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FLOOD MODELLING OF PREMULUNG RIVER, BENGAWAN SOLO

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Abstract*. Premulung River or commonly known as Kali Premulung is one of many branches of Bengawan Solo River in its upstream area. This river pass through one of the most historical cities in Central Java, Surakarta. The overcapacity of this river leads to flood event that has a negative impact on humans. The purpose of this research is to analyze the Premulung River capacity and simulate the flood caused by rainfall design. The hydrological matter was analyzed using Hydrognomon and HEC-HMS while flood modelling was analyzed using HEC-RAS software one- and two-dimension (1D & 2D) simulation. Model calibrations were carried out based on historical flood events (depth, duration, and area of inundation) and local interview due to data limitation. Based on the simulation, the flood modelling shows that the current capacity of Premulung River cannot accommodate its peak discharge for two (Q_2) and twenty years (Q_{20}) return period flood. There are two main spots identified flooded due to Q_2 flood with depth varies from 40 to 80 cm and duration from 4 hour to 7 hour. For Q_{20} flood, there are also two same spots identified flooded with depth varies from 1.2 m to 1.8 m and duration from 6 hour to 9 hour. The result of this study can be a reference for flood dike design in the future which still require further detailed investigation.*
Keywords: *flood; hydrology; inundation; river; model*

1. Introduction

Early human communities typically sprang up near water since it served as a supply of water for home and agricultural needs throughout the planet (Malmqvist & Rundle, 2002). Those communities grew within time into cities and larger urban centers, making them more vulnerable to water quality and quantity issues. Without adequate planning, often unregulated growth of cities put stress on water sources, altering the nature of hydrological pattern (Kundzewicz *et al*., 2003; Muller, 2007). Most places that grow up alongside rivers rely on its stream and the nearby aquifers for water supplies, but they unintentionally reduce the quantity and quality of water available. A city with a high population density uses more water, which increases its vulnerability to water shortages and puts strain on the water supply, especially when the sanitation system is not up to par. More natural land cover is being turned into impermeable areas as cities expand, which lessens the effectiveness of the infiltration of rainfall into the soil and raises the danger of flooding (Du *et al*., 2015; Feng *et al*., 2021; Tingsanchali, 2012). The growth of urban areas into upper catchment areas reduces the ability of catchment to retain rainfall, causing the discharge of catchment response to change faster and greater (Gunnell *et al*., 2019; Sheng & Wilson, 2008).

Flood is a natural event with huge consequences. In the moment of flood, water covers

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normally unaffected areas, causing economic disadvantage, displacement of human, and, in the worst circumstances, illnesses and death (Smith, 2013). Floods can be caused by river flood, pluvial flooding, sea-level activities, ice melt, hydraulic structure overtopping, or association of these factors. Heavy rainfall, poor drainage quality, storm surge, high tides or riverbank overflow can all contribute to urban flooding. A city located near floodplains is prone to excessive runoff from upstream, mainly when the expansion limits the river conveyance dramatically (Rohmat *et al.*, 2022).

Floods, droughts, hurricanes, landslides, fires, high waves, earthquakes, and volcanic eruptions were among the 5402 disaster occurrences recorded in Indonesia in 2021. One-third of such incidents (1794) were floods (Indonesian National Board for Disaster Management – BNPB, 2022). Jakarta City, Indonesia's capital, has had a significant amount of floods, with several researchers claiming that the city is extremely prone to flooding. (Farid *et al.*, 2017; Fuchs, 2010). The multi-aspect and understudied physical processes and human intervention make managing urban flood risk more difficult in developing states (Nkwunonwo *et al.*, 2020). The problem is exacerbated further by poorly regulated spatial planning. Moreover, urbanization give an important impact to the hydraulic capacity decrease which leads to flood event (Asdak *et al.*, 2018; Jones, 2017; Moe *et al.*, 2017). In Indonesia, most of the rivers those are located near to the center of economic experience reduction hydraulic capacity due to sedimentation and solid waste (Andreas *et al.*, 2018; Marfai *et al.*, 2015; Merten *et al.*, 2021; UNICEF, 2016; Voorst, 2016a, Voorst, 2016b).

Premulung River is one of many branches of Bengawan Solo River in its upstream area. This river passes through several districts: Boyolali District, Sukoharjo District, and Surakarta City. The reach length of the river is about 28 km with its catchment covers around 89 km^2 area in three aforementioned districts (BPSDA Bengawan Solo, 2017) as presented in Figure 1. The local government uses this river as an urban drainage. One of the frequent problems caused by this river is flood caused by the over conveyance of this river that impact livelihood (Hadiani *et al.*, 2020; Pradana *et al.*, 2017; Utomo *et al.*, 2019) especially in the area of Surakarta City, which is one of the important city in Central Java. Based on Regional Development Planning Agency of Surakarta City data (BPBD Kota Surakarta, 2021), some region along Premulung River identified as a high risk level of flooded zone. In fact, human settlement already occupied the flood plain of Premulung River (Figure 2).

