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Original Research Article

Hydrological and Hydraulic Analysis of Drainage System of Salamanmloyo Sub-district, Semarang, Indonesia

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Abstract

Salamanmloyo, one of the sub-districts in West Semarang District, Semarang City, is a densely populated area with nearly all of its land being built-up. Due to its location in the lower region of Semarang City, it is also vulnerable to flooding. Salamanmloyo has experienced floods and inundation as a result of insufficient pervious areas and inefficient drainage channels. This occurs when there is an imbalance between the drainage channel capacity and the discharge that needs to be handled, as well as when there is waste, sediment, and vegetation in the channel. As for the existing condition in Salamanmloyo Sub-district, no previous study regarding flooding and innundation has been conducted in this area. Therefore, it is necessary to conduct research and planning which aims to find out the existing condition of drainage channels, hydraulic and hydrological analysis results, as well as the suitable SUDS type to decrease the flooding volume level. Hydraulic and hydrological analyses will be performed as a part of this planning, after which will continued with EPA SWMM 5.1 modelling under four different conditions: current condition, maximum SUDS application, channel normalization, and channel re-design conditions. The outcomes of the SUDS planning were applied in the form of 497 units of infiltration wells and 16,345.6 m^2 of permeable pavement. SUDS implementation, drainage channel normalization and re-design helped to minimize the total flooding volume by 66.3%, from 231,456 m^3 to 78,008 m^3.

Keywords: Drainage; flooding; planning; Salamanmloyo Sub-district; SUDS, EPA SWMM 5.1

1. Introduction

The provision of urban infrastructures and facilities in urban areas has positively impacted people's lives. One of the urban infrastructures that needs to be developed in order to support the lives of urban communities is drainage channels. It is said that a drainage channel is a facility that flows excess water from a catchment area to the recipient water body (Suripin, 2004). Due to the urbanization, the total runoff volume that flows into the system also increases. This is caused by land use changes that occur in urban areas. In densely populated urban areas, where almost the entire pervious land surfaces are replaced by impervious surfaces, the volume of water that cannot be absorbed increases. Therefore, the excess water flow will increase the load that has to be discharged by the drainage channels.

The urban communities, infrastructure, and the environment are threatened by the continuous increase in surface runoff, which will lead to flooding and inundation. Flooding occurs when the surface runoff volume exceeds the drainage channel's capacity. In urban areas, drainage channels are often found under unsightly conditions, which results in a reduced capacity. The degradation of the drainage channels capacity is caused by the undesired presence of solid waste, sedimentation, and vegetation.

Furthermore, drainage channels are often not properly designed to accommodate large surface runoff volumes resulting from land-use change and climate change. Runoff travels across surfaces and then accumulates in low-lying areas until it eventually percolates, drains, or evaporates.

To reduce the risk of potential flooding and inundation, conventional drainage evaluations and various Sustainable Urban Drainage System/Low Impact Development practices need to be carried out. Therefore, simulation models are required to predict and visualize the flooding information (Babaei *et al.* 2018). In this research, EPA SWMM 5.1 is used to evaluate the current drainage system and also plan the suitable SUDS practices.

This research was conducted in the Salamanmloyo Sub-district, one of the sub-districts in West Semarang District, Semarang City. The area of 54 hectares is an area whose main activities are the economy and service sector. With almost 97% of its area is built on and it lies in the flood-prone area of Semarang City. According to the government data, there are some inundation spots with varying heights, ranging between 5 and 50 centimeters. The cause of inundation is not limited to the small pervious area, but also the topographical conditions and some drainage channels that cannot operate optimally. Suboptimal drainage operations are caused by disturbances from solid waste, sediment, and vegetation.

Based on the conditions mentioned above, it is necessary to conduct further analyses and research. The aim of this research is to evaluate the condition of the drainage channel and its capacity, determine the results of hydrology and hydraulic analyses, and determine the recommended design of the drainage system with SUDS practices that are suitable to the conditions of the planning area.

