A study on flood management with an integrated floodgate operation pattern at Pepe River in the city of Surakarta

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Abstract. Floods that occurred in Surakarta City were caused by increased flood discharge, reduced capacity in Kali Pepe, and backwater from Bengawan Solo which is the estuary of Kali Pepe. One of the efforts to control flooding in Surakarta is by building the Tirtonadi Rubber Weir and the Demangan Sluice Gate which is located near the confluence with the Bengawan Solo River. This study aims to examine the integration of the Sluice Gate Operation Pattern at the Tirtonadi Weir with the Sluice Gate and Pump Operation Pattern at the Old Demangan and New Demangan in flood control in Surakarta City. Simulations were carried out on an unsteady flow model with various scenarios of sluice gate and pump settings. The simulation model is carried out on the existing condition and after the New Demangan Sluice Gate operates. The results of the analysis show that with Q25 conditions (flood discharge) at Pepe River and Bengawan Solo River discharge, the floodgates in Old Demangan are opened, while the floodgates in New Demangan are closed and the pump is operated. With an integrated sluice arrangement, there is a potential for flood reduction with a decrease in water level of 0.8 m.

1. Introduction

Floods are one of the natural disasters that often occur in Indonesia, especially in conditions of high rainfall in areas with relatively flat topography. Floods can be in the form of inundation on lands that is usually dry, such as on agricultural land, settlements, and city centers. Floods can also occur because the discharge/volume of water flowing in a river or drainage channel exceeds or exceeds its drainage capacity (Arief Rosyidie, Floods: Facts and Impacts, and Effects of Land Use Change, 2013). The detrimental effects of floods begin to be felt like a problem if the activities of daily human life are disrupted and/or pose a risk of loss of life and material losses. The Cause of flooding is related to the carrying capacity of the river and its tributaries which are unable to accept the flow discharge that enters the river, besides that the river and its tributaries have been filled with sedimentation resulting in silting of the river. Other causes of flooding, apart from problems with river or channel capacity, can be due to the difficulty of removing water from drainage channels or rivers due to high water levels at the mouths, due to the influence of tides or high water levels in the mainstream river.

During the great flood in the Upstream Bengawan Solo watershed in 1966, almost the entire Surakarta area was flooded, including urban areas. The high inundation that occurred in Surakarta City reached 1 to 2 m and the death toll was 90 people. The flood in Kali Pepe Downstream is identical to the flood in Surakarta City because so far the biggest contributor to flooding in Surakarta City is from the Kali Pepe Downstream Sub-watershed which also functions as a drainage for the City of Surakarta. Based on the chronology of floods and the operation of the Demangan water pump issued by the Bengawan Solo River Basin Center, the inundation in Solo City in the December 2016 period occurred not because of overflowing water from the Bengawan Solo River, but as a result of drainage channels that were unable to drain water. to the main channel/river as a result of rising water levels in the Bengawan Solo river. Regarding the function of Pepe River which is also the drainage of Surakarta City, this research with the title “A study on flood management with an integrated floodgate operation pattern at Pepe River in the city of Surakarta” is very necessary.

2. Literature Review

2.1. Definition

Flood is the water level above normal in the river, which usually overflows beyond the height of the river bank and the overflow pools in an inundation area. Floods originate from runoff that flows through rivers or becomes puddles.

Flood control is a complex matter where the engineering dimension involves many engineering disciplines including hydrology, hydraulics, watershed erosion, river engineering, river morphology and sedimentation, engineering flood control systems, urban drainage systems, water structures, and others. The flood control gate functions to regulate the flow of water to be released from the river in connection with the interests of flood control. So what needs to be considered are the dimensions of the door (that is, the total width of the door and the height of the door) and the operation of the flood control door.

Inside the pumping station, there is a pump that is used to remove water that has accumulated in the retention pond or drainage network junction outside the coverage area. The basic principle of pump work is to suck water using a power source, be it electricity or diesel. Water can be discharged directly into the sea or river/canal flood which downstream will empties into the sea. The function of this flood pump system is to pump water from tributaries to the main river so that it is hoped that it can help speed up flood inundation time and reduce flood depth (Heru Gunawan Apriadi, Study of Flood Handling With Pump Systems in the River Weir, Palembang City, 2021).

