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Channel Capacity Evaluation Model Using Storm Water Management Model

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A B S T R A C T

Floods commonly occur in big cities with huge population densities. The increasing population number can cause a decrease in open land and green open space areas. It increases the surface runoff and induces inundation due to inadequate channel capacity. Therefore, a better design is required to minimize the inundation depth and area. This research aims to evaluate the drainage capacity of the channel dimension based on the flood discharge obtained from the rational method. The cross-section capacity was evaluated using the Storm Water Management Model by considering two types of rainfall distribution. The simulation result shows that the rainfall distribution influences the channel capacity. The flood discharge based on the Sri Harto distribution has a lower peak discharge than the Tadashi Tanimoto distribution. The result shows the significant effect of rainfall distribution types on the water depth. Therefore, it is necessary to determine the rainfall distribution method that represents the watershed characteristics used to design the drainage system.

1. Introduction

The inundation problem commonly occurs in big cities along with economic development. Economic developments influence land use changes. They convert green open space and open land into impervious areas. Decreased green open space and open land affect the increase of surface runoff and discharge, influencing the inundation. Surabaya is a big city in Indonesia that deals with flood and inundation problems. Flooding in Surabaya occurs due to several issues, including topography, channel capacity, unintegrated drainage network, and sedimentation. Therefore, better planning is required to obtain a suitable channel capacity. The drainage design is conducted based on the discharge obtained from the rational method by considering hydrology and hydraulic parameters. Those several parameters are runoff coefficient, rainfall intensity, and catchment area. The runoff coefficient is considered based on

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the land use and cover types. Then, the rainfall intensity is determined based on rainfall runoff and concentration time. The drainage network based on the study location layout influences the concentration time. Previous studies show that different layouts can control the efficiency of total outflow; therefore, cost-effectiveness can be improved. [1]. This research aims to evaluate the drainage capacity of the channel cross-section based on a rational method. Furthermore, the channel capacity resulting from the rational method is evaluated using the rainfall-runoff model by considering two types of rainfall intensity. The simulation model in this research was conducted using the Storm Water Management Model (SWMM) 5.2 as the hydrology-hydraulic model developed by the US Environmental Protection Agency (EPA).

The SWMM evaluates the drainage design based on the discharge obtained from the Rational Method. This model is reliable in generating the runoff assigned to each sub-catchment parameter that receives the rainfall, and it is possible to simulate the dynamic rainfall runoff in urban areas from single and continuous peak runoff. [2]. The SWMM was reliable in simulating the low-impact development (LID) concept using the LID editor within the model. A previous study by Vladimir Hamouz in 2019 generated the impact of green and grey roofs, showing that the SWMM could also simulate runoff. However, further research must be conducted to simulate volume errors during the winter season. [3]. A similar study was conducted in 2022; the SWMM was used to simulate the application of the LID concept to mitigate the inundation by implementing bio-retention cells, green roofs, infiltration trenches, permeable pavement, rain barrels, rain gardens, and vegetative swales. It shows that the combination of permeable pavement and bio-retention offers effective measures. [2]. Other than porous pavement, another LID concept that has been conducted using SWMM is vegetative swale implementation within residential areas to decrease surface runoff [4]. Rain barrels and rain gardens have been implemented as the LID concept in best management practices to minimize inundation, and it reduces the peak discharge and outflow time [5]. SWMM has also been used to optimize the integration of drainage networks to minimize inundation problems. It shows that the SWMM relied on verified impact of the drainage network changes to support the alternative selection. [6]. The SWMM also simulates the urban flood problems based on several return periods, and it shows promising results in predicting future conditions [7]. The SWMM combined with the 2D model to generate the inundation areas and inundation depth since the SWMM is a 1D simulation and has limitations in obtaining the inundation areas [8].

2. Research Method

The simulation model was calculated using a conceptual model that considered precipitation, infiltration, and evaporation to obtain the flood discharge. The conceptual model based on SWMM simulation calculates the water resources from rainfall and the water losses caused by evaporation and infiltration, resulting in the inundation excess at the catchment being as high as d. The inundation on the storage depth (ds) becomes the surface runoff (q), as represented in **Figure 1** [9]. This research uses a simulation model based on the rainfall return period distributed for several hours. Several types of hourly rainfall distribution exist, including the Tadashi Tanimoto and alternating block methods (ABM). Apart from those two methods, another method that was conducted by Sri Harto Brotowiryatmo in 2016 was considered in this research. The previous study compares the rainfall distribution of ABM and Tadashi Tanimoto with the rainfall distribution generated from the rainfall recorder, and it shows that the rainfall hourly distribution generated from rainfall history is more reliable. [10].