2. Methods

This research conducted in Salamanmloyo Sub-district, which locates in West Semarang District, Semarang City. The required data for this research are classified into primary data and secondary data. Primary data consist of existing drainage channels data (dimensions and material included) and the data of inundation points that can be collected through interview and observation. Secondary data consist of rainfall data from Simongan Station, drainage channels data from the Department of Public Works of Semarang City and data of study location's characteristics which were obtained from the Department of Public Works and Spatial Planning of Semarang City. Simongan Rain Station was chosen because according to the Semarang City Thiessen Polygon, Salamanmloyo Sub-district was included in Simongan Station Area and highly affected by this station. This research was conducted in three phases; existing condition analysys, hydrological and hydraulic analysis, and drainage system modeling in EPA SWMM 5.1.

During the existing condition analysis, the drainage channels' dimensions data and material are collected. The dimensions measuring process is done using tape measures. In this phase, interviews were also be conducted with local residents to learn more about the flood and inundation that have occurred in the study area. The dimensions data and material will later be used in the calculation of existing drainage capacity. The next phase is hydrological and hydraulic analysis. In this phase, the rainfall data obtained from Simongan Station was processed to obtain further values such as rain frequency, distribution, and intensity. Gumbel Distribution Method is used in this research, with rainfall repetition period of 2 and 5 years. These two repetition periods were chosen by considering the size of catchment land area and comparing it to the design module from the ministry. In addition, rainfall repetition period of 5 years will be used for primary drains planning, and rainfall repetition period of 2 years will be used for secondary and tertiary drains. The formula used to calculate planned rainfall distribution with Gumbel method is shown below:

$$Ks = \frac{Y_{Tr} - Y_n}{S_n} \qquad (1)$$

Where:

X_T = Planned rainfall

$\bar{X}$ = Average of rainfall data
Y_T = Reduced variate
Y_n = Reduction factor for n-number of data
S_n = Standard deviation for n-number of data
S = Standard deviation

It is necessary to calculate rain intensity to determine the planned flood discharge in this planning. To calculate rain intensity, Mononobe method is used in this planning with the availability of daily rainfall data. The Mononobe empirical formula is described below:

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

Where:
I : Rainfall intensity (mm/hour)
R_{24} : Maximum rainfall (mm)
T : Rainfall duration (hour)

After the hydrological analysis is carried out and rainfall intensity value is obtained, the hydraulic analysis is then carried out. The existing drainage channel capacity can be calculated from the dimensional and material data that were obtained from the survey. The planned flood discharge analysis was then calculated. The planned flood discharge analysis is carried out by rational method with reference to SNI 2415:2016. The formula to calculate the planned flood discharge is described below:

$$Q = 0{,}00278 \times C \times I \times A \quad (3)$$

Where:
C : Runoff coefficient
I : Rainfall intensity (mm/hour)
A : Subcatchment's area (hectare)

In the analysis of planned flood discharge, the flood value of which are summarized with the domestic wastewater discharge. The domestic wastewater discharge calculation was done by calculating 80% of total water usage.

The last phase of this research is modeling drainage system using EPA SWMM 5.1. According to Semarang District Regulation No 7 of 2014, some of the models that can be carried out in SWMM are precipitation model, soil surface model, and groundwater modeling. In this phase, some scenarios will be carried out into the model, such as SUDS application, drainage normalization, and re-design.

3. Result and Discussion

3.1. Existing Drainage Conditon

Salamanmloyo Sub-district is located in West Semarang District, Semarang City. According to Semarang City Regulation No 7 of 2014, Salamanmloyo Sub-district belongs to Siangker River Sub-system. This planning area is a dense populated sub-district which is also productive for economic activity (office, shops, warehouses).

Based on the result of observation, it is know that some of the drainage channels in the study region cannot function optimally due to the deterioration of the channel's capacity. Channel's deterioration is caused by sediment, solid waste, and vegetation inside the channel. Another drainage related problem was found based on the interviews held with local residents. From the interview, it is known that there are a number of inundation with varying height, ranging from 5 to 50 centimeters. For example, inundation happened at Puspowarno X Street with 50 centimeters on its height. This interview data help to pinpoint the actual inundation places.