Premulung River is under authorization of River Basin Organization of Bengawan Solo or more popular called as *Balai Besar Wilayah Sungai* (BBWS) Bengawan Solo (BBWS BS term is used for this paper). Several flood events caused by Premulung River were recorded. Nonetheless, they have not received much attention. There were only a few publications which addressed Premulung's flood problem. Most of them even only discuss several spots which focus on analyzing the volume of discharge and area inundated caused by flood of Premulung River in several spots, using HEC-RAS (Hadiani *et al*., 2020; Utomo *et al*., 2019). The recurring pattern and the increase of rainfall intensity in the study area leads to the need for an extensive study of flood mechanism. More research is required to overcome the knowledge barrier and make sure that appropriate flood control strategies are applied. The purpose of this research is to analyze the Premulung River capacity and simulate the flood caused by rainfall design. In this study, HEC-HMS was used to simulate flood based on available data to develop a numerical flood model. A 2D HEC-RAS numerical hydraulic model was then used to map flood depth and extent (Romali *et al*., 2018; Muñoz *et al*., 2022). Therefore, in this study, hydraulic model was used for flood simulation and create accurate 2D flood maps according to precipitation design. Insights gained from this study open new avenues for more accurately simulating and predicting flood conditions caused by the Premulung River and its surrounding areas. Lessons learned from this paper will support Indonesia's Flood Risk Management (FRM) strategy as a lot of states attempt to meet the UN Sustainable Development Goals (SDGs) for 2030. This case study also will provide detailed FRM ideas for the city of Surakarta and can be applied to other parts places in Indonesia.

2. Methods

This paper uses two major analyses: hydrological and flood model. Hydrological analysis aims to calculate discharge of the flood that will be used as an input in the next analysis. On the other hand, flood modelling will focus on predicting depth, duration, and inundated flood areas. Figure 3 presents the method used in this paper. Several important processes of research include data collection, delineation of catchment, generation flood hydrograph, flood modeling, and result analysis. There is no water level recorder in the research area (Rezagama *et al*., 2020), therefore channel bankfull method was used to calibrate the designed flood discharge (He & Wilkerson, 2011).

Hydrologic data mainly rainfall data was obtained from Bengawan Solo River Basin Organization from the website https://hidrologi.bbws-bsolo.net. The rainfall design would be analyzed using Hydrognomon version 4.0.3. This open-source software provides statistical tools such as frequency distribution analysis and fitness test for distribution. Four frequency distributions which commonly used in Indonesia were utilized: normal, log-normal, log-Pearson, and gumbell distribution while two fitness tests for frequency distribution were used: Chi-Square and Smirnov-Kolmogorov test. All this statistical analysis was carried out by this software. The least mean absolute error (MAE) value was used to decide the best frequency distribution. (Schneider *et al*., 2022).

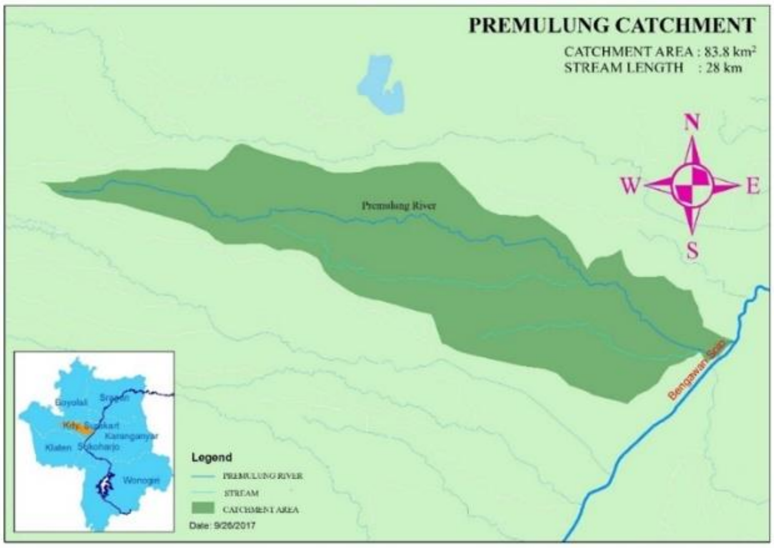

Figure 1. Premulung River Catchment


Figure 2. Human Settlement occupies the flood plain of Premulung River (2022)