The flood discharge obtained from the rational method was used for the hydraulic analysis to generate the channel capacity. The rational method assumes the rainfall intensity is constant during the storm and the rainfall distribution is uniform in all watershed areas [11]. Moreover, the channel dimension result will be evaluated using the rainfall-runoff simulation. The rainfall-runoff simulation is completed using the Storm Water Management Model (SWMM) to acquire the maximum full value of the channel capacity. The max full value within the SWMM

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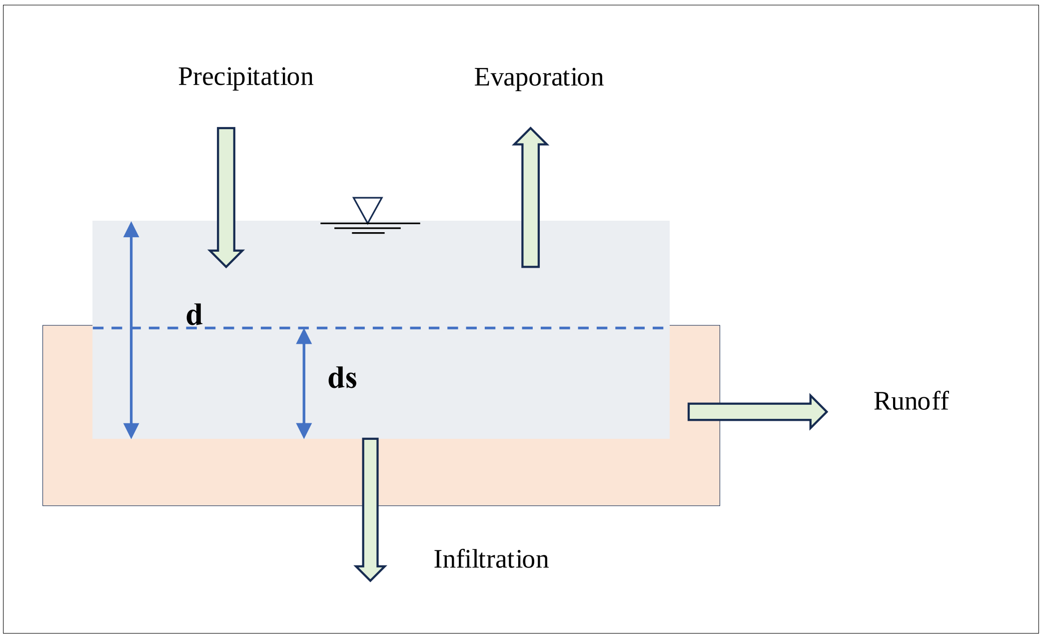
compares water depth to channel depth. It indicates whether the channel cross-section achieves full bank capacity or overflows by the value 1.



Source: Conceptual Model of SWMM [9]

Figure 1. The Conceptual Model of Storm Water Management Model

3. Description and Technical

There are several steps conducted in this research, consisting of:

1. Literature review
   This research has conducted a literature review to describe the current condition of the drainage system and evaluate the problems that have occurred. This step generates the research goals.
2. Data collecting
   This research needs data to support the analysis, including rainfall data, drainage network data, topography, land use types, soil types, and channel capacity. The data used in this research are secondary data obtained from the government, including rainfall, channel capacity, and drainage network. The topography data in this research was used to determine the inverted elevation within the rainfall-runoff simulation. It is required to determine the parameter since the infiltration method used in this research is the Curve Number method. The CN value was generated by considering the land use and soil types.
3. Analysis and Calculation
   a. Spatial Analysis
      The spatial analysis in this research was conducted to classify the infiltration parameter. The infiltration parameter used is the Curve Number value, which is considered based on land use and soil types. The land use and soil types were obtained from satellite data, overlaid, and intersected based on the watershed boundary.
   b. Hydrology Analysis
      The hydrology analysis in this research consists of rainfall analysis and flood discharge analysis. The rainfall analysis aims to generate the rainfall return period and its distribution. The rainfall return period was used to obtain the flood discharge based on the rational method. Then, the rainfall distribution is used as the input data for the rainfall-runoff simulation using SWMM. This research used two types of rainfall distribution, including the rainfall distribution method from Tadashi Tanimoto and Sri Harto.

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c. Hydraulic Analysis
The hydraulic analysis aims to evaluate and redesign the channel capacity. The hydraulic analysis was conducted based on the manning equation by considering the flood discharge obtained from the rational method. The redesign result will be evaluated using the rainfall-runoff simulation based on two rainfall distribution types to answer which can be applied to the channel design.

4. Rainfall-Runoff Simulation Model
The simulation model in this research was conducted using the Storm Water Management Model (SWMM). The SWMM model combined the hydrology and hydraulic analysis to evaluate the channel capacity. The schematic models are built based on the drainage system, considering the drainage network. Several parameters must be inputted, including infiltration, impervious percentages, pervious percentages, manning values, channel dimension, and invert elevation. Several data sets are required to determine the parameter model, including land use and land cover. These land use and land cover define the infiltration parameters by the curve number (CN) values since the infiltration method used in this research is the Curve Number Method.

