Proceedings of the 4th ITB Graduate School Conference
Innovation and Discovery for Sustainability
July 6, 2023

Regional Hydraulic Geometry of Banger River Related to Sediment Prediction and River Morphology Stability

Sandhi Akhmad Juliadi[1,*], Indratmo Soekarno[2], Eka Oktariyanto Nugroho[2] & Widyaningtias[2]

[1]Master Study Program of Water Resources Management, Civil Engineering Study Program, Faculty of Civil and Environmental Engineering, Bandung Institute of Technology, Jalan Ganesa 10, Bandung 40132, Indonesia
[2]Water Resources Engineering Research Group, Civil Engineering Study Program, Faculty of Civil Engineering and Environmental, Bandung Institute of Technology, Jalan Ganesa 10, Bandung 40132, Indonesia
[*]Email: sandhi.akhmad@pu.go.id

Abstract. Pekalongan City is located in the lowlands which has a very gentle slope of the land surface. In some northern areas, most of the land surface is below sea level, making it difficult for water to flow into the sea because it is held back by water from the sea (rob). In this paper an analysis will be carried out regarding the distribution of floods and see how the regional hydraulic geometry occurs in the Banger River. Furthermore, this research aims to examine the conditions of sediment transport and the stability of river morphology that occur in the Banger River. Flood modeling and sediment transport analysis in this study were conducted using HEC-RAS software. The results of this research indicate that during a 2-year return period flood, approximately 400.14 hectares of area, mainly in downstream areas will be inundated due to the river's morphological instability related to its width, depth, and slope. This study is highly valuable because the stability of the river regime, which may contribute to flood occurrences, is often overlooked in river management planning.

Keywords: *banger; flood; morphology; geometry; sediment.*

1 Introduction

Pekalongan City is one of the cities with a strong economic growth in Central Java Province. The location of Pekalongan City is in the orbit between 6°50'44" 6°55'44" South Latitude and 109°37'55"- 109°42'19" East Longitude. Topographically, the northern area of Pekalongan City is in the lowlands which has a very gentle slope. Floods and tidal inundation are still a problem in Pekalongan City, especially for residents who live in the North Pekalongan District, such as Kandang Panjang Village, Panjang Wetan Village, Krapyak, to Degayu Village. These areas often experience tidal inundation, because their location is around the mouth of the Kupang River (Kali Loji) and the Banger River.

Based on the watershed boundaries released by Ina-Geoportal [1], there are three watersheds that influence Pekalongan City, namely the Sengkarang Watershed, Kupang Watershed and Susukan Watershed. The extent of influence of each watershed in Pekalongan City can be seen in the following Figure 1.

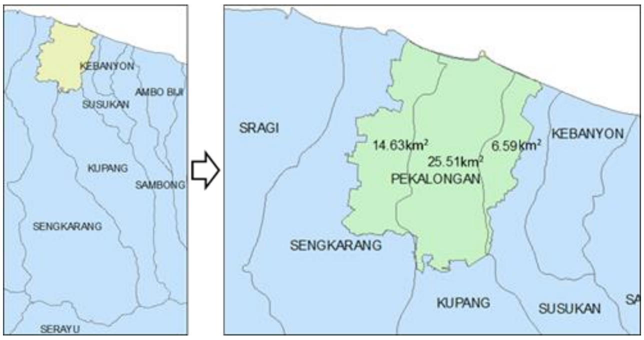
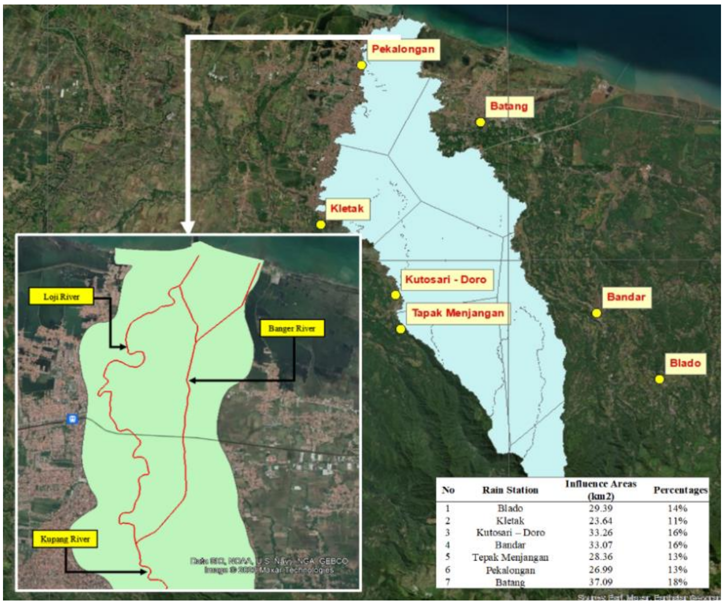


Figure 1 Research sites.

