope is the difference in elevation between two points on a stream divided by the distance between them measured along the stream channel [28]. Differences between channel slopes will affect the stream velocity.

7) *Channel capacity:* Channel capacity can be calculated with Manning's formula.

$$R = \frac{A}{P} \quad (11)$$

$$V = \frac{1}{n}R^{2/3}S^{1/2} \quad (12)$$

$$Q = \frac{1}{n}A\,R^{2/3}S^{1/2} \quad (13)$$

Q: discharge (m^3/s); n: manning coefficient; R: hydraulic radius (m); S: channel slope; A: flow area (m^2); V : average speed (m/s); p: wetted perimeter (m)

8) *Manning coefficient:* The Manning coefficient is commonly used in the analysis of channels. It usually reflects the resistance characteristics of different underlying surface conditions. It is a key parameter that affects flow concentration and flood evolution. Some factors determine the manning coefficient, such as surface roughness, deposition, irregularity, grinding, and water or flow level.

9) *Best hydraulic section:* On a certain flow, the flow area will be minimum if the channel has a maximum hydraulic radius (R) and minimum wetted perimeter (P). Drainage channels that have these characteristics are called the best hydraulic sections.

10) *Freeboard:* A freeboard is a secured space of height measured from the maximum water surface to the embankment surface and the ground (if the channel does not have an embankment) [29]. Freeboard anticipates rising water levels caused by waves, flow change, sedimentation, and manning coefficient change.

11) *Storm Water Management Model:* SWMM is a dynamic rainfall-runoff model used for a single event or long-term (continuous) simulation of runoff quantity and quality from primarily urban areas [5]. This software can simulate the impact of rainfall-runoff in an area on its drainage system for an extended period and has an alternative facility to anticipate flooding [4], [15], [30].

The method can be figured out as follows:

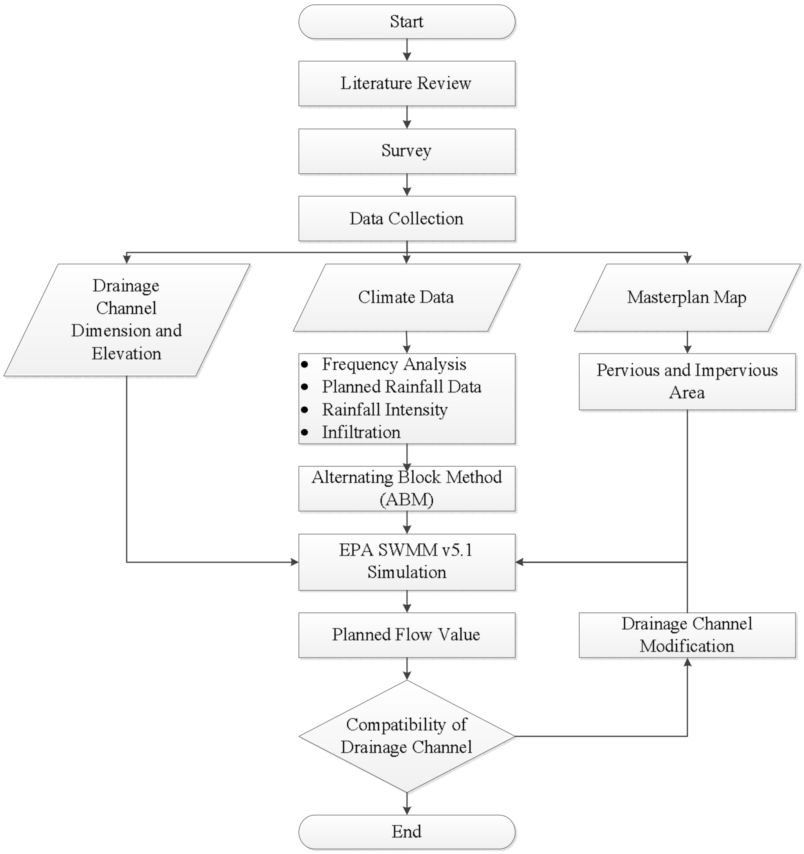


Fig. 4 Research flowchart

III. Result and Discussion

A. Hydrological Analysis

After all rainfall data are taken, we can use those data to determine a distribution method that is valid to use. Data were obtained using the formula of skewness, coefficient of kurtosis, and coefficient of variation. The values of the coefficient of skewness (Cs), coefficient of kurtosis (Ck), and coefficient of variation (Cv) are -2.38, 8.10, and 0.57