4. Results and Discussions

This research evaluates the drainage system capacity based on the Manning equation by considering the flood discharge obtained from the Rational Method. Furthermore, the channel dimension from the calculation will be evaluated based on the rainfall-runoff simulation. Factors influencing the flood discharge calculation include rainfall, runoff coefficient, and concentration time. The rainfall used in this analysis is a 5-year rainfall return period considering the rainfall data based on the maximum daily rainfall by the minimum number of data, which is 10 years [12]. The runoff coefficient is determined based on the land use types of the watershed. Then, the concentration time is defined based on the drainage network since the channel length will influence the concentration time. The calculation result based on the rational method and Manning equation is also used to evaluate whether the existing dimension can accommodate the flood discharge, as is shown in **Table 1.**

Table 1. The Channel Dimension Comparison of Existing and re-Design

No	Node	L	A (m2)	Discharge (m3/s)	Existing		re-Design	
					B	H	B	H
1	A1.1 - A.1	454.42	629300	4.27	1.6	1.2	2.5	2.5
2	A2- A1	845.51	259200	1.23	1.8	2.3	2.0	1.6
3	A1 - A	1464.13	1359300	5.39	1.8	2.3	3.5	2.3
4	B5.2 - B5.1	172.39	26550	0.19	1.6	1.2	1.6	1.2
5	B5_1_1 - B5_1	822.16	274400	1.40	1.4	1.6	2.0	1.8
6	B5_1 - B5	582.81	539900	2.53	1.6	1.2	2.5	2.4
7	B6 -B5	865.82	480800	2.41	1.5	1.3	2.5	2.3
8	B5 - B4	994.88	1186600	4.41	1.5	0.6	3.0	3.3
9	B4 - B1	368.31	1346900	5.09	1.5	1.5	3.5	3.3
10	B2_1 - B2	241.55	105000	0.73	2.2	2.6	2.2	2.6
11	B3 - B2	629.23	303500	1.69	2.2	2.6	2.2	2.6
12	B2 - B1	46.99	408500	2.58	2.2	2.6	2.5	2.6

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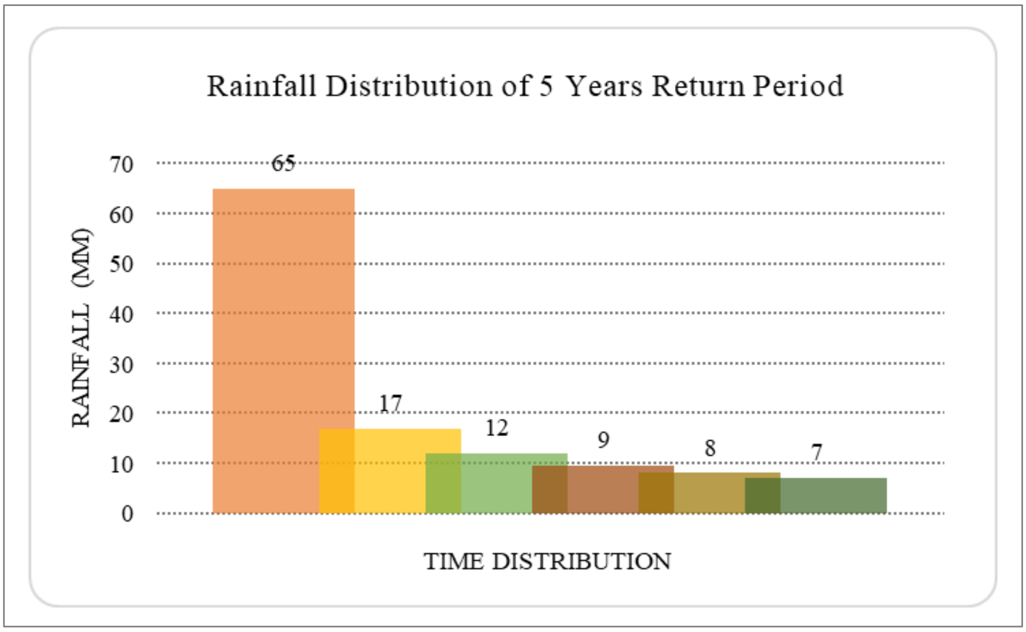
No	Node	L	A (m2)	Discharge (m3/s)	Existing		re-Design	
					B	H	B	H
13	B1 - B	195.66	1755400	10.50	2.2	2.6	4.0	3.5

Source: Kediri drainage master plan and analysis result.

This research used the rainfall-runoff simulation model to generate the total inflow within the drainage system. In a previous study using SWMM conducted by Suhyung Jang in 2007, the SWMM generated flood discharge in natural watersheds. It shows that SWMM is reliable for obtaining synthetic hydrographs for a single watershed. [13]. This rainfall-runoff simulation model is generally implemented in urban drainage systems. However, it can also be used to evaluate dams' effectiveness based on the SWMM's runoff [14]. Apart from hydrology analysis, the SWMM combines hydrology and hydraulic analysis within the simulation model. Several scenarios are simulated in this study by considering two types of rainfall intensity, as seen in the distribution in **Figure 2** and **Figure 3**. These two distributions show that both types have different characteristics. The Tadashi Tanimoto types have high distribution values at the first hour and decrease, while the highest distribution values for Sri Harto types occur at the second hour. Therefore, this simulation aims to identify whether the channel capacity that resulted from the rational method is reliable enough to accommodate both rainfall distributions.