Referring to Figure 1 above, it can be seen that most of Pekalongan City is influenced by the Kupang Watershed, which is 25.51 km^2 or around 55% of the total area of Pekalongan City. The Kupang watershed has 3 main rivers, namely the Kupang River in the upstream area and in the downstream area there are the Loji River and the Banger River. The main river system and the distribution of rainfall stations in the Kupang Watershed can be seen in Figure 2.



No	Rain Station	Influence Areas (km2)	Percentages
1	Blado	29.39	14%
2	Kletak	23.64	11%
3	Kutosari – Doro	33.26	16%
4	Bandar	33.07	16%
5	Tepak Menjangan	28.36	13%
6	Pekalongan	26.99	13%
7	Batang	37.09	18%

Figure 2 River system of Kupang Watershed.

The management of floods and robs is a big hope for the people of Pekalongan City, especially those who live in the north Pekalongan district which has been affected by floods and robs for more than 12 years.

The current velocity decreased by around 0,05 m/s and the wave height increased by around 0,05 meters to 0,15 meters after land subsidence occurred [2]. Based on previous studies, the river estuary in Pekalongan City cannot be accommodated using HEC-RAS software due to its inability to account for flocculation phenomenon [3].

Therefore, the aim of this study is to describing the relationship between the morphological stability and sediment transport in the Banger River and the occurrence of the flood. The calculation of morphological stability and sediment transport is carried out by considering the influence of tides and river flow from the upstream. Due to data limitations, the study only examines about 7 kilometers in the downstream of the Kupang Watershade.

2 Materials & methods

The outputs from this research involve examining flood distribution and changes in the riverbed using the HEC-RAS software. Additionally, this study explores the stability of the river morphology in Sungai Banger, which can be utilized as input for flood control planning in Sungai Banger. Currently, flood control planning rarely incorporates calculations of river morphology stability.

The secondary data used in conducting this research are river cross-section measurement data, rain data, tide data and Digital Elevation Model (DEM) data from DEMNAS. The boundary conditions used in the modeling are the flood hydrograph for the upstream area and the tidal height for the downstream area.

2.1 Hydrological Analysis

Hydrological analysis is used to predict incoming water discharge at certain return periods [4]. The secondary data required for hydrological analysis is rainfall data. Rainfall data is used to obtain planned rainfall with a certain return period through frequency analysis.

After the planned rainfall is obtained, the next step is to calculate the amount of water discharge that enters the river using a synthetic unit hydrograph. There are several synthetic unit hydrograph methods commonly used in Indonesia, including the Snyder-SCS, Snyder-Alexeyev, Nakayasu, Gama-1, HSS-$\alpha\beta\gamma$, and Limantara methods [5]. The SCS-CN method is usually used to calculate runoff by considering several variables such as land use, initial abstraction, impervious, and lag time.

Curve Number (CN) is a hydrological model parameter developed by the Soil Conservation Service which describes the physical condition of a watershed with a value of 1 – 100 [6],[7]. The CN value ranges from 0-100 depending on the Hydrologic Soil Group (HSG), land use and Antecedent Moisture Condition (AMC). For watersheds larger than 15 km^2 this method can be applied by weighting the curve number associated with land use/land cover in the watershed or what is commonly called the Curve Number Composite (CN composite) [8]. The CN composite equation can be seen in equation 1.

$$CNcomposite = \frac{\sum(CN_i\ x\ A_i)}{A} \tag{1}$$

The initial abstraction (Ia) is a representation of all losses (Losses) prior to runoff and is given by empirical equations [9]. Initial Abstracion (Ia) can be obtained by using equation 2.