2.2. Previous research

The availability of water in Pepe River is needed to support drainage functions, flushing for sanitation control, and support water tourism programs. Tirtonadi Rubber Weir and drain gate, Tirtonadi Sluice Gate and Demangan Sluice Gate are water structures in Pepe River whose functions are related to the two water disasters (Dian Triastuti RM, Performance Study of Water Building System in Pepe River Section in Solo City for Rainy Season Disaster Mitigation and Drought, 2015). In the 50-year flood condition of the Bengawan Solo River, the existing pump capacity is only able to drain the annual flood discharge in the Downstream Pepe River. In the Q25 flood condition, the existing pump capacity needs to be increased from 12 m^3/s to 34 m^3/s (Yuhanes Widi Widodo, Technical Study of the New Demangan Sluice Gate as a Flood Control for Surakarta City, 2020).

2.3. Hydrological Analysis

The Hydrological analysis is an initial part of the whole series in the design of water structures. referring to SNI 2415:2016 The procedure for calculating the planned flood discharge.

The purpose of hydrological data analysis is to prepare the design flood discharge in the flood hydrograph presentation for several return periods. In general, the hydrological analysis procedure will include rain analysis, design flood calculations.

2.3.1. Rainfall Frequency Analysis Methodology

Rain frequency analysis aims to estimate the rain height that may occur for a certain return period. The properties of the rain data series are indicated by the values of the statistical parameters of the probability distribution of the data.

- Gumbel Method

  To calculate the planned rainfall using the Gumbel Type I distribution method, an empirical frequency distribution equation is used

$$Xt = \bar{X} + \frac{S}{Sn}(Yt - Yn) \tag{1}$$

where:

Xt = value of variance that is expected to occur

$\bar{X}$ = mean value of variance

S = standard deviation (standard deviation)

$$S = \left(\frac{\Sigma(X_i - \bar{X})^2}{n-1}\right)^{1/2} \tag{2}$$

Yt = variance reduction value of the variable that is expected to occur in a certain return period

$$Yt = -\ln\left[-\ln\frac{T-1}{T}\right] \tag{3}$$

For T ≥ 20, then Yt = ln T

Yn = the average value of the reduced variance the value depends on the amount of data (n)

Sn = standard deviation of reduced variance the value depends on the amount of data (n)

2.4. Hydraulics Analysis

2.4.1. HEC-RAS Modeling

HEC-RAS is an application program for modeling flow in rivers, the River Analysis System (RAS), created by the Hydraulic Engineering Center (HEC) which is a division within the Institute for Water Resources (IWR), under the US Army Corps of Engineers (HEC). USACE). HEC-RAS is a steady and unsteady one-dimensional flow model.

The water level profile is calculated from a cross-section with the Energy Equation through an iterative procedure called the standard step method. The energy equation in question is (Chow, 1997):

$$Y_1 + Z_1 + \frac{\alpha_1 v_1^2}{2g} = Y_2 + Z_2 + \frac{\alpha_2 v_2^2}{2g} + h_f + h_e \tag{4}$$

where:

Y_1 = Depth of water at cross-section 1 (m)

Y_2 = Depth of water at cross-section 2 (m)

Z_1,Z_2 = Height of Water from Datum (m)

V_1,V_2 = Average flow velocity (m/sec)

α_1,α_2 = Energy Coefficient

g = Gravity Acceleration (m/s^2)

he = Loss of height due to changes in cross-section (m)

hf = Loss of height due to friction (m)

A sketch of the energy equation in an open channel is shown in Figure 1

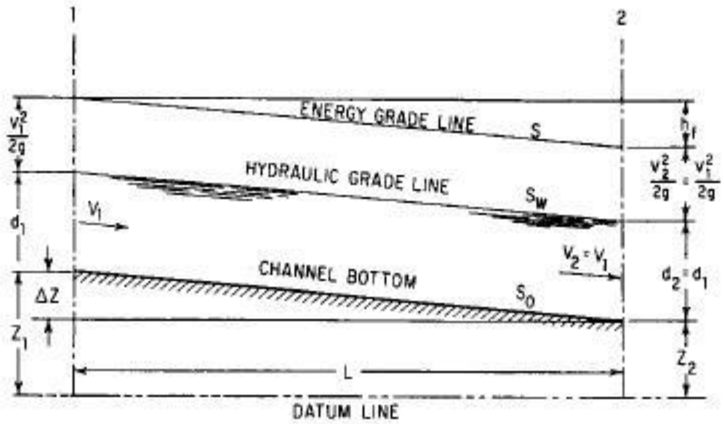

Figure 1. Energy in Open Channels.