Figure 1. Existing Drainage Condition

3.2. Rainfall Data

For this research which located in Salamanmloyo Sub-district, The Simongan Rain Station is used to obtain rainfall data. Simongan Rain Station is located near Banjir Kanal Barat River. Rainfall data is required to calculate the annual maximum rainfall in the study area (Isotta et al., 2014). The used rainfall data is composed of 11-year data from 2013 – 2023. The highest daily rainfall occured in 2015, which equivalent to 177 milimeters. To reduce the likelihood of over-design in drainage planning, Area Reduction Factor is used in this research. Based on the area of the study location, the ARF value equals to 0.99. The rainfall data used in this research is shown in the table below:

Table 1. Simongan Rain Station Annual Rainfall Data

No	Year	Maximum Rainfall (mm)
1	2013	111
2	2014	125
3	2015	177
4	2016	98
5	2017	126
6	2018	123
7	2019	105
8	2020	139
9	2021	152
10	2022	92
11	2023	155

Furthermore, this rainfall data will be analyzed using the algebraic average method. The obtained average rainfall data will then be analyzed through frequency analysis to gain the planned rainfall value.

3.3. Frequency and Planned Rainfall Distribution Analysis

In this research, the Gumbel Distrubution Method is used to analyze planned rainfall distribution. The Gumbel Distribution can also be used to represent distributions of hydrological extreme values such as flood peak and maximum rainfall. Formula used in this analysis is displayed as Equation 1. The result of planned rainfall distribution is shown on Table 2 below.

Table 2. Planned Rainfall Distribution Using the Gumbel Method

t	*X*	Yt	Yn	Sn	Xt
2	126,27	0,37			122,75
5	126,27	1,50			153,45
10	126,27	2,25			173,78
15	126,27	2,61	0,4966	0,9676	183,40
25	126,27	3,20			199,49
50	126,27	3,90			218,52
100	126,27	4,60			237,44

From the calulation results, it is obtained that the designed/planned rainfall for 2-years return period is 122.75 mm and for 5-years return period is 153.45 mm.

3.4. Goodness-of-Fit Test

The goodness-of-fit is conducted to determine whether the expected rainfall distribution agrees with the collected data or not. The Chi-Square test and the Smirnov-Kolmogorov test are used in this research. The Chi-Square test is performed to test the data against both a continuous and discrete distribution. Meanwhile, the Smirnov Kolmogorov test is used to test whether the data is distributed normally or not. The summary of goodness-of-fit test is shown in Table 3.

Table 3. Calculation Result Summary of Chi-Square Test and Smirnov-Kolmogorov Test

The Chi-Square Test			**Smirnov-Kolmogorov Test**		
X^2 Count	<	X^2 Critical	ΔP_{max} Count	<	ΔP Critical
0,073		0,575	0,07		0,391
Accepted			Accepted		

From the result of Chi Square Test and Smirnov-Kolmogorov Test above, it showed that the Gumbel Distribution planned rainfall data met the requirements for both goodness-of-fit tests. It is determined that the Gumbel Distribution was chosen as the most suitable distribution method for deriving the planned rainfall data. The Gumbel distribution planned rainfall data will further be used to carry out the planned rain intensity analysis.

3.5. Planned Rain Intensity Analysis

The calculation process of planned rain intensity was done using the Mononobe method, which described on Equation 2. This is due to the availibility of rainfall data, which is the maximum daily rainfall data. As the area of the study site has a total area of 50 Ha, which belongs to the interval of 10 Ha – 100 Ha, and belongs to the large city typology, the rainfall repetition period of 2 and 5 years were used in this planning. The calculation result of the planned rain intensity analysis is shown in the table and figure below:

Table 4. Planned Rainfall Intensity Calculation Results

t (hours)	Rainfall Intensity (mm/hrs) I2	I5	I10	I25
0.25	107,23	134,05	151,81	174,27
0.5	67,55	84,45	95,63	109,78
0.75	51,55	64,45	72,98	83,78
1.00	42,55	53,20	60,24	69,16
1.25	36,67	45,84	51,92	59,60
1.50	32,47	40,60	45,98	52,78