$$I_a = 0{,}2\ S \tag{2}$$

Where S is the maximum retention potential can be seen in equation 3.

$$S = \frac{1000}{CN} - 10 \tag{3}$$

The above formula is applied to the British metric system (S in inches). To make it the International Standard or SI units (S in mm), the formula should be used as equation 4

$$S = \frac{25400}{CN} - 254 \tag{4}$$

The equation for determining the size of the time lag parameter is shown by the equation 5.

$$t_p = C_1 C_t (LL_C)^{0.3} \tag{5}$$

Where tp is the time lag, L is the longest flow path of the basin in km, and Lc is the flow path from the centroid of the basin to the outlet in km. C1 is a constant related to the system of units used and Ct is a time constant related to the characteristics of a basin [10].

To verify the validity of the planned flood hydrograph that has been calculated, it is necessary to calibrate it with data from observations. The calibration process in this study was carried out by comparing the planned flood discharge with the flow discharge from the Automatic Water Level Recorder (AWLR).

2.2 Hydraulics Analysis

Hydraulics analysis was carried out to determine the capacity of the canal by taking into account the hydraulic properties that occur in the watershed [4]. In this study the hydraulics analysis was carried out using the 2 dimensional HEC-RAS software. Mapping a 2-Dimensional flood model is very useful to identify areas that are potentially affected by flooding [11].

The HEC-RAS software has four types of modeling, namely: (1) Steady flow simulation; (2) Unsteady flow simulation; (3) Simulation of sediment transport; and (4) Water quality simulation. The laws of physics governing the simulation of unsteady flow in a river are the principle of conservation of mass (continuity) and the principle of conservation of momentum [12]. The continuity equation can be seen in equation 6.

$$\frac{\partial A_T}{\partial t} + \frac{\partial Q}{\partial x} = q_t \tag{6}$$

$\frac{\partial A_T}{\partial t}$	=	the rate of change of the cross-sectional area with respect to time. It indicates how the area is changing over time
$\frac{\partial Q}{\partial x}$	=	the rate of change of the discharge with respect to position. It describes how the flow is changing along the channel
q_t	=	Lateral inflow per unit length

While the momentum equation can be seen in equation 7.

$$\frac{\partial Q}{\partial t} + \frac{\partial (Q\,V)}{\partial x} + g\,A\left(\frac{\partial Z_s}{\partial x} + S_f\right) = 0 \tag{7}$$

$\frac{\partial Q}{\partial t}$	=	the rate of change of the cross-sectional area with respect to time. It indicates how the area is changing over time
$\frac{\partial (Q\,V)}{\partial x}$	=	the rate of change of the discharge with respect to position. It describes how the flow is changing along the channel
gA	=	Lateral inflow per unit length
$\frac{\partial Z_s}{\partial x}$	=	Rate of change of the channel bottom elevation (Zs) with respect to position (x). It represents the slope of the channel bottom

S_f	=	he friction slope, which is a measure of the energy loss due to friction between the flowing fluid and the channel walls

The results of this hydraulic analysis are used to validate the bankfull analysis based on the available discharge data and Manning's coefficient.

2.3 Sediment Transport Analysis

The analysis was carried out with the aim of knowing the stability of the river bed in the vertical direction (degradation/agradation). The analysis was carried out using HEC-RAS (quasi unsteady) with the main input data, namely: cross section of the river, daily discharge data, and sediment data. The sediment equation is calculated using the Meyer Peter Muller (MPM) formula as follows [12]:

$$\left(\frac{k_r}{k'_r}\right)^{\frac{3}{2}} \gamma RS = 0.047(\gamma_s - \gamma)d_m + 0.25\left(\frac{\gamma}{g}\right)^{\frac{1}{3}}\left(\frac{\gamma_s-\gamma}{\gamma_s}\right) {g_s}^{\frac{2}{3}} \quad (8)$$

gs	=	Sediment transport rate
cr	=	Roughness coefficient
k'r	=	Coefficient of grain roughness
γ	=	Specific gravity of water
γs	=	Sediment specific gravity
g	=	Gravity acceleration
dm	=	Particle diameter (median)
R	=	Hydraulic spokes
S	=	Energy gradient

2.4 River Morphology Stability

The stability of the river geometry is analyzed by observing the width of the upstream and downstream sections, depth of flow, and bed slope of the river.