Source Chow, 1997.

The loss of energy height between 2 (two) sections due to channel widening or narrowing is as follows

$$h_c = L.\bar{S_f} + C\left|\frac{\alpha_2 + v_2^2}{2g} - \frac{\alpha_1 + v_1^2}{2g}\right| \quad (5)$$

where:

L = Distance between embankments (m)

$\bar{S_f}$ = slope of the energy line

C = Coefficient of loss due to channel widening or narrowing

The average river length L, calculated by the formula:

$$L = \frac{L_{lob}\bar{Q}_{lob} + L_{ch}\bar{Q}_{ch} + L_{rob}\bar{Q}_{rob}}{\bar{Q}_{lob} + \bar{Q}_{ch} + \bar{Q}_{rob}} \quad (6)$$

where:

L_{lob}, L_{ch}, L_{rob} = Length of a longitudinal cross-section of left, main and right rivers (m)

$\bar{Q}_{lob}, \bar{Q}_{ch}, \bar{Q}_{rob}$ = Average cross-sectional discharge of left, main and right rivers (m^3/s)

3. Methodology

The method used in this study includes the following sequence of work steps: initial identification of the problem, followed by data collection and compilation, hydrological analysis using HEC-HMS software and flood simulation using HEC-RAS software, and drawing conclusions and suggestions based on the results. modeling analysis.

3.1. Data collection

This study uses relevant primary and secondary data from various sources, including:

- Rainfall Data for 2001-2020
- Topographic maps and River Geometry
- Study of Previous Design Details
- Other supporting data

3.2. Hydrological Analysis

The purpose of hydrological data analysis is to prepare the design flood discharge in the flood hydrograph presentation for several repeat periods. In general, the hydrological analysis procedure will include rain analysis, design flood calculations.

4. Results and Discussion

K. Pepe watershed area = 310,894 Km^2 with the length of the main river = 57.78 Km

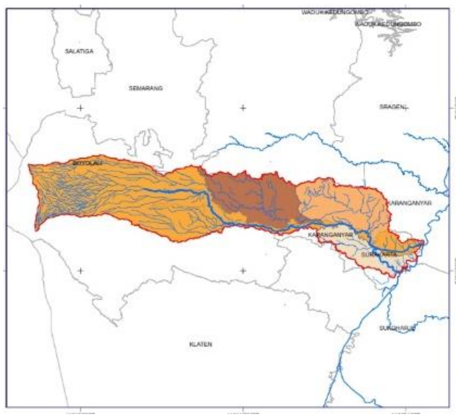

Figure 2. Map of the Kali Pepe watershed.

The results of the analysis of the flood design discharge calculated using the four Synthesis Unit Hydrograph (HSS) methods, namely SCS, Nakayasu, ITB-1, and ITB-2, were compared with the Bankfull Capacity discharge in Kali Pepe River Downstream with the assumption that Q2 is a bankfull discharge. From the cross-section at the Upper Tirtonadi Weir and topographic data, it is obtained A = 114.48 m^2; P = 70.68 m; S = 0.0092; by using the average manning value, it can be calculated that Q in bankfull conditions is 442.03 m^3/sec

$$Q = \frac{1}{n} R^{\frac{2}{3}} S^{\frac{1}{2}} A = \frac{1}{0.035} \left(\frac{114.48}{70.68}\right)^{\frac{2}{3}} (0.009)^{\frac{1}{2}} = \mathbf{442.03\ m^3/s}$$