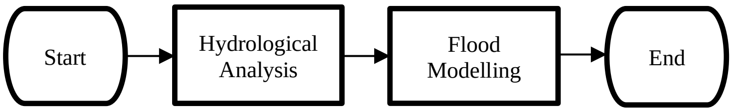

Figure 3. Research Methodology

The flood discharge design was analyzed using Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) software version 4.10. This free software is suitable for rainfall-runoff process modelling including flood events (Chu *et al*., 2009). Several essential parameters such as river and basin characteristic were analyzed by this software. Soil Conservation Service-Curve Number (SCS-CN) method was used for loss method and transform method. The method are developed for small catchment (Ponce & Hawkins 1996) and considering land cover influence of the catchment which is represented by Curve Number, CN (Dingman, 2015). The CN value was analyzed using land cover map from https://www.indonesia-geospasial.com/ and soil type map from the harmonized world soil database (HWSD) (Nachtergaele *et al*., 2010). From CN value, the initial abstraction (I_a) value was calculated using equation (1) and (2) with S is storage capacity of the soil. Time lag (t_p) was calculated using equation (3) considering time concentration (T_c), stream length (L) and catchment slope (i). The value of I_a and t_p was input in HEC-HMS modelling. Equation (5) was used to calculate continuing abstraction (F_a) in order to obtain effective rainfall from total rainfall (P). The PSA-007 method (Waskito, 2022) for 6 hours (Table 1) was used to distribute the rainfall design because the hourly rainfall distribution data are not available. All of these processes were carried out to obtain the flood discharge design.

$$I_a = 0.2\,S \quad (1)$$

$$S = \frac{1000}{CN} - 10 \quad (2)$$

$$t_p = 0.6\,T_c \quad (3)$$

$$T_c = 0.01947 L^{0.77} i^{-0.385} \quad (4)$$

$$F_a = \frac{S(P-I_a)}{P-I_a+S} \quad (5)$$

Table 1. Rainfall Distribution

Hour	Percentage
0	0%
1	5%
2	10%
3	60%
4	16%
5	6%
6	3%

The flood event scenario was evaluated using two years (Q_2) and twenty years (Q_{20}) return period discharge following the Indonesian government regulation (PUPR, 2015) related to riparian zone. Bankfull discharge which was calculated using Manning formula (Chow, 1959) was taken as Q_2 (He & Wilkerson, 2011) for calibration process while Q_{20} was taken as a maximum flood discharge design for rural area. Designed flood discharge (Q_2) was calibrated using bankfull discharge by adjusting CN value.

Terrain data, Digital Elevation Model Nasional or commonly known as DEMNAS (the DEMNAS description is detailed on https://tanahair.indonesia.go.id/) and the location of the confluence of the Premulung and Bengawan-Solo rivers were used as inputs for the watershed boundaries. DEMNAS is commonly acceptable for modeling basin-scale precipitation and runoff process in steep rural regions. Hence, a primarily surveyed Digital Terrain Model (DTM) is recommended for flood modeling whenever possible. DEMNAS captures the body water surfaces; therefore, it was not recommended for river bed topography analysis.

This process was followed by hydraulic modeling using the Hydrological Engineering Center's River Analysis System (HEC-RAS). It is open-source software that can be used to model 1D, 2D, or combined 1D and 2D hydraulic processes in natural and man-made canals and terrains. The software can also model steady-state or transient flows, as well as additional modules to calculate sediment, temperature, and quality of water (Brunner, 2002; Brunner, 1995). This research used 1D and 2D HEC-RAS modeling of unsteady flows as the modeling framework. The terrain form DEMNAS combined with the 2017 topographic survey of river geometries by BBWS BS was used as an input of geometry. Historical flood events (flood inundation depth, duration, and area) and local interview were used to calibrate the flood model. The roughness coefficient for channel used Manning value based on visual observation of river due to lack of field measurement data. The urban drainage systems were not included in analysis but recommended for future analysis.

3. Results and Discussion

3.1. Hydrological Analysis

Two rainfall gauges that were close to the catchment were used for analysis: Nepen and Pabelan rain gauge. Figure 4 shows the location of the gauges, observed river segment (A-B-C), and four subbasins that was automatically generated by HEC-MS model. The daily annual maximum rainfall then was collected from each station as presented in Table 2. The arithmetic average value was statistically analyzed using Hydrognomon. Based on the analysis, normal distribution was chosen for distribution frequency among the others because it has the smallest MAE and passed the fitness test. The predicted rainfall design for the two and twenty years return period is shown in Table 3. Next, the rainfall design was distributed into hourly data using PSA-007 standard for six hours. The rainfall distribution data was input into HEC-HMS along with CN composite value in order to obtain effective rainfall. The calculation of CN composite value is summarized in Table 4. The value of CN for each component was determined based on land coverage and soil type which is presented in Figure 5 and Figure 6. Most of Premulung catchment majorly consists of Regosol soil type. This type of soil has character as high infiltration rate soil (Molya *et al*., 2023). Therefore, type B soil was used for initial value. The last input parameter is lagging time that was calculated using Equation 3 for each subbasin. Ideally, flood discharge calibration is carried out using data from stream gauge. Unfortunately, due to the unavailability of data, the process was conducted by bankfull discharge method.