2.4.1 Regional Hydraulic Geometry

Regional Hydraulic Geometry is the study of the relationship between the geometric dimensions of a river or canal and its hydraulic characteristics within a given geographical area. This involves measuring and analyzing physical data from rivers or canals at various locations to identify consistent patterns in the relationship between channel width, depth, flow velocity, and other hydraulic parameters.

Wharton (1995) suggested the following guideline for developing and applying the channel-geometry method [13].

(1) Selecting reaches for measuring river channel geometry.
(2) Selecting cross-sections

(3) Measuring river channel dimensions
(4) Computing flood discharges.

The relationship between discharge and river width can be seen in the two empirical equations as showed in Table 1 [14],[15].

Table 1 Channel geometry relations.

Country/ Authors	Streams	Relation	Notation
Canada			
Bray (1975)	Gravel bed rivers in Alberta	$w_b = 4.75Q_2{}^{0.527}$	wb = channel width at the bankfull level (m)
Great Britain			
Nixon (1959)	Rivers in England and Wales	$w_b = 1.65Q_b{}^{0.50}$	

also, Leopold and Miller (1956) found an equation that relates the slope of the river and the width of the river as follows [16].

$$S = 0.12\, w^{-0.5}$$

2.4.2 Regime Theory

In hydraulics, a regime channel is neither scoured or filled. A regime channel can be understood to be a channel in which amount of scour is equal to the amount of fill and is in dynamic equilibrium or stable condition. In this analysis, it is necessary to input flow discharge from hydrological analysis and sediment grain diameter (d50). The method used in analyzing the stability of the river geometry showed in Table 2 [17]:

Table 2 River geometry stability methods.

No	Theory	Equation			Note
		Width(w)	Depth (d)	Slopes (S)	
1	Lacey	$3.6\,(Q^{0.42})$	$0.28\,(Q^{0.42})$	$\frac{fs^{(\frac{3}{5})}}{1.79\,(Q^{\frac{1}{6}})}$	$fs = (2500\,D)^{0.5}$
2	Blench	$\left(\frac{FB\,.\,Q}{FS}\right)^{0.5}$	$\left(\frac{FS\,.\,Q}{FB^2}\right)^{1/3}$	$\frac{FB^{5/6}FS^{1/12}Q^{-1/6}}{k}$	$K = 3.63\, g/v^{1/4}$ (v: kinematic viscosity); K = 2080 for v = 10-5 $FB = 2\sqrt{D}$

No	Theory	Equation			Note
		Width(w)	Depth (d)	Slopes (S)	
					D = Bed material diameter (mm) FS= 0.3 (glacial till material, tough clay banks), 0.2 (silty sand-loam material, or silty, clay, and loam banks), 0.1 (little cohesion or friable banks), 0.05 (sand sides of river below tide level)
3	Generalized Regimes	0.9P	1.73r	$\left(\frac{n_m Q}{1.486\, AR^{2/3}}\right)^2$	$P = 2.12\ (Q^{0.512})$ $R = 0.51(Q^{0.631})$
4	Process-Based Regimes	$Q^{0.548}D^{-0.0235}$	$Q^{0.384}D^{-0.1276}$	$\frac{fm^{5/3}}{(1.83\ Q^{1/6})}$	$fm = \sqrt{fRS\ .\ fys}$ $fys = 0.75\frac{v^2}{d}$ $fRS = 192\ d^{1/3}S^{2/3}$
5	Kellerhals	$1.8\sqrt{Q}$	$0.166(Q^{0.4})(ks^{-0.12})$	$0.12(Q^{-0.4})(ks^{0.92})$	ks = D50 (equivalent grain size toughness)
6	Griffiths	$7.09\ (Q^{0.48})$	$0.21\ (Q^{0.43})$	$0.02\ (Q^{-0.49})$	
7	Hey & Thorne	$3.67\ (Q^{0.45})$	$0.22\ (Q^{0.37})(D_{50}{}^{-0.11})$	$0.008(Q^{-0.31})(D_{50}{}^{0.71})$	

3 Results and discussion

3.1 Hydrological Analysis

The watershed used in this study is the Kupang watershed, which contains the Banger River. The size of the Kupang watershed is 211.80 km^2. Furthermore, to obtain the design discharge flowing in the Banger River, the analysis of the planned flood discharge is carried out using the rainfall-runoff relationship approach using rainfall data. The collection and determination of rain data is based on the distribution of rainfall stations around the Kupang watershed. The distribution of rain posts and their effects can be seen in Figure 2.