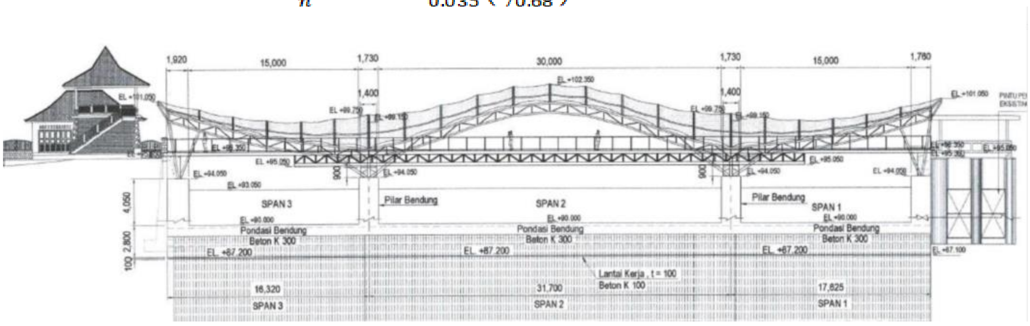

Figure 3. Cross Section at the Upper Tirtonadi Weir

From the calculation results, the design flood discharge that is closest to the bankfull capacity discharge at Kali Pepe is HSS SCS/HEC-HMS. Furthermore, the results of the planned flood discharge using the HSS SCS/HEC-HMS method will be used at various return periods. Based on the results of the frequency analysis and distribution suitability test, it can be seen that the planned flood discharge of the Pepe River is as follows:

Table 1. The design flood discharge with the return period.

No	Return Periode (Years)	Design Flood Discharge (m^3/s)
1	2	441.33
2	5	548.91
3	10	621.93
4	20	715.87
5	25	786.56
6	50	857.47
7	100	928.72
8	200	1095.83

4.1. Modeling Schematic

1D hydraulic simulation was performed using HEC-RAS 6.1.0 software. this simulation is only done with a 1-dimensional model to get the water level elevation and the operation pattern of the sluice gate with an integrated pump from upstream to downstream of the river.

4.1.1. Existing Condition

In this simulation, it is reviewed on the existing condition of Pepe River, namely Flood conditions with a Q25 discharge with conditions before handling in the form of the New Demangan Sluice as a result of the interaction of the flood hydrograph load entering the river with the influence of backwater from the Bengawan Solo River at the Lower Pepe River.

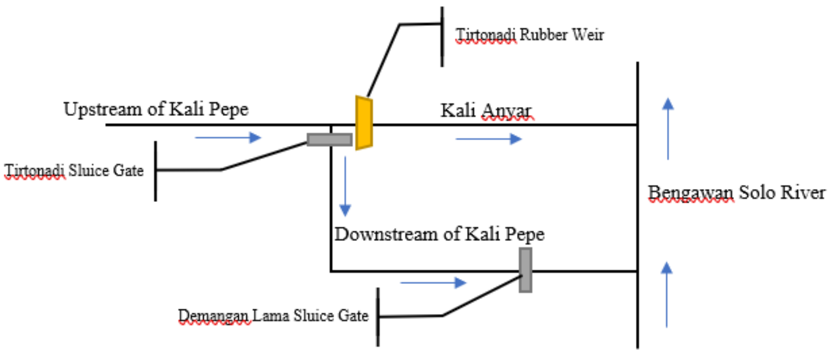

Figure 4. Schematic of Existing Condition Modeling.