One important parameter when analyzing bankfull discharge is the Manning coefficient. Ideally, this value is obtained from field measurement since Manning value is a specific character for river roughness. Due to unavailability of data, the Manning value was analyzed by visual observation of river condition. Figure 7 shows the physical condition of Premulung river in some spots in July 2023. According to visual observation and manning range value classification (Chow, 1959), Premulung river is categorized as clean, straight, full stage, no rifts or deep pools. Therefore, the reasonable manning value ranges from 0.025 to 0.035. The average value that is 0.030 was taken as the Manning coefficient value.

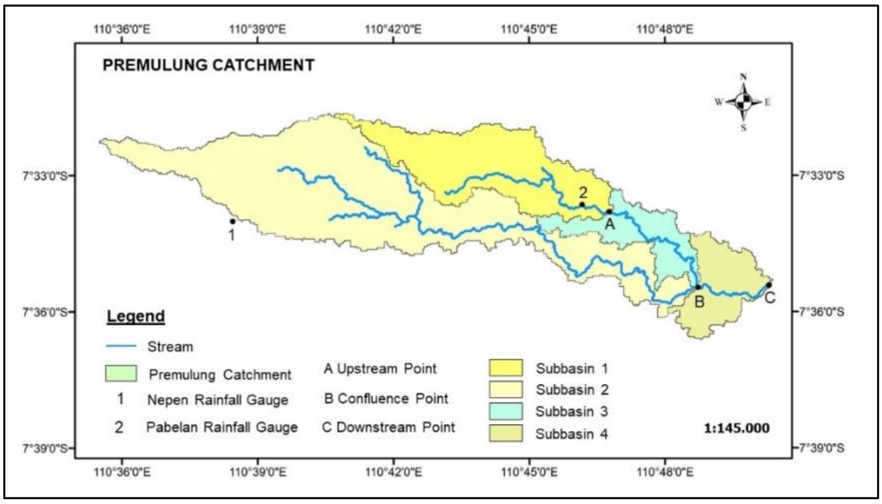

Figure 4. Premulung Catchment and Its Important Features

The calibrated flood hydrograph is presented in Figure 8 with calibrated CN value was presented in Table 5. The CN value was adjusted so that the result of designed flood discharge is close to the bankfull discharge (Table 6). Calibrated CN value still seems acceptable since based on the soil type map in Figure 6, the soil of Premulung consist of high infiltration rate soil type.

Table 2. Daily Annual Maximum Rainfall

Year	St. Nepen (mm)	St. Pabelan (mm)	Average (mm)
2001	65	80	73
2002	75	80	78
2003	64	85	75
2004	108	104	106
2005	112	89	101
2006	142	92	117
2007	97	133	115
2008	84	126	105
2009	125	142	134
2010	71	103	87
2011	125	114	120
2012	120	99	110
2013	75	76	76
2014	121	123	122
2015	125	166	146
2016	82	138	110
2017	119	118	119
2018	105	69	87
2019	88	116	102
2020	120	113	117
2021	89	167	128

Table 3. Rainfall Design

Return Period (years)	Rainfall (mm)
2	106
20	140

Table 4. CN Composite Calculation

Land Cover	Area (km^2)	CN	CN x Area
Settlement	52.00	77	4004
Dry Land	2.96	62	184
Paddy Field	44.07	62	2732
Total	99.03		6920
CN Composite			70