Analysis of the planned rainfall at the research location used data from 6 rain stations located around the Kupang watershed, namely the Blado Rain Station, Kletak Rain Station, Kutosari – Doro Rain Post, Bandar Rain Post, Tapak Menjangan Rain Post, Pekalongan Rain Station, and Batang Rain Pos. Regional rainfall is obtained using the Thiessen Polygon method by weighing each area of influence of the rain post.

The results of the planned rainfall calculations with several return periods can be seen in Table 3 below.

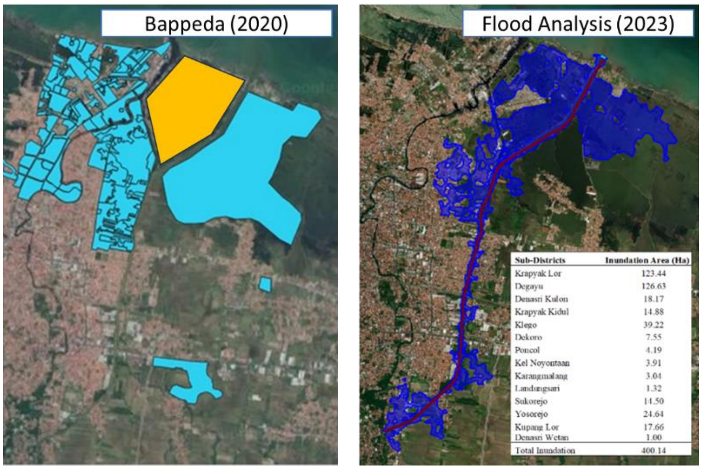
Table 3 Frequency analysis of rainfall for several return period on each method.

Return Periods	Frequency Analysis of Planned Rainfall (mm/day)		
	Normal	**Gumbel**	**Pearson III logs**
TR 02	141.07	136.27	135.67
TR 05	170.03	182.46	169.55
TR 10	185.19	213.04	191.62
TR 25	197.60	251.67	219.29
TR 50	211.73	280.33	239.80
tr 100	221.38	308.79	260.33

The next step after obtaining the amount of effective rainfall is to calculate the amount of discharge plan. The design discharge is calculated using the HSS SCS because the calculation involves watershed condition parameters by using a 2-year return period. The result of the 2-year return period flood discharge obtained using the HSS SCS method in the Kupang watershed is 330,9 m3/s.

3.2 Hydraulics Analysis

The flood discharge used in the hydraulic analysis is a flood discharge with a return period of 2 years to describe bankfull conditions. The boundary conditions used are flow hydrograph for the upstream and stage hydrograph for the downstream. Flow hydrograph is used as the upstream boundary to estimate the floods caused by a specific discharge. Meanwhile, for the downstream boundary, a stage hydrograph is used because the downstream of the river is influenced by tides. The tidal data used in this study are the tides observed for 33 days from 01 May 2018 to 02 June 2018. The results of the flood inundation modeling for existing conditions in the 2-year return period In comparison to the flood inundation report from Regional Planning Agency (Bappeda) of Pekalongan City in 2020 [18] can be seen in Figure 3 below.



Figures 3 Comparison between Bappeda's flood inundation (2020) and flood analysis (2023) with a 2-year return period of discharge.

The difference in results is caused by the analysis of flood inundation conducted by the Regional Development Planning Agency (Bappeda) in the downstream area of Krapyak Lor sub-district (indicated by the color yellow) is considered as a lowland and not considered as flood inundation. Furthermore, the results of this hydraulic analysis are used as a basis for conducting sediment transport analysis and river morphology analysis.

3.3 Sediment Transport Analysis

Riverbed stability analysis is carried out to determine the potential for riverbed changes (agradation or degradation) in the future. One of the important parameters in the analysis of the river bed is the sediment gradation and daily discharge from the results of the previous hydrological analysis. The analysis was carried out using one-dimensional HEC-RAS (1D) with the results of the analysis shown in Figure 4. From the results of the analysis it can be seen that the Banger River has changed in the riverbed as circled in red below.