Source: analysis result

Figure 2. The Rainfall Distribution based on Tadashi Tanimoto

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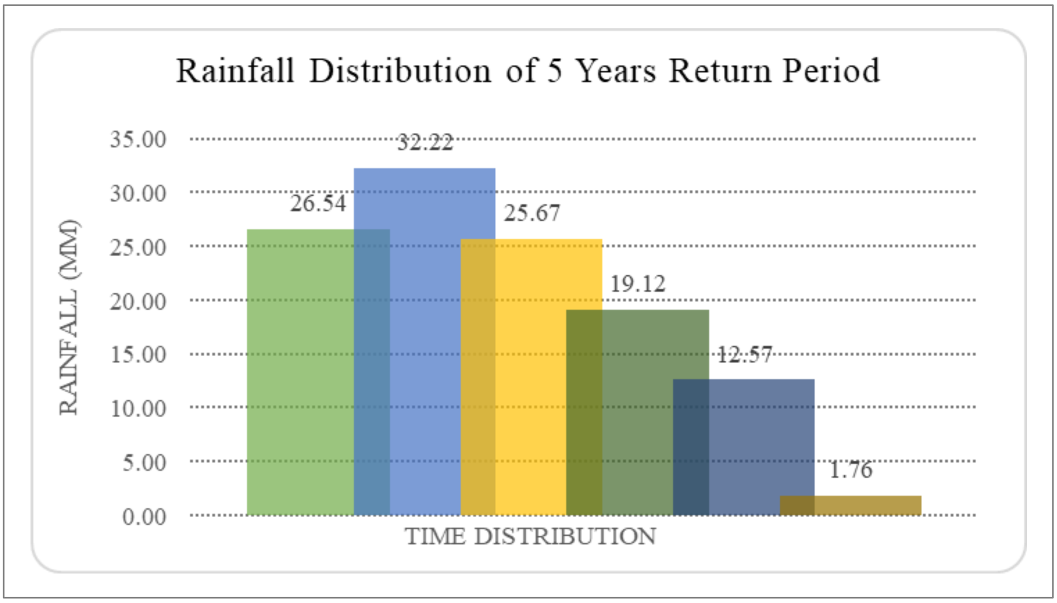
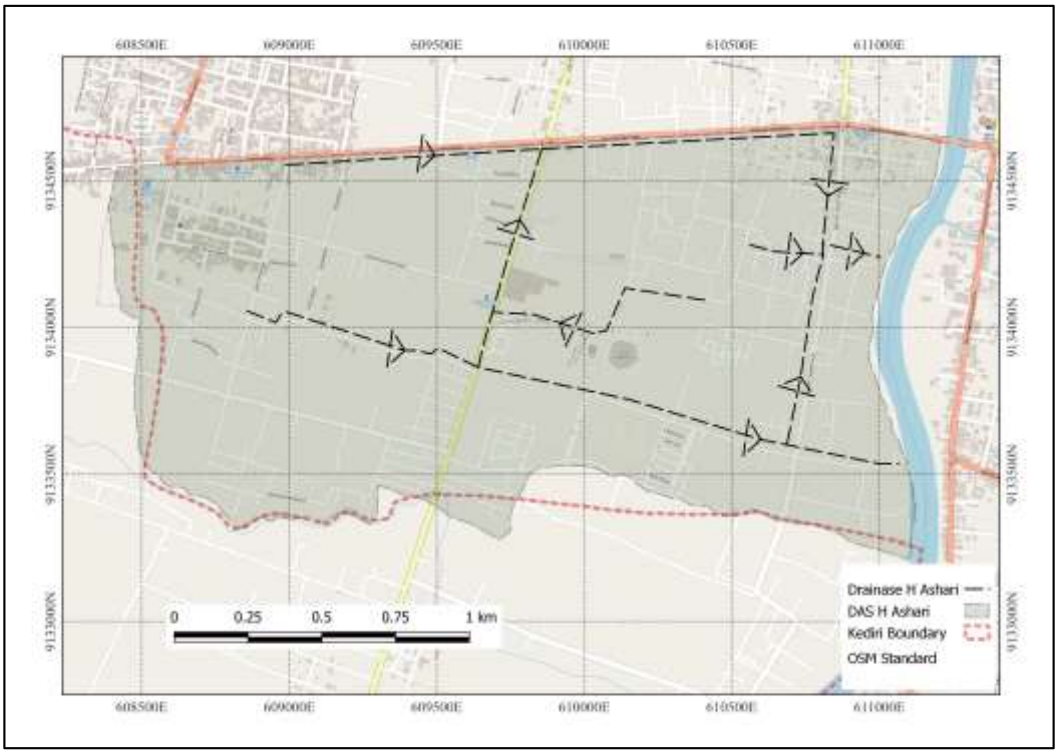


Source: analysis result

Figure 3. The Rainfall Distribution based on Sri Harto

Several matters are required to define the schematic model, including sub-catchment, junction, and reach. The data that support those parameters consist of rainfall data, drainage network, channel material, channel dimension, and topography data representing the land and bed channel elevation. The cross-section dimension used as the input data in the SWMM Model was obtained from the existing condition and the result of the rational method calculation. The rainfall-runoff simulation using the SWMM model was implemented at the drainage system in Kediri, as shown in **Figure 4**. This drainage system represents the channel network within the watershed and is used to build the schematic model, as shown in **Figure 5**.