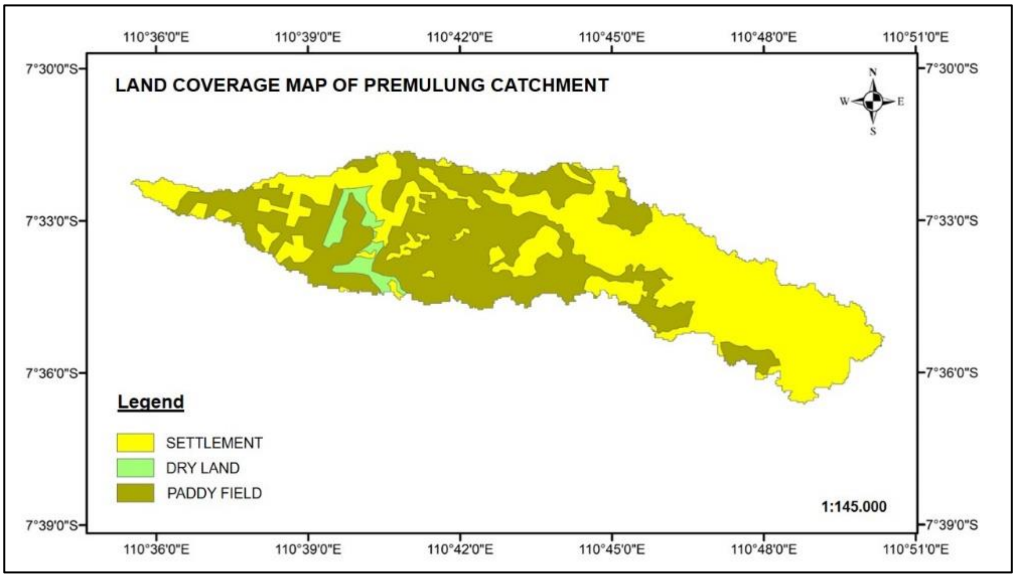

Figure 5. Land Coverage Map of Premulung Catchment

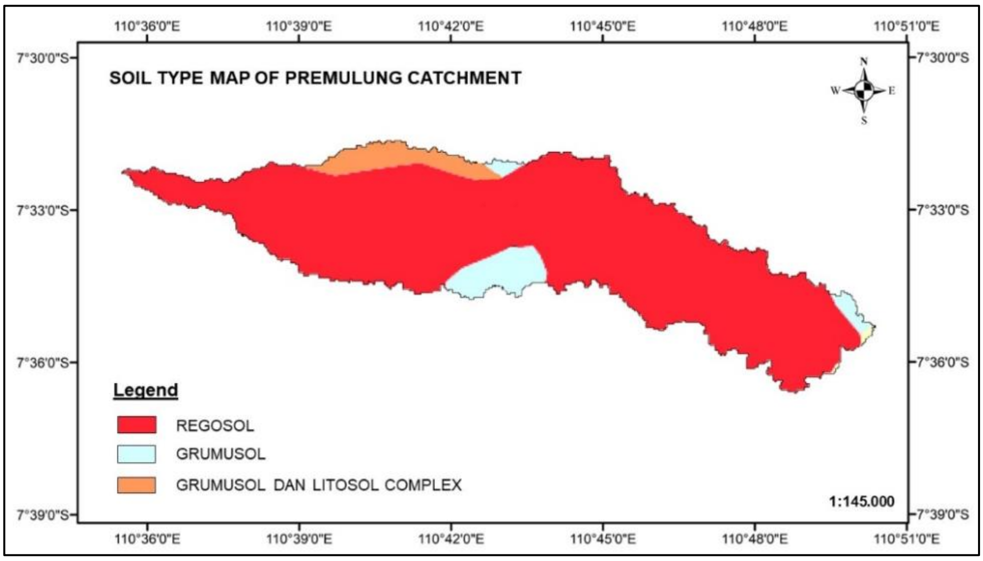

Figure 6. Soil Type Map of Premulung Catchment

Figure 7. Physical Condition of Premulung River

Table 5. Parameter Calibration

Parameter	Initial	Calibrated
CN Value	70	53

Table 6. Discharge Calibration

Designed Discharge (m3/s)	Bankfull Discharge (m3/s)	Error
11.50	10.95	5.06%

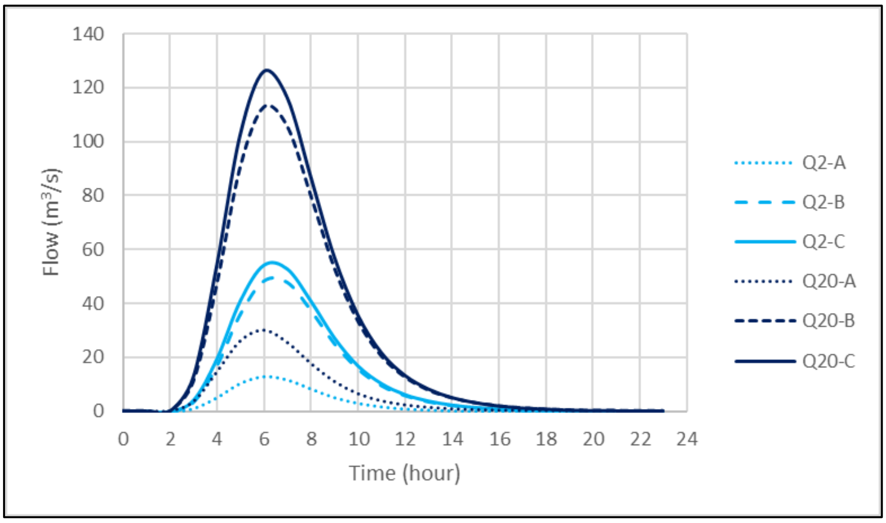

Figure 8. Flow Hydrograph for Q_2 and Q_{20} Flood at Point A, B, and C (Refer to Figure 4)

3.2. Flood Analysis

HEC-RAS version 6.3.1 was used for flood simulation in one-dimension (1D) and two-dimension (2D) frame to analyze depth, duration, and area of flood. Two scenarios were made to simulate Q_2 and Q_{20} flood event. Some important input features for flood modelling are flow data which has been previously discussed and geometry data sources from DEMNAS (terrain) and BBWS BS (river cross section). There are 105 river cross sections in a 9.4 km river segment that was input into HEC-RAS for flood modelling. The boundary condition was flood hydrograph from previous hydrological analysis for upstream part and normal depth for downstream part (for ideal simulation, rating curve data can be used for downstream boundary condition to simulate the backwater from main river).