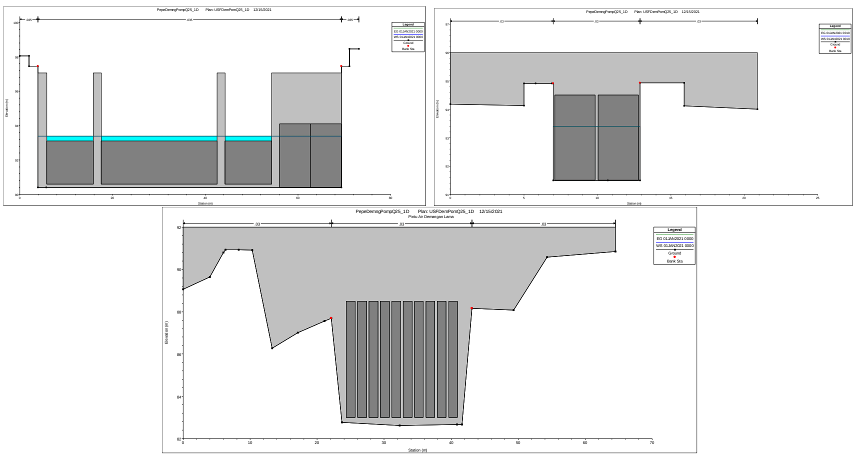

Figure 5. Example Plot Structure of Weir and Sluice Gate on HEC-RAS

Table 2 . Operational scenario The door is in an existing condition

NO	STRUCTURE	GATE AND PUMP OPERATION
1	Tirtonadi Rubber Weir	Segment 3 is opened when the water level upstream of the weir is +93.5 and closed at an elevation of +92.0
		Segment 1 is opened when the water level upstream of the weir is +93.7 and closed at an elevation of +93.5
		Segment 2 is opened when the water level upstream of the weir is +95 and closed at an elevation of +93.7
2	Tirtonadi Floodgate	2 gates are opened when the water level upstream of the weir is +92.5 and closed at an elevation of +92.0
3	Old Demangan Floodgate	10 gates are opened simultaneously if the downstream elevation is 0.1 m lower and closed if the downstream elevation is 0.1 m higher
4	Old Demangan Pump	The pump with a capacity of 1 m^3/dt of 3 units and a capacity of 3 m^3/dt of 3 units is activated when the elevation of the water surface upstream of the sluice is at +84.50 and is turned off when the elevation of the water surface upstream of the sluice gate is + 84.00