Source: Kediri drainage master plan

Figure 4. The Drainage System of Research Study

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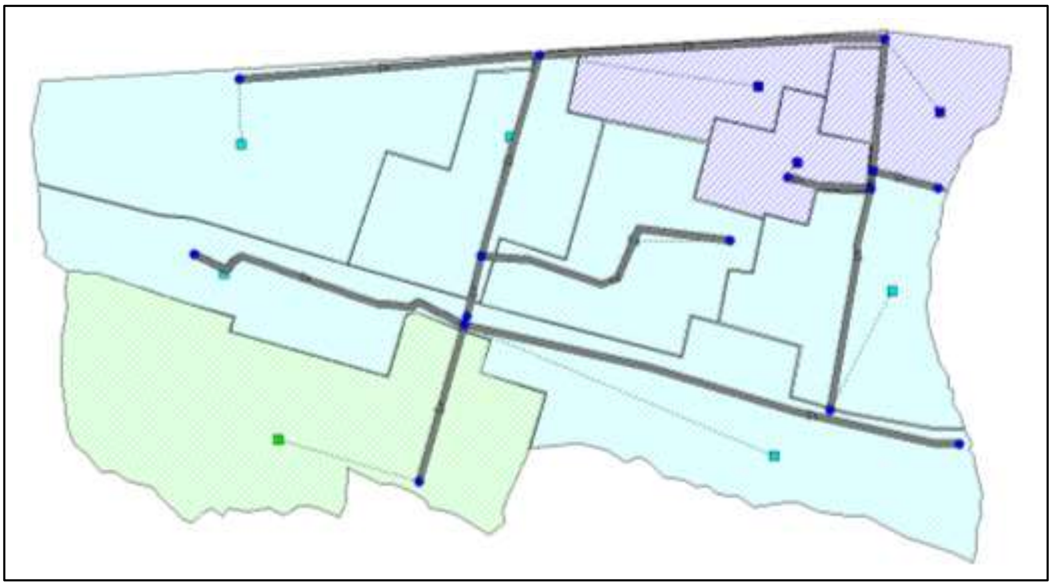
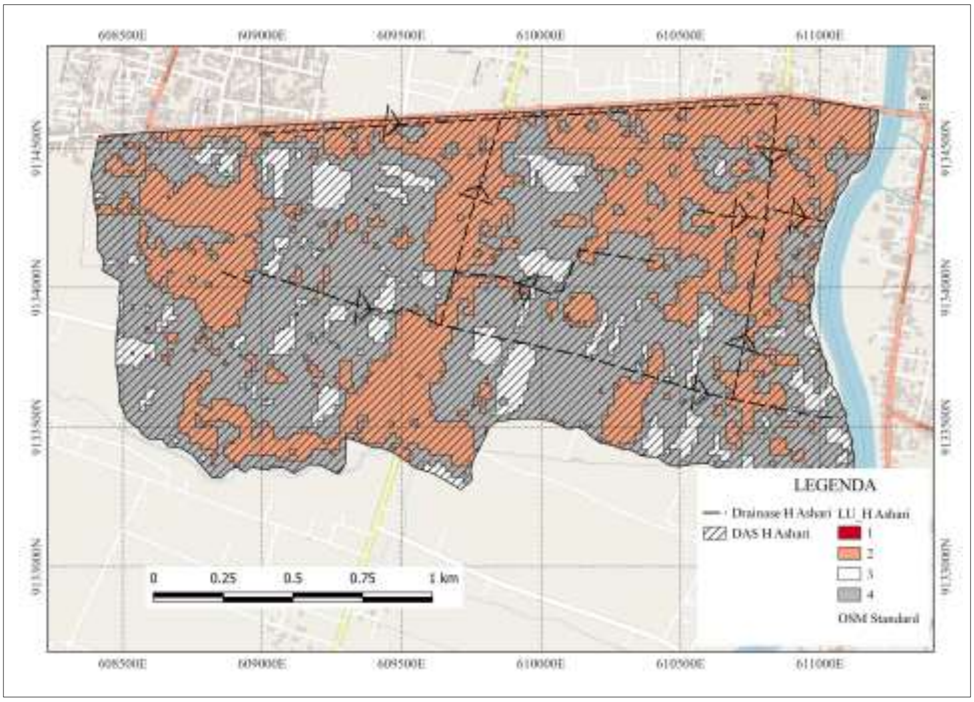


Source: Storm Water Management Model simulation result
Figure 5. The Schematic Model of Storm Water Management Model (SWMM)

The schematic model background used in the simulation was generated from spatial analysis. The hydrograph method used in the SWMM model is SCS Hydrograph. Therefore the spatial analysis was used to obtain the parameter-related runoff coefficient, which represents the curve number (CN) that is considered based on land use and soil types of data, as shown in **Figure 6** and **Figure 7**. The previous study shows that the reliability of the SWMM model has been verified by calibrating the model parameters [15] [16] [17], such as the manning coefficient of the channel and the infiltration parameters [18]. However, the significant parameter which influences the model is the Manning coefficient [18]. A similar study related to model parameter calibration was conducted in Greece, and it shows that SWMM has good agreement with the observed hydrographs [19].