[Figure 9](#) shows the result of 1D flood simulation for Q_2 and Q_{20}. Based on the model, there are two main spots with water elevation surpassing the river dike. The depth and duration of the flood is summarized on Table 7. Location 1 and 2 are the location of field calibration where flood frequently occurred. Figure 10 and Figure 11 depicts the maximum water elevation in HEC-RAS and actual condition of river. Location 1 is commonly called RW 14 Pajang (Laweyan District) which was based on field observation, that segment of river has no flood dike which caused flood. According to local interview (Figure 12), most of every year the flood often occurs caused by the river, from ankle to knee depth with relatively short duration. Location 2 is the location of a local market known as Pasar Jongke where trade and economic activities occur. Flood caused by Premulung river also occurs annually in this location Therefore, the flood measure is currently on going by constructing flood dike (Figure 11).

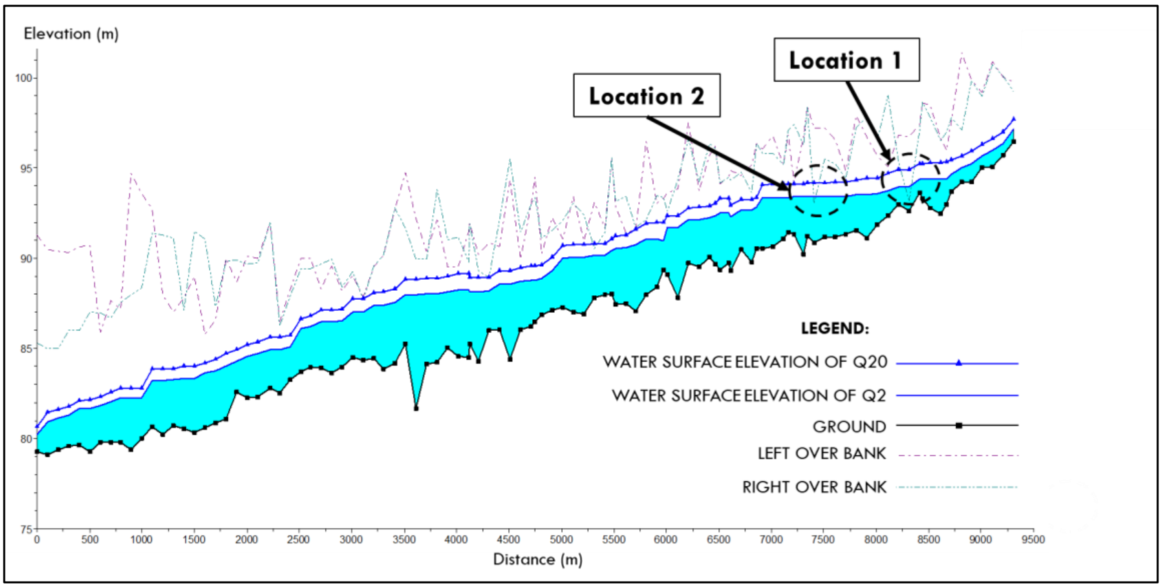

Figure 9. 1D-Flood Simulation for Q_2 and Q_{20} Flood

Table 7. 1D Flood Simulation Summary

Location	Q2		Q20	
	Depth (m)	Duration (hour)	Depth (m)	Duration (hour)
1	0.80	7	1.80	9
2	0.40	4	1.20	6

The area of inundation was easily identified from 2D flood simulation. The two-dimension model is heavily dependent on terrain quality and amount of cross section. The Figure 13 shows the result of 2D flood simulation of Premulung river. Focusing on the spot that most frequently flooded, the area inundation around Location 1 in Figure 13 is around 0.18 and 0.23 hectare caused by Q_2 and Q_{20} flood, respectively. For more accurate and precise analysis of inundation area, more cross section with dense space is required. This is important because HEC-RAS interpolate linearly the unavailable cross section segment which does not always represent the actual condition (Figure

13). Besides, the terrain quality with high resolution plays a significant role in 2D flood simulation. One alternative to improve flood modelling is using LiDAR data for terrain which has been implemented successfully although this method also has limitations and challenges (Li et al., 2021; Wedajo, 2017).