TABLE III
Maximum Annual Rainfall Data

Year	Koto Tuo (mm)	Gunung Nago (mm)
2020	143.00	231.00
2019	111.00	126.00
2018	151.00	146.00
2017	140.00	241.00
2016	218.00	1015.00
2015	145.00	231.00
2014	153.00	139.00
2013	174.00	191.00
2012	151.60	150.00
2011	154.80	170.00
2010	215.00	180.00
2009	82.00	196.00
2008	89.00	239.00
2007	114.00	98.00
2006	147.97	270.20
2005	500.00	270.00
2004	207.00	186.00
2003	229.00	186.00
2002	290.00	186.00
2001	204.00	257.00

1) Frequency Analysis: After all, the parameter is calculated, and all data provided will be used to determine which distribution method qualifies its parameter. It is determined that the distribution method that qualifies is the Log Pearson III method. So, the Log Pearson III method is used to calculate the planned rainfall value. The results of the planned rainfall value in every return period are listed below.

TABLE IV
Log Pearson III Distribution Method

T	Log Xr	K_T	S Log X	Log X_T	X_T
2	2.22	-0.27	0.18	2.17	147.00
5	2.22	0.65	0.18	2.33	214.14
10	2.22	1.32	0.18	2.45	280.78
25	2.22	2.18	0.18	2.60	398.31
50	2.22	2.25	0.18	2.61	409.85
100	2.22	2.51	0.18	2.66	454.54

The method that is used for the goodness of fit test is the chi-square method. We must calculate the class distribution and interval to begin using this method. After calculating those data, we can group our annual rainfall data with the Log Pearson III distribution method to our calculated interval. The result of the chi-square values calculated is 5.8. The theoretical chi-square value based on the data provided is 7.82, which means that the Log Pearson III method qualifies as this research distribution method.

2) Infiltration: The infiltration method used for this research is Horton's method [31], [32]. With EPA SWMM v5.1, we can automatically calculate infiltration data just by inserting the maximum infiltration value (f_0), minimum infiltration value (f∞), and decay constant (Kd) in this area. After our surveys in the field, we found the results as follows.

TABLE V
INFILTROMETER CALCULATION RESULT

T (minute)	H	dt	dh	dh/dt (cm/minute)	dh/dt (in/hr)
0	21.2				
		10	4.1	0.41	9.7
10	17.1				
		10	1	0.1	2.4
20	16.1				
		10	0.7	0.07	1.7
30	15.4				
		10	0.6	0.06	1.4
40	14.8				
		10	0.6	0.06	1.4
50	14.2				

Table V shows that the maximum and minimum infiltration values are 9.7 in/hr and 1.4 in/hr. The value of the percent decline of infiltration capacity calculated from its maximum and minimum infiltration is 85%. The decay coefficient (Kd) value can be obtained using interpolating on the table of decay coefficient and percentage decline on infiltration capacity. After we interpolated it, the result of the decay coefficient (Kd) obtained was 2.47.

3) Rainfall intensity: The calculation between two rainfall stations is calculated using the mononobe formula and shown in the Intensity Duration Frequency (IDF) curve. Intensity–duration–frequency curves are used extensively in engineering to assess the return periods of rainfall events [33]. After the IDF curve is made, Hyetograph should be made using the Alternating Block Method (ABM). Applying the design storm method with an alternating block hyetograph is very applicable in this model.

TABLE VI
CALCULATION OF RAINFALL INTENSITY USING THE MONONOBE FORMULA.

t (minute)	R_t (mm)	I (mm/hr)
5	146.10	267.11
10	146.10	168.27
15	146.10	128.41
25	146.10	91.35
30	146.10	80.90
60	146.10	50.96
120	146.10	32.10
180	146.10	24.50
360	146.10	15.43

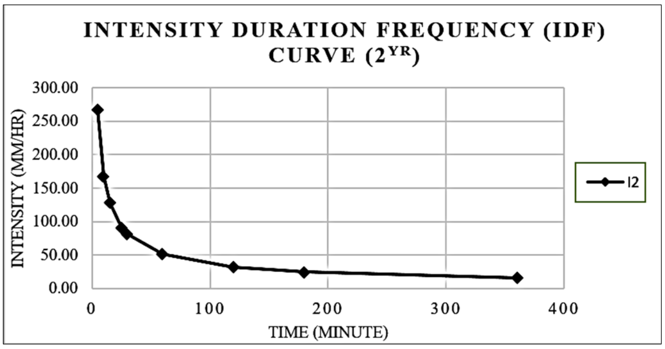


Fig. 5 Intensity Duration Frequency Curve

TABLE VII
HYETOGRAPH CALCULATION USING THE ABM METHOD FOR TWO YEARS RETURN PERIOD

Td (hr)	Δt (hr)	It(mm/hr)	It Td (mm)	Δp (mm)	Pi (%)	Hyetograph	
						(%)	(mm)
1	0-1	50.96	50.9	50.96	55.0	6.8	9.92
2	1-2	32.10	64.2	13.25	14.3	10.0	14.7
3	2-3	24.50	73.5	9.29	10.0	55.0	80.9
4	3-4	20.22	80.9	7.40	8.00	14.3	21.0
5	4-5	17.43	87.1	6.25	6.75	8.00	11.7
6	5-6	15.43	92.6	5.46	5.90	5.90	8.67