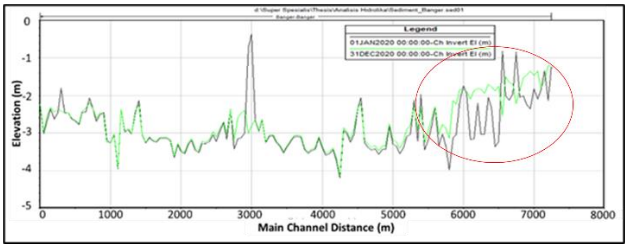


Figure 4 Result of sediment transport for riverbed analysis.

3.4 River Morphology Stability

In analyzing the stability of the geometry, the river is divided into 3 sections, namely the downstream (S1), middle stream (S2) and upstream (S3). The division of river sections along with the slope of each segment can be seen in figure 5.

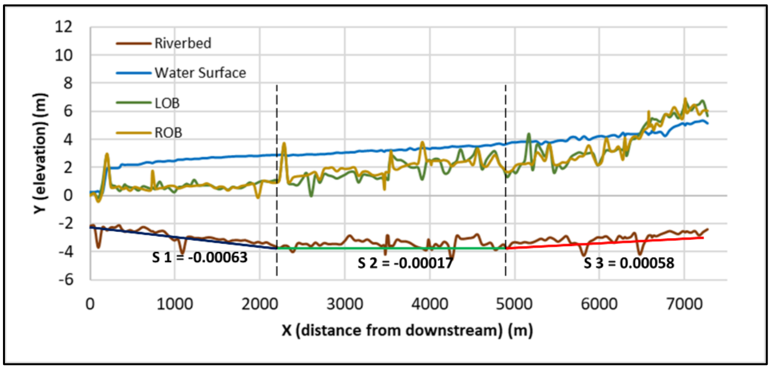


Figure 5 Banger River section.

The Figure 5 shows a longitudinal section of the Banger River from downstream to upstream, consisting of the water surface, riverbed, left over bank (LoB), and right over bank (RoB).

Although the river section is divided into three segments, the conclusions drawn are based solely on the analysis results of the upstream and middle segments. This decision was made because the downstream segment is influenced by cohesive factors and flocculation phenomenon that were not addressed in this study.

3.4.1 Regional Hydraulic Geometry Analysis

There are two calculations for Regional Hydraulic Geometry (RHG) analysis, namely the calculation of the river width using the Bray method (1975) and the calculation of the slope of the river using the Leopold and Miller method (1956). The results of these calculations can be seen in the Table 4 and Table 5 as follows.

Table 4 Comparison of regional hydraulic geometry calculation results with actual conditions.

River Section	w (RHG)	w actual
Upstream	64,43 m	51,23 m
Middle	64,37 m	49,79 m
Downstream	70,70 m	114,29 m

Table 5 Comparison of the slope of the river calculated by regional hydraulic geometry with actual conditions.

River Section	S (RHG)	S actual
Upstream	0.0083	0.0006
Middle	0.0069	-0.0002
Downstream	0.0062	-0.0006

Based on the results above, it can be seen that the width of the river is in the range of around 60 m - 70 m, so that in the upstream area it is necessary to widen the river while in the downstream area it is necessary to narrow the river. Meanwhile, if we seen from the slope of the river, based on regional hydraulic calculations from upstream to downstream, it is necessary to increase the slope of the river.

3.4.2 Regime Theory

In this section, we will discuss the analysis of geometric stability based on regime theory. The stability of the river geometry is calculated from upstream to downstream using 7 methods as described in table 2. The method used as a reference is the method with the smallest error. Based on the obtained results, the method that used as a reference is the Generalized regime method for the width dimension, the Lacey method for the depth dimension, and the Blench method for the slope dimension. The unstable dimensional and slope cross-sectional can be seen in Figures 6-8.