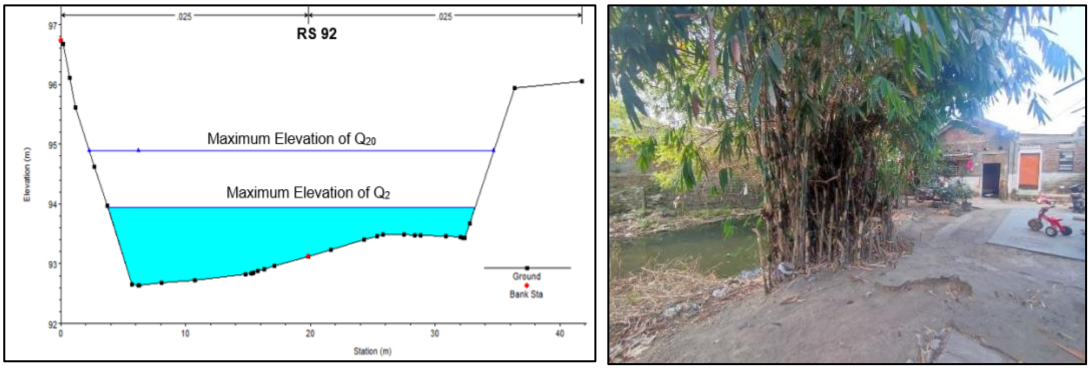

Figure 10. Cross Section View of Location 1 in HEC-RAS (left) and actual location (right)

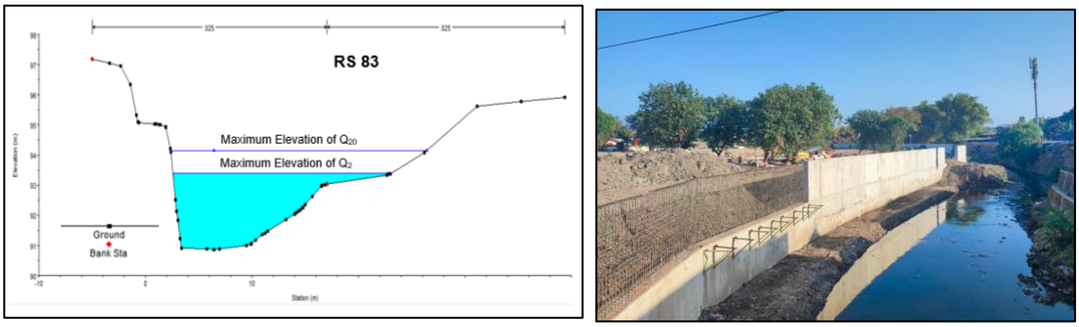

Figure 11. Cross Section View of Location 2 in HEC-RAS (left) and actual location (right)


Figure 12. Local Interview

One possible and obvious solution to deal with Premulung flood case is to build flood dike. Table 7 can be a reference for flood dike design to improve river conveyance. Another possible option is to deepen the river by normalization. Both of these alternatives also need further analysis which is beyond the scope of this paper. However, such local corrective actions come with risks. The prominent risk is that rising river flow will move floodwaters downstream instead of solving the problem. Increasing the cross-sectional area of a river is effective in elevating river transport but can counterproductively exacerbate the sediment problem. At low flows, suspended sediment will be deposited on the riverbed. In the long term, sedimentation can reduce water intake capacity and cause flooding problems. Those approaches are commonly found in Indonesia, with some of notorious measures by improving channel and river normalization in the Ciliwung River Discharge Channel system in Jakarta (Lin *et al*., 2016) and FRM in Semarang City (Marfai & King, 2008).