Based on Figure 6, the Alternating Block Method shows that the peak of the Hyetograph occurs after 3 hours, with the maximum rainfall reaching 81 mm.

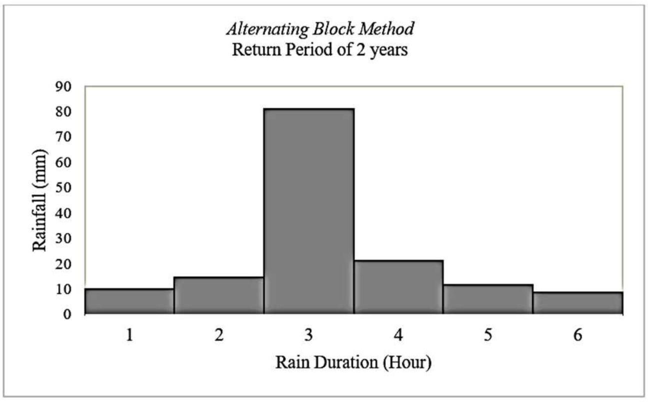


Fig. 6 ABM graph for two years returns period.

B. Hydraulics Modeling Using SWMM

Finding the urban drainage system's ability to convey Water requires estimating the peak first and then the urban runoff volume. Explaining drainage system issues and determining the degree of a flood or surcharge can be done by simulating urban floods[10]. The scheme of the drainage channel network in the Belimbing Area is drawn in the EPA SWMM model. It comprises 26 sub-catchments, 84 junctions, 83 conduits, and 7 outfalls.

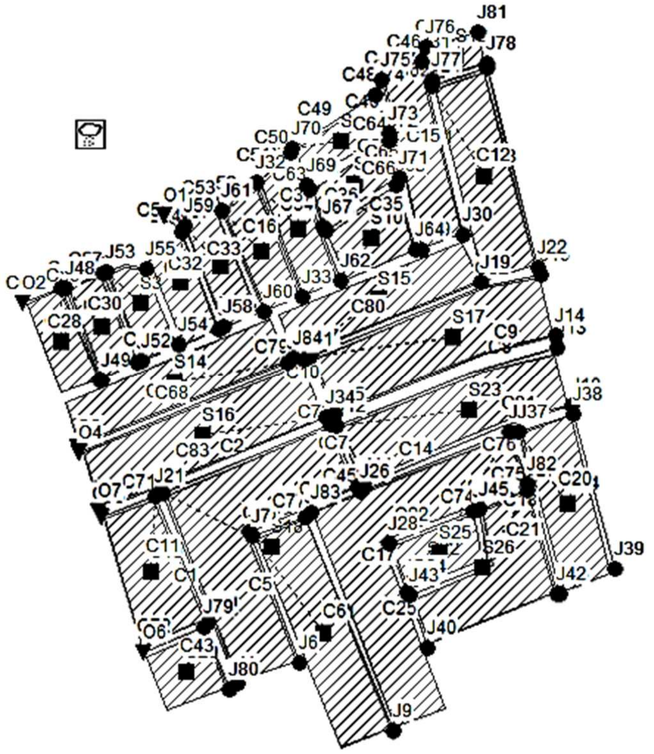


Fig. 7 The scheme of the drainage channel network.

The drainage channel network simulation result using EPA SWMM v5.1 software shows the current error surface runoff value -0.43% and flow routing 0.00%. The result showed that the highest runoff lies on sub-catchment 18 at 04:00:00. However, the sub-catchment itself can still maintain its runoff.