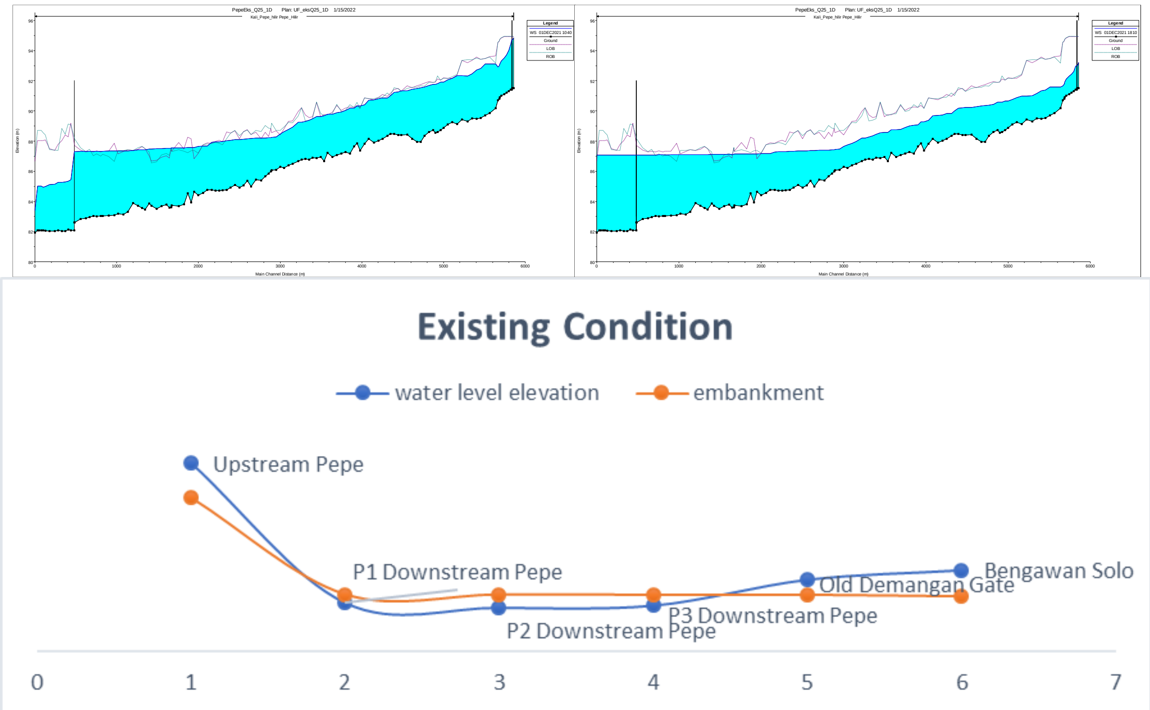

Figure 6. Existing Modeling Results

In this simulation, the inflow discharge in 1D modeling used is the design discharge for Kali Pepe and Bengawan Solo River with return periods of 2, 5, 10, and 25 years. Kali Pepe Upstream experienced overtopping occurred at the design discharge Q5, Q10, and Q25. At Kali Pepe Downstream overtopping occurs at the upstream of the Old Demangan sluice gate along the 2.2 km upstream. Overtopping occurred at the planned discharge Q25 and Q20, due to rising water levels in the Bengawan Solo river so that water in the Kali Pepe Downstream was restrained and discharged into the Bengawan Solo river only through a water pump with a maximum capacity of 12 m^3/s. While in Q2, Q5, and Q10 there is no overtopping.

This overtopping occurs as a result of the non-optimal function of the Old Demangan Sluice gate in flood control which is only able to be opened as many as 4 sluice gatess out of a total capacity of 10 sluice gates due to the age of the sluice structure which is old and it is feared that the structure will fail if it is completely open during a flood.

4.1.2. The Scenario of Handling conditions with the New Demangan Sluice
In this simulation, it is reviewed on the handling conditions of the Kali Pepe, namely Flood conditions with a Q25 discharge with conditions after handling the form of the New Demangan Sluice gate and the result of the interaction of the flood hydrograph load entering the river with the influence of backwater from the Bengawan Solo River at the Kali Pepe Downstream.

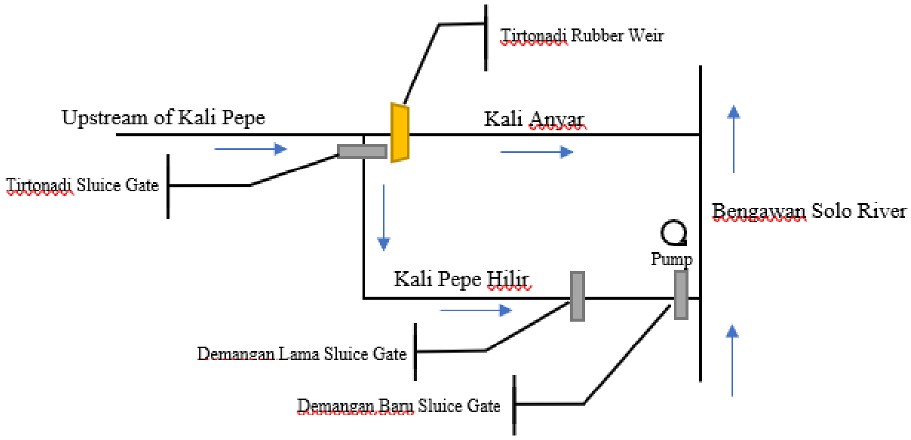

Figure 7. Handling Condition Modeling Schematic

Table 3 . Operational scenario Door handling conditions

NO	STRUCTURE	GATE AND PUMP OPERATION
1	Tirtonadi Rubber Weir	Segment 3 is opened when the water level upstream of the weir is +93.5 and closed at an elevation of +92.0
		Segment 1 is opened when the water level upstream of the weir is +93.7 and closed at an elevation of +93.5
		Segment 2 is opened when the water level upstream of the weir is +95 and closed at an elevation of +93.7
2	Tirtonadi Floodgate	2 sluice gate are opened when the water level upstream of the weir is +92.5 and closed at an elevation of +92
3	Old Demangan Floodgate	10 gate are opened simultaneously if the downstream elevation is 0.1 m lower and closed if the downstream elevation is 0.1 m higher
4	Old Demangan Pump	The pump with a capacity of 1 m^3/dt of 3 units and a capacity of 3 m^3/dt of 3 units is activated when the elevation of the water surface upstream of the sluice is at +84.50 and is turned off when the elevation of the water surface upstream of the sluice gate is + 84.00
5	New Demangan Floodgate	3 Doors are opened simultaneously if the downstream elevation is 0.1 m lower and closed if the downstream elevation is 0.1 m higher
6	New Demangan Pump	Pump with a capacity of 2.5 m^3/dt of 5 units is activated when the elevation of the water surface upstream of the sluice at +84.50 and turned off when the elevation of the water surface upstream of the sluice is + 84.00

In this simulation, it is reviewed on the handling conditions of Kali Pepe with flood discharge conditions of Q25 and several alternative operating patterns of floodgates and pumps.