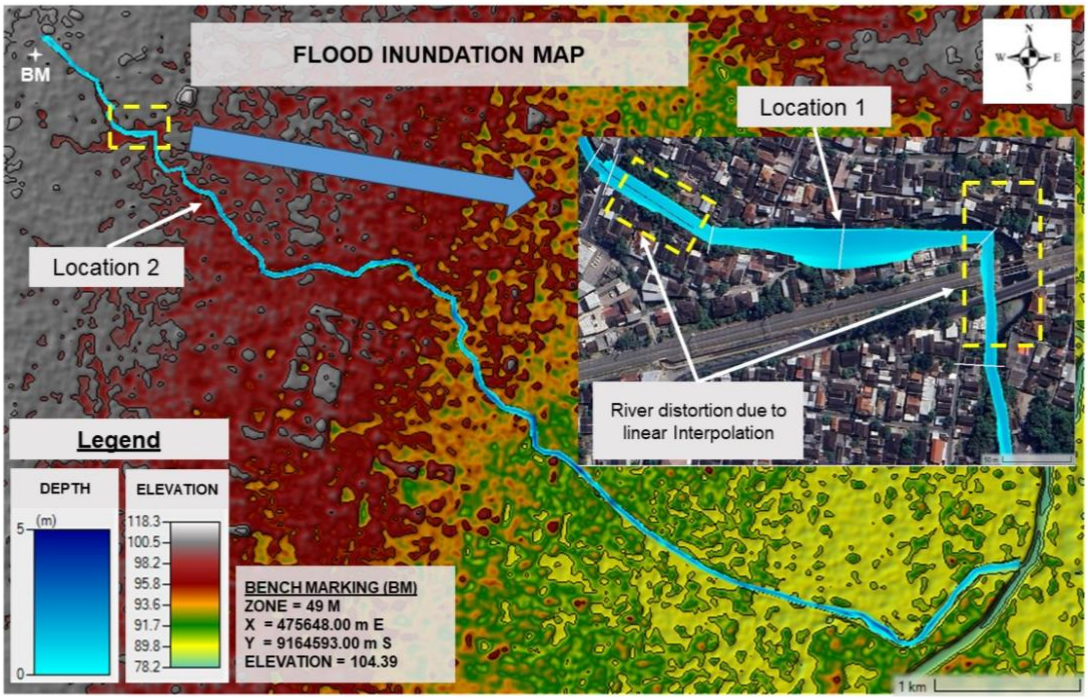

Figure 13. 2D-Flood Simulation Result

Rapid changes in land use are inevitable, with population growth and occupational shifts, primarily from agricultural workers to factory and retail workers. However, the problem lies in the people's mindset about where to live and inadequate basic infrastructure. Reluctance to adopt high-rise housing and lack of basic infrastructure, especially in locations far from metropolitan areas, hampers the more space-efficient communities' adoption. People near the Premulung River depend on groundwater for daily needs. Simultaneously, it also has its own septic tank, as there is no city or municipal sewage system. Reconfiguring urban settlements to improve urban drainage system is important in dealing with floods but will require comprehensive research and strong political will.

In a wider context, Premulung Flood Case Study characterizes flood features in developing regions in Indonesia and other places. Significant uncertainties in numerical modeling are caused by unmanaged flood hazards and incomplete data (Osti & Nakasu, 2016). In developing communities like Premulung and other places, there is a growing need to accelerate and improve the response to floods. Based on what we learned from Premulung's case study, it is recommended to study on how to understand the issues, problem, and formulate a solution for flood measures.

More specific analysis is recommended in the area of hydrological, flood meteorological, and hydraulic processes specific to developing nations. For instance, the study of precipitation, runoff, and flood characteristics requires deeper analysis. Discontinuity and unintegrated of data are a common issue in flood and hydrological research in developing nations. However, increasing the quantity and quality of flood event data is an essential tool for obtaining more detailed hydrological models and a deeper understanding of flood problems for better FRM strategies. As mentioned before, there is no water level recorder in Premulung River. Therefore, one of the most tangible and simple activities in order to improve flood mitigation strategy is by installing water level recorder to record stream discharge.

Planning and implementing flood management measures for future flood events requires designing flood events with a specified return period or estimated occurrence frequency. Such planned flood discharges are analyzed by statistical analysis of annual maximum series (AMS). One way to mitigate such uncertainties is to reconstruct historical evidence of previous events, such as watermarks in newspapers and trade publications, written reports, photographs of floods, and most importantly extending the record into the past by installing water level recorders in rivers. Stamataki and Kjeldsen (2021) present a comprehensive case study using hydraulic models to reconstruct peak discharges of past flood events in city of Bath, UK. The study described a detailed methodology for reconstructing past flood events based on archival stuffs such as historical maps, photographs, engineering drawings and inscriptions. The study presented a series of composite flows consisting of data from 1866 to the present, showing up to a 30% increase in the 100-year return period. Such method can be adopted in the case of Premulung to understand the past and prepare for future responses to floods.

Water quality and climate change are also essential issues related to Kali Premulung. Laweyan is a district in Surakarta City which is renowned for its batik industry or even called as a batik village. It has 31 stamped batik, 3 printed batik industries, 11 hand drawn batik industries and 122 household-managed batik industries (Novani *et al*., 2014). Some of these industries dump their dye waste into Premulung River. A previous study (Minarno *et al*., 2022) shows the poor pollutant load carrying capacity of Premulung River in several parts of stream. Therefore, the regulation for waste management is also important to be discussed. On the other hand, detailed analysis of flooding potential due to future climate change is also an important issue. These are essential to provide potential FRM strategies that can be applied worldwide.

4. Conclusions

Based on the analysis, the flood modelling shows that current capacity of Premulung River cannot accommodate its peak discharge (2-years and 20-years return period flood). There are two main spots identified flooded due to Q_2 flood with depth varies from 40 to 80 cm and duration from 4 hour to 7 hour. For Q_{20} flood, there are also two same spots identified flooded with depth varies from 1.2 m to 1.8 m and duration from 6 hour to 9 hour. For more accurate and precise analysis of inundation area, more cross section with dense space is required. This is important because HEC-RAS interpolate linearly the unavailable cross section segment which does not always represent the actual condition. Besides, the terrain quality with high resolution plays an important role in 2D flood simulation. A possible and obvious solution to deal with Premulung flood case to is build flood dike. Another possible option is to deepen the river by normalization. This study can be a reference for flood dike design to improve river conveyance. In reality, applying this solution requires flood plain restoration which also gives other consequences such as land acquisition, social problem and so on. Therefore, deeper analysis is still required. Eventually, it is becoming crucial to speed up and strengthen flood resilience development efforts, especially in rapidly growing communities such as the city of Surakarta and others.

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