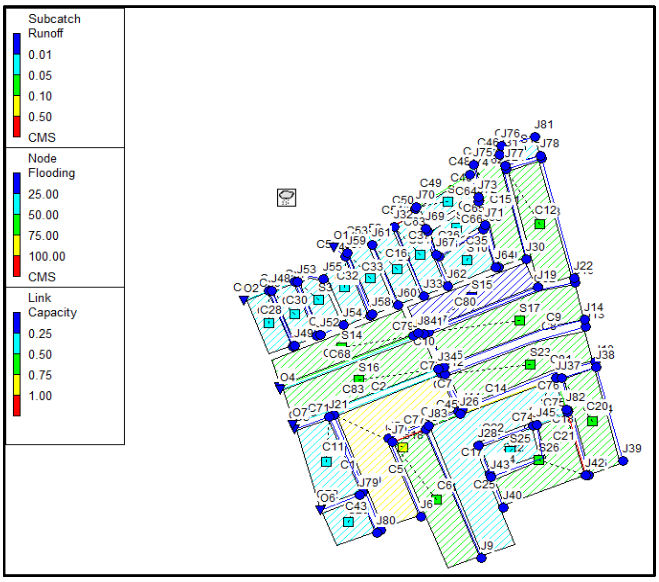
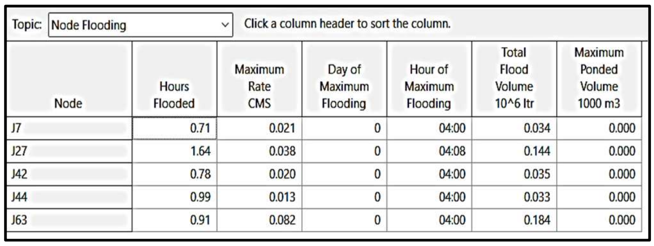


Fig. 8 Drainage channel network simulation result

The red indicates the worse situation in the areas, and the dark blue indicates the areas are safe from flooding. The result of the simulation shows that five nodes overflow their capacity. Those nodes are J7, J27, J42, J44, and J63. The longest hours flooded is 1.64 hours. The result also shows an overflowing conduit on Conduit 21 between Junction 42 and Junction 27. The maximum duration of inundation reached 4 hours, and the peak of the flood occurred around 1 hour, with a maximum discharge is 0.082 at J63.



Topic: Node Flooding Click a column header to sort the column.

Node	Hours Flooded	Maximum Rate CMS	Day of Maximum Flooding	Hour of Maximum Flooding	Total Flood Volume 10^6 ltr	Maximum Ponded Volume 1000 m3
J7	0.71	0.021	0	04:00	0.034	0.000
J27	1.64	0.038	0	04:08	0.144	0.000
J42	0.78	0.020	0	04:00	0.035	0.000
J44	0.99	0.013	0	04:00	0.033	0.000
J63	0.91	0.082	0	04:00	0.184	0.000

Fig. 9 Flooding Nodes

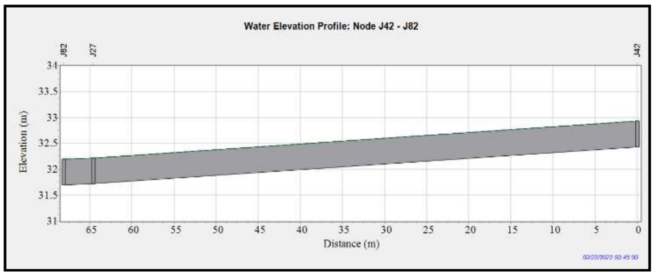


Fig. 10 Cross-section on conduit 21.

Figure 11 presents the river overflow beginning from 03:15 to 04:00 hours. Based on the graph, flood inundation is found at node J42, and the peak discharge during this period is determined to reach 0.02 $m^{3/}s$. The drainage channel network simulation in the Belimbing area shows no sign of severe flooding or significant runoff. However, the existing drainage channel does not function properly. This may happen because the existing drainage channels are filled with trash, and plants and moss bury some.

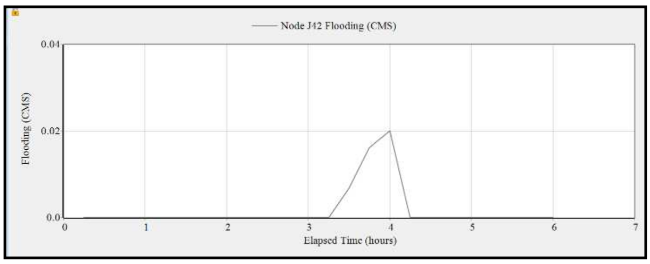


Fig. 11 Flooding graph on node J42.

IV. Conclusion

The drainage channel network simulation results show no signs of severe flooding or significant runoff. But even with great simulation results, the existing condition in the area does not show the same result because its drainage channels are not functioning properly. Most of them are filled with piles of trash and plants. Five spots on the drainage channel do not maintain their runoff efficiently. To recover all dysfunctional drainage channels, it is encouraged for the government to do a project to clean those drainage channels in the Belimbing area. It is also recommended that people who live in Belimbing Area should maintain their drainage channel properly and clean it periodically.

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