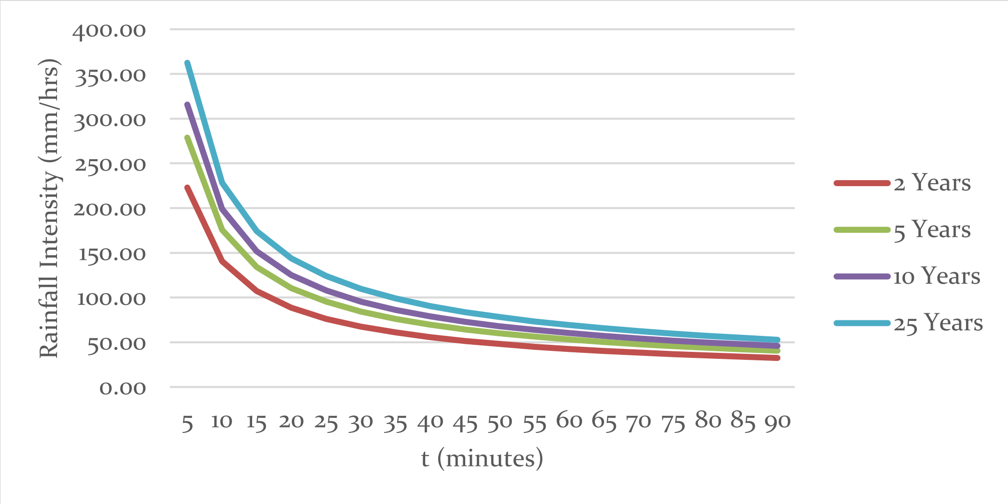

Figure 2. Mononobe IDF Curve

3.6. Existing Drainage Capacity Analysis

This analysis is conducted to find out the existing drainage capacity on the study location. The existing drainage capacity analysis is closely related to the Mononobe planned rainfall intensity, the area of the subcatchment, and the runoff coefficient which is based on the land use in the specified area. the capacity analysis is carried out using the flow formula which is done by multiplying the value of area and velocity. The area of drainage channel is determined by multiplying the channel's height and width. The existing drainage capacity analysis for Channel 1 until Channel 5 is displayed in the table below:

Table 5. Calculation Result of Existing Drainage Capacity Analysis

Channel	H (m)	B (m)	A (m^2)	Q (m^3/s)
C1	0,4	0,5	0,2	0,22
C2	0,4	0,5	0,2	0,14
C3	0,9	1,0	0,9	0,65
C4	0,4	0,5	0,2	0,09
C5	0,3	0,3	0,1	0,03

3.7. Planned Flood Discharge Analysis

In this research, the planned flood discharge value was highly affected by the domestic wastewater discharge and the recieved planned flood discharge. Thus, the calculation of the domestic wastewater discharge and the recieved planned flood discharge must be performed. The intial planned flood discharge analysis is carried out by each subcatchment area using the rational method formula which shown in Equation 3.

The domestic wastewater discharge needs to be calculated alongside with the stormwater runoff due to the combined drainage system that is used in the study location. In this analysis, the calculation of domestic wastewater discharge was done using water usage approach which is based on land use at each catchment area. Then, the amount of domestic wastewater discharge was then calculated by calculating 80% of total water consumption.

A recieved planned flood discharge calculation must be performed because of a drainage channel at the study location also accommodated stormwater runoff from another sub-district,. To calculate it, the watershed around the drainage channel must be digitized first. After that, the calculation is continued by calculating the recieved planned flood discharge using rational method formula which shown in Equation 3.

The total planned flood discharge analysis is conducted by adding up the value of the intial planned flood discharge, the domestic wastewater discharge, and the recieved planned flood discharge. The calculation result is shown on Table 6 below:

Table 6. Calculation Result of Total Planned Flood Discharge Analysis

Channel	C	Q Flood (m^3/s)	Q Domestic Wastewater (m^3/s)	Q recieved (m^3/s)	Q total (m^3/s)
C1	0,80	0,42	0,13		0,56
C2	0,80	0,08	0,06		0,14
C3	0,80	0,49	0,26		0,74
C4	0,80	0,12	0,10		0,23
C5	0,48	0,11	0,10		0,21
C60	0,55	0,35	0,12	2,81	3,29
C61	0,57	0,10	0,04		0,14
C62	0,57	0,12	0,03		0,15
C63	0,60	0,16	0,09		0,26
C64	0,59	0,42	0,11		0,53
C65	0,49	0,69	0,10		0,79

3.8. EPA SWMM 5.1 Analysis

For the SWMM analysis, Salamanmloyo Sub-district is divided into 71 subcatchment areas, which are shown in the Figure 3 below. Existing drainage model construction is conducted by on-screen digitalization on the Google Earth map to map Subcatchments, Nodes, Junctions, and Outfalls. In this reseach, SWMM analysis is done four times on different conditions which are explained below.