Table 4. Alternative Sluice and Pump Operation Pattern

OPERATION	FLOODGATE			PUMP		POMPA
PATTERN	TIRTONADI	OLD DEMANGAN	NEW DEMANGAN	1 m^3/s	3 m^3/s	2.5 m^3/s
ALT 1	CLOSE	OPEN	OPEN	OFF	OFF	OFF
ALT 2	OPEN	OPEN	OPEN	OFF	OFF	OFF
ALT 3	OPEN	OPEN	CLOSE	OFF	OFF	ON 2 UNIT
ALT 4	OPEN	OPEN	CLOSE	OFF	OFF	ON 5 UNIT
ALT 5	OPEN	OPEN	CLOSE	ON 1 UNIT	OFF	ON 2 UNIT
ALT 6	OPEN	OPEN	CLOSE	ON 3 UNIT	OFF	ON 5 UNIT
ALT 7	OPEN	OPEN	CLOSE	OFF	ON 3 UNIT	ON 5 UNIT
ALT 8	OPEN	OPEN	CLOSE	ON 3 UNIT	ON 3 UNIT	ON 2 UNIT
ALT 9	OPEN	OPEN	CLOSE	ON 3 UNIT	ON 3 UNIT	ON 5 UNIT

This modeling scenario is modeling the handling conditions with the operation of Sluices and pumps integrated at the Tirtonadi Weir Sluice Gate, Old Demangan Sluice Gate, and New Demangan Sluice Gate with planned flood discharge conditions Q2, Q5, Q10, and Q25. The following is a description of the results of 1D modeling in Q25 conditions.

Table 5. Alternative Sluice and Pump Operation Pattern

DESIGN	OPERATION	WATER LEVEL ELEVATION			DESCRIPTION
DISCHARGE (m^3/sec)	PATTERN	OLD DEMANGAN	NEW DEMANGAN	BENGAWAN SOLO	
Q25	ALT 6	+ 88.26	+ 86.38	+ 87.19	Overtopping
	ALT 7	+ 86.79	+ 86.78	+ 87.19	Overtopping
	ALT 8	+ 86.85	+ 87.09	+ 87.19	Safe
	ALT 9	+ 86.74	+ 86.32	+ 87.19	Safe