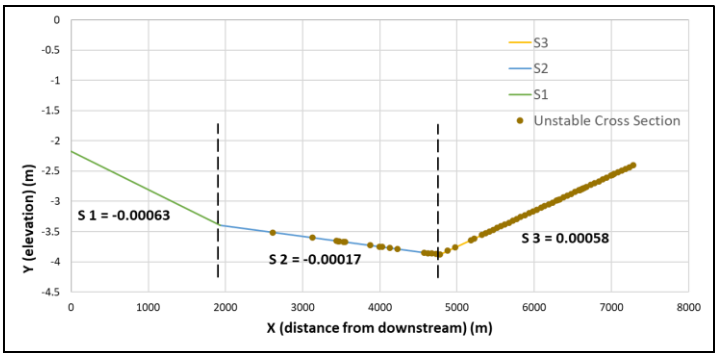


Figure 6 Cross section with stability width dimension

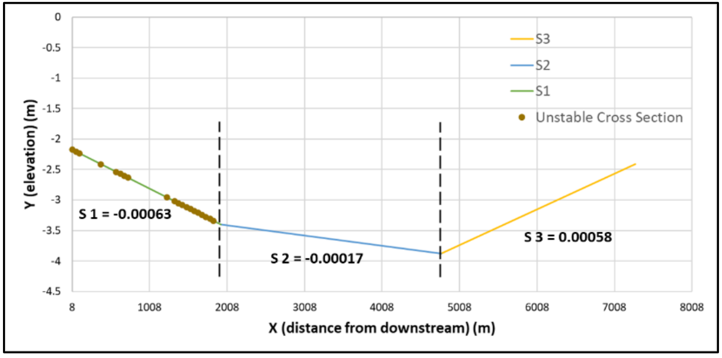


Figure 7 Cross section with stability depth dimension.

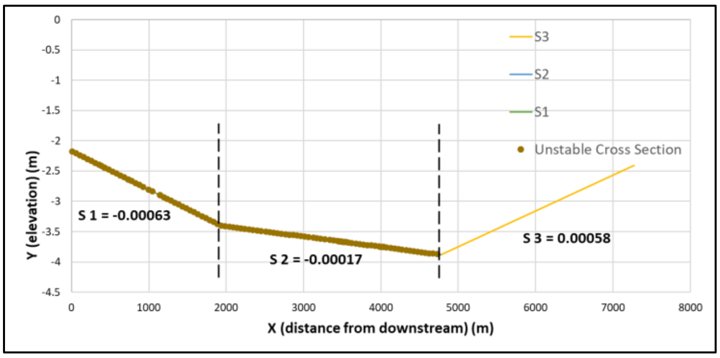


Figure 8 Cross section with stability bed slope.

The stability analysis above resulted in the conclusion that there are 67 river sections that are unstable in width, 20 river sections that are unstable in depth and 105 river sections that are unstable in slope. So it can be concluded that from Sta 47+50 to Sta 72+50 river widening needs to be carried out, from Sta 0+00 to Sta 18+50 the river depth needs to be increased, and from Sta 0+00 to Sta 47+00 the slope of the river needs to be steepened.

4 Conclusions

The results of flood simulation using HEC-RAS software indicate that the overflow from Sungai Banger will still inundate a significant portion of the Pekalongan area, around 400.14 hectares, with a 2-year return period. The conclusions drawn in this study are based only on the middle and upper reaches of the river, as the downstream area is influenced by cohesive factors and flocculation phenomenon. From a regional hydraulic geometry perspective, it can be observed that in the upstream area, river expansion of approximately 13 meters is required and in the middle area, river narrowing of about 15 meters is needed in consideration of the difference in the results of the Regional Hydraulic

Geometry Analysis calculation compared to its existing condition. Furthermore, considering the river slope, based on regional hydraulic calculations from upstream to downstream, an increase in river slope is required to enhance sediment transport towards the sea. This is supported by the calculation of river morphology stability based on regime theory and sediment transport analysis, which reveals that there are 67 cross-sections unstable in terms of width in the middle to upper reaches and 64 cross-sections unstable in terms of slope in the middle section.

For better results, it is advisable to conduct further research taking into account cohesive factors and flocculation phenomenon in the downstream area.

Acknowledgement

This research was made possible with the financial support from the Ministry of Public Works and Housing and guided by the Water Resources Engineering Research Group, Faculty of Civil Engineering and Environmental, Bandung Institute of Technology.