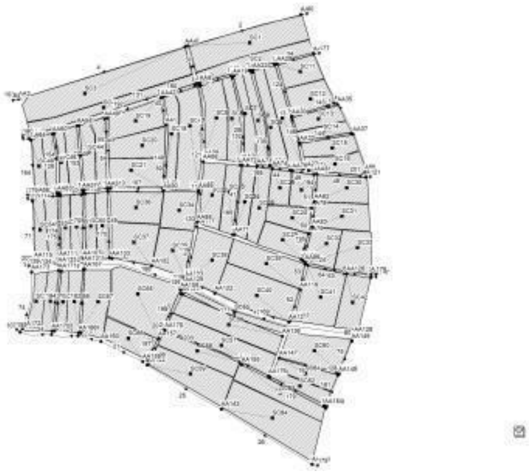

Figure 3. SWMM Existing Drainage Model

3.8.1. Analysis on Existing Condition

This simulation is conducted based on the study location's existing condition. Horton infiltration method and Dynamic Wave flow are used to run the model. Utilizing the simulation results from the SWMM analysis, we were able to obtain valuable information such as total flooding volume, overflowing channels, and channels' plot profile.

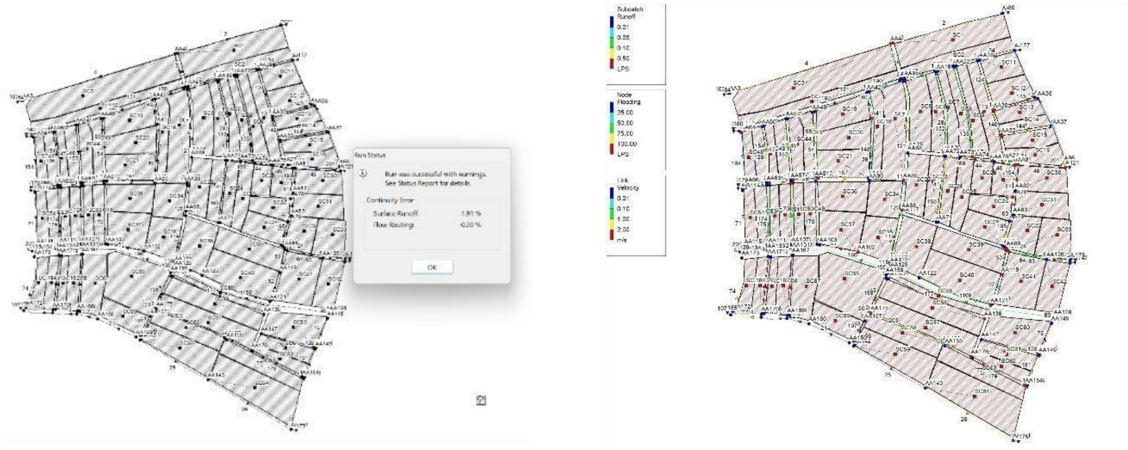

Figure 4. (a) SWMM Simulation Result ; (b) Details of SWMM Simulation Result

From the simulation result displayed on the figure above, it was known that the surface runoff value was -1,91% and the flow routing value was -0,20%. The simulation was considered as a successful simulation because the results were less 5%. It was also revealed that there were 76 nodes overflowed with a total flooding volume of 231,456 m³. Based on this conditon, further action was needed to overcome this situation. Thus, such actions as SUDS application, normalization, and channel dimension modification is performed.

3.8.2. Analysis on SUDS Application Condition

The planned SUDS application was chosen based on the location's characteristics. In this research, the chosen SUDS applications are permeable pavement and infiltration well.