Source: spatial analysis result based on satellite data
Figure 6. The Land Use Types of Research Location

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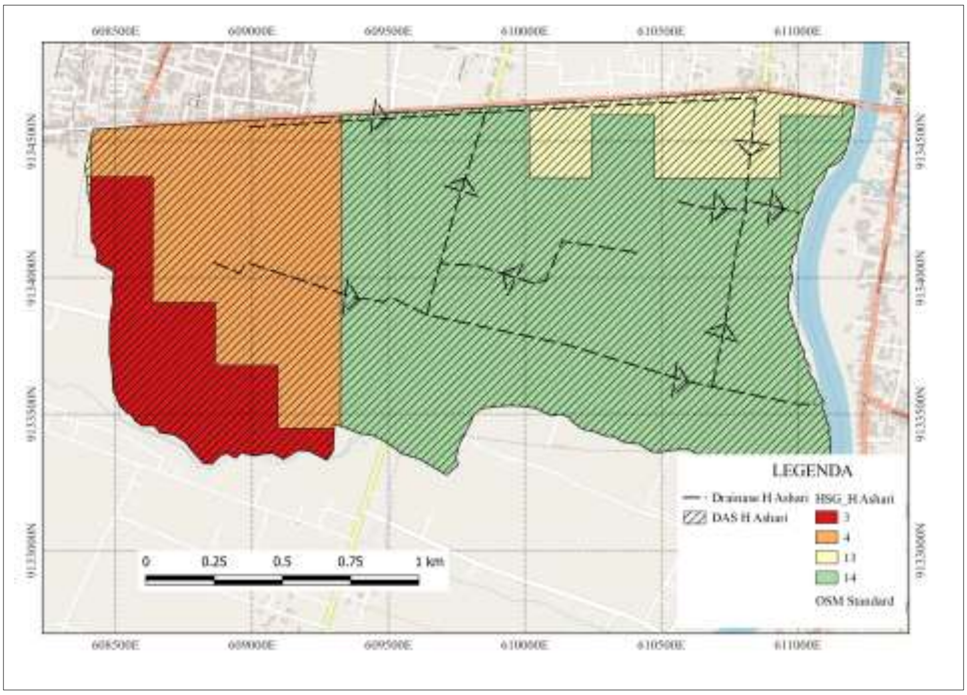

Source: spatial analysis result based on satellite data
Figure 7. The Soil Types of Research Location

The land use types are represented based on spatial analysis from satellite data. They comprise green open space, open land, residential and industrial areas. The residential areas dominate within the watershed areas. **Figure 7** shows the spatial analysis of the soil types obtained from HYSOGs250m. The land use types in this research were classified based on SCS curve number, as can be seen in **Table 2**.

Table 2. The Curve Number Value Based on SCS NCRS

Land Use	Cover Treatment or Practice	Hydrologic Condition	Hydrologic Soil Group			
			A	B	C	D
Fallow	Straight Row	---	77	86	91	94
Row Crops	Straight Row	Poor	72	81	88	91
		Good	67	78	85	89
	Contoured	Poor	70	79	84	88
		Good	65	75	82	86
	Terraced	Poor	66	74	80	82
		Good	62	71	78	81
Small Grain	Straight Row	Poor	65	76	84	88
		Good	63	75	83	87
	Contoured	Poor	63	74	82	85
		Good	61	73	81	84
	Terraced	Poor	61	72	79	82
		Good	59	70	78	81
Close-seeded Legumes or Rotation Meadow	Straight Row	Poor	66	77	85	89
		Good	58	72	81	85
	Contoured	Poor	64	75	83	85
		Good	55	69	78	83
	Terraced	Poor	63	73	80	83