References

[1] Geospatial Information Agency (*Badan Informasi Geospasial*), https://tanahair.indonesia.go.id

[2] Martin, R.J., Kurniawan, A., Nugroho, E.O., Wijaya, F.S., Muhammad, I.F., Yola, *The effect of land subsidence on hydrodynamic conditions in Pekalongan coast*, IOP Conference Series: Earth and Environmental Science. 2022;1065(1):012009. doi: 10.1088/1755-1315/1065/1/012009

[3] Lutfitiana, P, Ramadhani, R.P., Cahyono, M., Nugroho, E.O., Kumala, Y.E. and Lestari, S., *Study of Loji Riverbed Change in Pekalongan City*, The Fourth International Conference on Sustainable Infrastructure and Built Environment: Sustainable Infrastructure and Built Environment - Challenges on Sustainable and Resilient Infrastructure and Built Environment, **4**, pp. 558-566, Mar 2022. http://sibe.itb.ac.id/wp-content/uploads/SIBE22-558.pdf

[4] Harjono & Widhisatuti, Y., Hydrology and Hydraulics Analysis of the Kalo Pacal Watershed (DAS) in Bojonegoro, Rekayasa Sipil, **13**(1), pp. 16-23, 2019.

[5] Natakusumah, D., Hatmoko, W., Harlan, D., General procedures for calculating synthetic unit hydrographs using the ITB method and some examples of their application, Jurnal Teknik Sipil, **18**(3), pp. 251-291, Dec 2011.

[6] Ramadan, A.N.A, Nurmayadi, D., Sadili, A., Solihin, R.R., Sumardi, Z., Study of Determining the Curve Number Value of the Pataruman

Watershed based on Indonesian Land Map Units, Media Komunikasi Teknik Sipil, **26**(2), pp. 258-266, 2020.

[7] USDA-SCS, Part 630 hydrology national engineering handbook chapter 10 estimation of direct runoff from storm rainfall, National Engineering Handbook, 1972.

[8] Matomela, N., Tianxin, L., Morahanye, L., Bishoge, O.K., Ikhumben, H.O., Rainfall-runoff estimation of Bojiang lake watershed using SCS-CN model coupled with GIS for watershed management, Phoenix Research Publishers, **4**(1), pp. 16-24, Jan.2019. http://dx.doi.org/10.21839/jaar.2019.v4i1.263

[9] Jesus, JD & Cho, Y., Estimate Surface Runoff Using SCS-CN Method With GIS Application: A Case Study at Laclo River Watershed, Manatuto Timor Leste, Submitted for publication.

[10] Deviana, A., Kridasantausa, I., Suryadi, Y., Spatial Flood Modeling Study to Support River Boundary Policy and Regional Spatial Planning (Case Study of Baleendah Development Area), Doctoral dissertation, Faculty of Civil and Environmental Engineering, Bandung Institute of Technology, Bandung, 2011.

[11] Formanek, R., Silasari, R., Kusuma, M.S.B., Kardhana, H., Two-dmensional Model of Ciliwung River Flood in DKI Jakarta for Development of Regional Flood Index Map, Journal of Engineering and Technological Sciences, **45**(3), pp. 307 – 325, 2013.

[12] HEC-RAS Manual, https://www.hec.usage.army.mil/

[13] Wharton, G., Arnell, N.W., Gregory, K.J., Gurnell, A.M., River discharge estimated from river channel dimensions, Journal of Hydrology, vol 106, pp. 365-376, 1989.

[14] Bray, D.I., Representative discharge for gravel -bed rivers in Alberta, Canada, Journal of Hydrology, **27**, pp. 143 – 153, 1975.

[15] Nixon, M, A study of bankfull discharges of rivers in England and Wales, Proceedings of Institution of Engineers, **12**(2), pp. 157-174, 1959.

[16] Leopold, L. and Miller, J, Ephemeral stream: Hydraulic factors and their relation to the drainage net, USGS Professional Paper 282-A, pp.37, 1956.

[17] Singh,V.P., Handbook of Hydraulic Geometry: Theories and advances, first edition, Cambridge University Press, 2022.

[18] Final Report on the Preparation of the Revision of the Drainage Masterplan for Pekalongan City, Regional Development Planning Agency (Bappeda) of Pekalongan City, 2020.