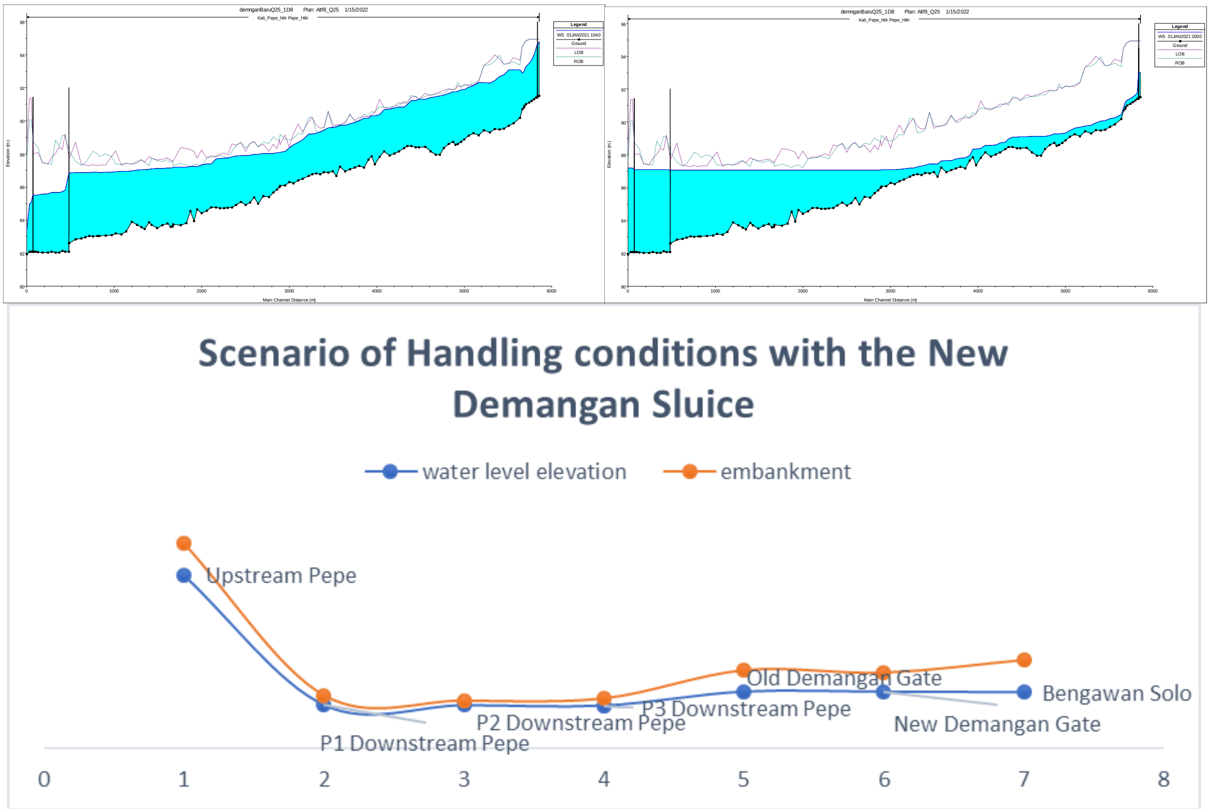

Figure 8. Results of Handling Condition Modeling with alternative 8

There is no overtopping in the Kali Pepe Upstream, Kali Anyar, and Kali Pepe Downstream with Alternative 8. The operating pattern in alternative 8 is carried out by opening the Tirtonadi Weir floodgate if the water level elevation at the upstream sluice reaches +93.10 and is closed at +93.00 elevation. while the floodgates at Old Demangan only opened 4 floodgates. Meanwhile, the floodgates at the New Demangan Sluice Gate were completely closed to prevent backwater from the Bengawan Solo river. Pump operation is carried out by activating the pump at the Old Demangan Sluice with a capacity of 3 m^3/sec as many as 3 units activated at an elevation of +87.00 for 6 hours and deactivated at an elevation of +86.00 and 1 m^3/sec as many as 3 units activated at an elevation of +86.00 for 18 hours and disabled at +85.00 elevation. Meanwhile, at the New Demangan Sluice, the pump with a capacity of 2.5 m^3/sec is activated for 2 units at an elevation of +84.00 for 14 hours and is deactivated at an elevation of +83.00. The results obtained are the water level elevation at the Old Demangan sluice gate, which is +86.85 and the water level at the New Demangan sluice gate which is +87.09, with the floodwater level at the Bengawan Solo River which is +87.19.

5. Conclusion and Suggestions

5.1. Conclusion

in the existing condition of flooding at Kali Pepe Downstream due to the non-maximum function of the Old Demangan Sluice Gate in flood control which is only able to be opened as many as 4 sluice gates out of a total capacity of 10 gates due to the age of the sluice gate structure which is old and it is feared that there will be structural failure if it is open. When there is a flood, it is necessary to build a New Demangan floodgate for flood control in the Kali Pepe Downstream. while in the handling conditions, the optimal and effective integrated pattern of sluice and pump operation is obtained is Alternative 8 by opening a total of 3 Tirtonadi floodgates, opening 4 old water gates and activating all pumps with a total capacity of 12 m^3/sec, closing the total new demangan sluice gate and activate 2 pump units with a total capacity of 5 m^3/sec, so that the difference in water level between Bengawan Solo River and Downstream Pepe River is not too large and stable in flood control.

5.2. Suggestion

Based on the results of this study on flood control in Surakarta City, especially in Kali Pepe Downstream, it is expected that the pattern of sluice and pump operation at Kali Pepe Downstream is integrated with all existing sluice gates along Kali Pepe in accordance with alternative 8 in the design flood discharge conditions of Q25. In addition, at the Downstream Pepe River, the section between the Old Demangan Sluice gate and the New Demangan Sluice gate, it is necessary to strengthen the cliffs in the form of revetments so that the condition of the right and left sides of the river remains stable and also needs to be used as a sediment catcher on this section to make routine maintenance easier.

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