A. Permeable Pavement

Permeable pavement catches rain water through its permeable surface and transports the water until it reaches the in-situ soil layer. Permeable pavement application increases the number of infiltration events. In this research, the planned permeable pavement will be built of a 8 centimeters high porous paving block layer, a bedding layer consisting of a sand bed 8 cm thick, and continued with a gravel base course layer 16 centimeters thick, also a in-situ soil layer as a supporting layer. This design doesn't include underdrain. The overall permeable pavement application is 16,345.6 m², distributed across 42 subcatchments area.

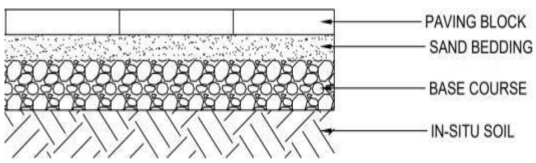

Figure 5. Permeable Pavement Sketch

B. Infiltration Well

Infiltration well is a vertical well that gathers water vertically and then disposes the water vertically and horizontally along the field of the well. In this research, it is planned to use a vertical infiltration well with a diameter of 1 meter and a depth of 2 meters. The total of 497 infiltration wells are planned to be applied on 70 subcatchments.

The SUDS applications in this research was able to reduce total surface runoff percentage by 1.07% from the existing condition. The remaining total flooding volume is 228,990 m³.

3.8.3. Analysis on Channel Normalization Condition

Drainage channel's capacity degradation, that was found during the survey and observation, was caused by sedimentation, waste, and vegetations. That condition was the cause of flood and inundation that happened in Salamanmloyo Sub-district. Thus, normalization operation must be perform. Normalization operation performed by cleaning/dredging the sediment at drainage channels. Drainage channel dimension changes due to the normalization are shown in the Table below:

Table 7. Channel Dimension Changes After Normalization

Channel	Length	Existing Dimension		After Normalization Dimension	
	m	H (m)	B (m)	H (m)	B (m)
C1	254	0,4	0,5	0,5	0,5
C2	251,3	0,4	0,5	0,6	0,5
C3	371,0	0,4	0,5	0,5	0,5
C5	150	0,65	0,25	0,75	0,25
C6	180	0,5	0,4	0,6	0,4
C7	182	0,5	0,4	0,6	0,4
C8	194	0,7	0,35	0,75	0,35
C9	190	0,7	0,35	0,75	0,35
C11	251	0,9	1	1,1	1
C12	94,2	0,25	0,45	0,3	0,45
C13	96,4	0,25	0,45	0,3	0,45
C14	108	0,35	0,28	0,4	0,28
C15	108	0,35	0,28	0,4	0,28
C17	211	0,3	0,35	0,4	0,35
C19	361,5	0,75	0,4	0,9	0,4
C21	142,2	0,4	0,5	0,6	0,5
C22	125	0,45	0,3	0,55	0,3
C23	141	0,45	0,4	0,5	0,4
C24	141	0,5	0,4	0,5	0,4
C34	84,4	1	0,7	1,1	0,7
C35	86,6	1	0,7	1,1	0,7
C38	109	0,3	0,3	0,5	0,3
C40	224	0,2	0,25	0,45	0,25
C61	122	0,4	0,3	0,5	0,3
C62	123	0,4	0,35	0,5	0,35
C63	183	0,4	0,35	0,5	0,35

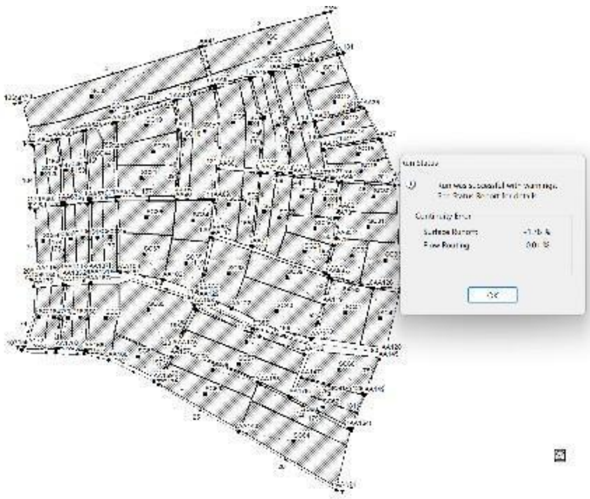

Figure 6. Normalization Condition Simulation Result

From the figure above, it was known that the surface runoff value was -1.78% and the flow routing value was 0,01%. The simulation was considered successful because the result values were less than 5%. The operation of normalization was able to reduce the total flooding volume by 6.9% so that the remaining total flooding volume is 206,619 m^3. It was also found out that some of the previously overflowed channels were no longer overflowed.