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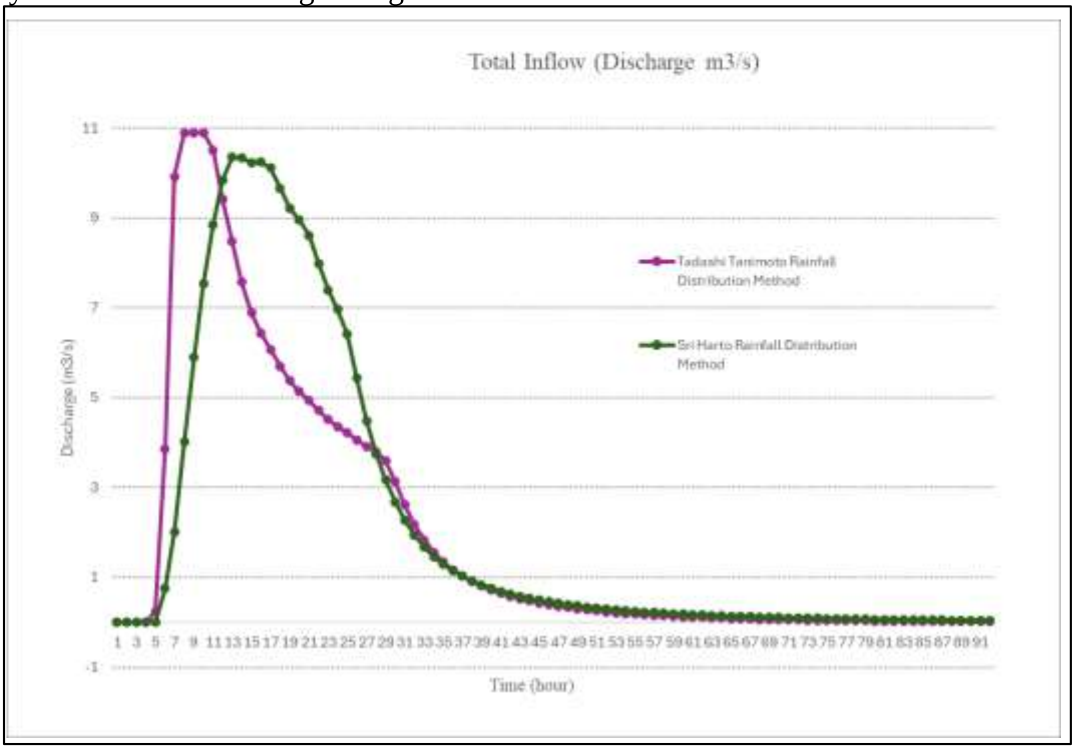
Land Use	Cover Treatment or Practice	Hydrologic Condition	Hydrologic Soil Group A	B	C	D
		Good	51	67	76	80
		Poor	68	79	86	89
	Natural	Fair	49	69	79	84
Pasture or Range		Good	39	61	74	80
		Poor	47	67	81	88
	Contoured	Fair	25	59	75	83
		Good	6	35	70	79
Meadow	Natural	Good	30	58	71	78
		Poor	45	66	77	83
Woods	Natural	Fair	36	60	73	79
		Good	25	55	70	77
Farmsteads	---	---	59	74	82	86
Roads	(dirt)	---	72	82	87	89
	(Hard surface)	---	74	84	90	92

Source: U.S. Department of Agriculture-Natural Resources Conservation Service (USDA-NRCS) National Engineering Handbook.

The flood discharge from the simulation result was conducted based on two types of distribution: Tadashi Tanimoto and Sri Harto distributions, as shown in **Figure 8**. This flood discharge is the total inflow at the end of the drainage system, represented as the drainage outlet. The comparison result from both distributions shows that the total inflow generated from the Tadashi Tanimoto distribution is higher than the Sri Harto distribution, representing the hourly rainfall distribution characteristics. Therefore, it is necessary to determine whether this result greatly influences the drainage design.



Source: SWMM simulation result.

Figure 8. The Total Inflow Comparison in Drainage System Based on Two Types of Distribution