After the normalization operation was carried out, it was found that there were still 69 nodes that still overflow. Since the goal of this study is to decrease the flooding/overflowing events, further action towards the remaining overflowing channel must be planned and performed. Hence, further operation of drainage remodelling must be carried out.

3.8.4. Analysis on Re-design Condition

Re-design operation is channel's dimension modification with the aim of increasing the channel capacity. The re-design operation is considered as needed because if was found that there were still 69 channels that experienced overflowing events even after SUDS implementation and normalization. The re-design operation of some drainage channel was performed by considering the availability of land under the existing conditions. If a drainage channel is found adjacent to houses and road bodies, resulting that there is no land that can be used for the dimensions change, then the re-design operation cannot be performed. The re-design results are shown in the table below:

Table 8. Existing and Planned Dimensions Comparisons

Channels	Existing Dimensions		Planned Dimensions		
	H (m)	B (m)	H+f (m)	H (m)	B (m)
C1	0,4	0,5	0,8	0,8	0,8
C4	0,2	0,25	0,5	0,5	0,5
C10	0,55	0,4	0,5	0,5	0,5
C12	0,25	0,45	0,5	0,5	0,5
C13	0,25	0,45	0,45	0,5	0,5
C14	0,35	0,28	0,4	0,4	0,4
C15	0,35	0,28	0,4	0,4	0,4
C16	0,4	0,4	0,5	0,5	0,5
C17	0,65	0,25	0,8	0,8	0,8
C18	0,5	0,2	0,5	0,5	0,5
C27	0,6	0,6	0,8	0,8	0,8
C37	0,2	0,25	0,5	0,5	0,5
C38	0,3	0,3	0,6	0,6	0,6
C41	0,4	0,4	0,5	0,5	0,5
C42	0,45	0,45	0,5	0,5	0,5
C47	0,3	0,4	0,4	0,4	0,4
C52	0,3	0,4	0,4	0,4	0,4
C53	0,3	0,4	0,4	0,4	0,4
C56	0,2	0,2	0,5	0,5	0,5
C57	0,4	0,35	0,5	0,5	0,5
C58	0,4	0,35	0,4	0,5	0,5
C63	0,4	0,35	0,5	0,5	0,5

Figure 7. Channel Re-design SWMM Simulation Result

After some dimension changes were made, the total flooding volume percentage was reduced by 62.2% and the remaining total flooding volume is 78,008 m³. The number of channels that experienced overflow event was also reduced to 51 nodes. This decreased number of overflowing channels indicates that the re-design operation suceeded on lowering both the flooding volume and flooding location points.

Figure 8 and Figure 9 show examples of the channel's profile plot condition before and after re-design operation.

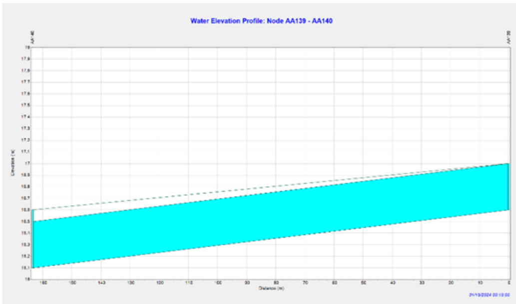

Figure 8. Cross Section Profile of Node AA139 – AA 140 in Existing Condition

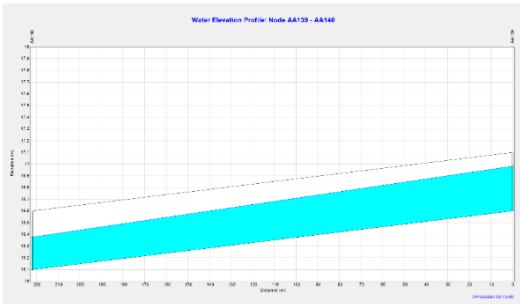

Figure 9. Cross Section Profile of Node AA139 – AA 140 After Dimension Change

After the SUDS implementation, the normalization, and the re-design of the drainage channels operations, there was a reduction in the total flooding volume percentage and it reached 66.30% so that the total flooding volume remains only 78,008 m³. To determine whether this condition has met the requirements to be categorized as safe flood conditions, it is necessary to calculate a flooding period graph. The flooding period graph is shown on Figure 10 below. While the summary of the total flood volume reduction is shown on Table 9 below :