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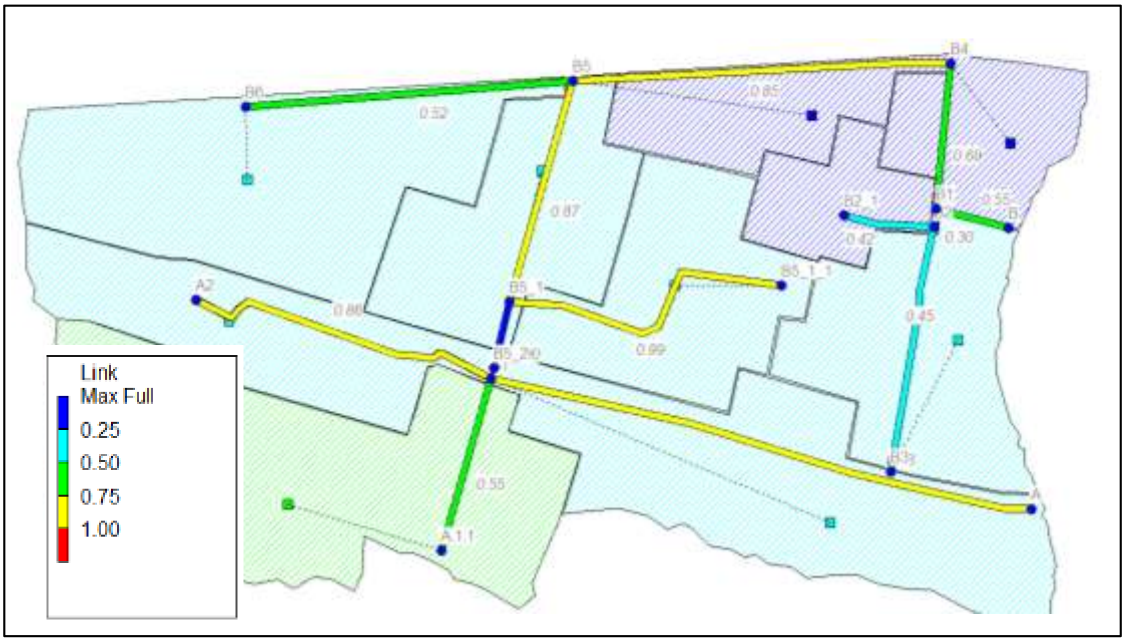
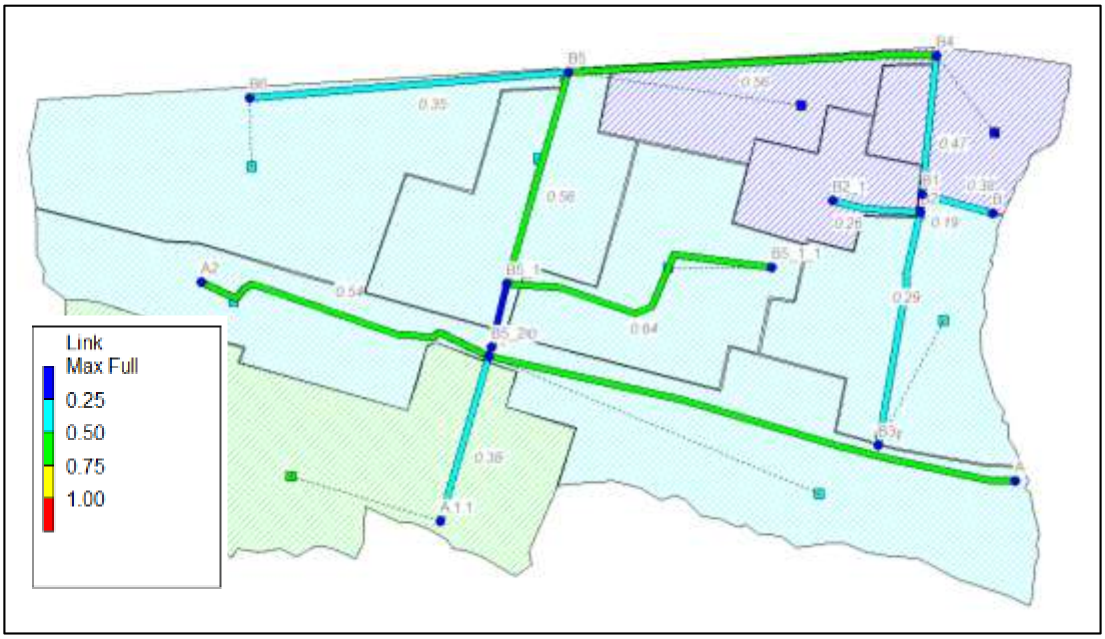


Source: SWMM simulation result.

Figure 9. The Simulation Result of Re-design Condition Based on Tadashi Tanimoto Distribution Rainfall



Source: SWMM simulation result.

Figure 10. The Simulation Result of Re-design Condition Based on Sri Harto Distribution Rainfall

The rainfall-runoff simulation model was conducted for each scenario, as it is shown in **Figure 9** and **Figure 10**. Each figure represents the drainage channel's maximum full for the redesigned channel capacity based on two types of rainfall distribution. The maximum full condition in this simulation is presented in several colors, including dark blue, light blue, green, yellow, and red. These colors show the max full condition range value, which compares the water depth to the channel depth. The max full by the value one shows that the water depth reaches the full bank condition or exceeds the channel depth. Furthermore, the simulation result for the redesigned channel shows that the dimensions obtained from the rational method are reliable

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for flowing the flood discharge, as shown in **Figure 8**. The simulation result indicates adequate channel capacity for both rainfall distributions. However, the maximum full evaluation of the Tadashi Tanimoto rainfall distribution is higher than that of the Sri Harto rainfall distribution. Based on the Tadashi Tanimoto rainfall distribution, the water depth for several channel cross sections reaches 80% of the channel depth, representing that the freeboard is less than 30%. Moreover, the Sri Harto rainfall distribution result shows that the water depth is less than 70% and achieved the minimum freeboard of 30% from the channel depth.

5. Conclusion and Suggestion

5.1 Conclusion

This research shows that the flood discharge based on the Sri Harto distribution has a lower peak discharge than the Tadashi Tanimoto distribution. The simulation result shows that the rainfall distribution influences the water depth. Therefore, rainfall distribution must also be considered since the result shows the significant effect of rainfall distribution types on the maximum full value. The chosen rainfall distribution should also represent the watershed characteristics to obtain a suitable result for flood discharge.

5.2 Suggestion

This research evaluates the channel capacity using the rainfall-runoff simulation model. It considers two types of rainfall distribution, the Tadashi Tanimoto and Sri Harto distributions. However, various distributions exist apart from both, and the other rainfall distribution must be considered.

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