Table 9. Flooding Volume and Percentage Reduction Summary

No	Condition	*Total Flooding Volume* (m³)		% of Reduction
		Before	After	
1	Existing Condition	231.456	-	-
2	SUDS Application	231.456	228.990	1,07%
3	Normalization	228.990	206.619	9,77%
4	Re-design	206.619	78.008	62,25%
	Total			66,30%

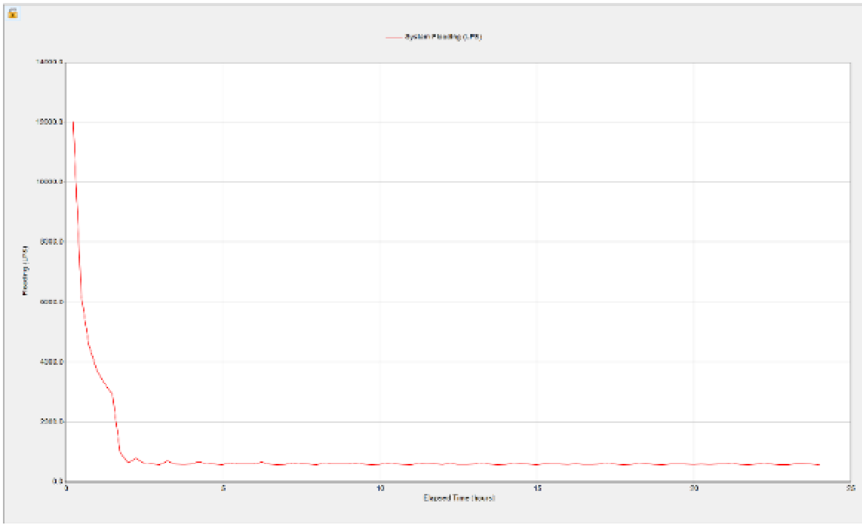

Figure 10. Flood Graph After Evaluation and Planning

Based on Figure 10 above, it was known that the peak of flood occurs in the early hours of event and continue to decrease until the end of the second hours. According to the Flood Warning Module published by Indonesian Department of Public Works, flood condition that recedes in less than 6 hours, as shown in the graph above, are categorized as safe conditions. Thus, further construction work planning is not needed. However it is essential to perform sequence of drainage channel manintenance program to keep the drainage performance optimized. Drainage channel maintenance operation can be performed refering to Appendix 3 of The Regulation of the Minister of Public Works Number 12 of the year 2014.

4. Conclusions

There are numbers of drainage channels in Salamanmloyo that are not capable to operate optimally. This condition is because the drainge channels are clogged with vegetation, sediment, and trash, as well as the unmatched capacity with the runoff that should be accommodated. The result of hydrological and hydraulic analyses also shows that there are numbers of channels that are unable to accomodate rainwater and domestic wastewater volume, resulting in sewage leakage. As for the hydrological analysis, it also shows that the designed/planned rainfall for 2-years return period is 122.75 mm and for 5-years return period is 153.45 mm. Several programs were modeled to decrease the flooding volume. Those programs were SUDS implementation, normalization, and channel re-design. For SUDS implementation, a total of 16,345 m² of permeable pavement was planned, distributed across 42 subcatchments. The planned number of infiltration wells is 497 wells with the planned dimension is 2 metters deep and a diameter of 1 meter. The SUDS application can reduce total runoff volume in each subcatchment by an average of 7.4%. Channel normalization operation is performed on several drainage channels which the channel flow was disturbed by sediment, waste and vegetation. Further channel re-design operation is also being carried out to optimize the drainage channel's performance. Overall, the efforts to implement SUDS, channels normalization, and redesign reduced the leakage percentage by 66.3% compared to the pre-implementation level, from 231,456 m^3 to 78,008 m^3.

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