Journal of Engineering and Sustainable Development
Vol. 28, No. 06, November 2024
https://jeasd.uomustansiriyah.edu.iq/index.php/jeasd
ISSN 2520-0917
Research Article
https://doi.org/10.31272/jeasd.28.6.3

Hydraulic Modeling-Based Design of Retaining Wall Height for Flood Mitigation

Yuliastuti Juliastuti[1*], Yureana Wijayanti[2], Mohamad Fajar[3], Martin Anda[4]

[1,3]Civil Engineering Department, Faculty of Engineering, Bina Nusantara University, Jakarta, 11480, Indonesia
[2]Waste Food Environmental Nexus Research Interest Group, Bina Nusantara University, Jakarta, 11480, Indonesia
[4]Environmental Engineering, Engineering and Energy, Murdoch University, Australia

[1] https://orcid.org/0000-0001-5994-1890
[2] https://orcid.org/0000-0002-9341-9681
[3] https://orcid.org/0009-0007-8510-0666
[4] https://orcid.org/0000-0001-7398-4192
*Email: juliastuti@binus.ac.id

Article Info

Received	20/06/2024
Revised	08/09/2024
Accepted	17/09/2024

Abstract

The Bekasi River in Jakarta, Indonesia, faces significant flood risks due to high rainfall intensity, extensive urban development, and climate change. This paper aims to reduce the impact of floods by implementing efficient flood management measures, such as constructing retaining walls along the river. The appropriate height and stability of retaining walls were determined by conducting hydrological and hydraulic analyses using HEC-HMS and HEC-RAS, respectively, accounting for maximum rainfall and flood discharge levels. The results showed that the rainfall intensity in the Bekasi watershed with a return period of 2 years obtained a designed rainfall of 132 mm/hour using the Log Pearson III distribution, the maximum flood discharge for the return period Q_{50} is 1155 m^3/second, the retaining wall design dimensions will be obtained 3-meter height with cross-section slope 0.002. Results indicated that almost all river channels overflow except near the Bekasi Dam, necessitating riverbank restoration and increased channel capacity. The paper highlights the need for reinforced retaining walls to protect the riverbank and improve flood resilience.

Keywords: Flood resilience, Hydrology, Modelling, Retaining wall, Riverbank

1. Introduction

Urban flooding, particularly in cities such as Jakarta, is exacerbated by high rainfall intensity and the increasing impermeability of urban landscapes [1]. This impermeability is often due to extensive urban development, which reduces green space, thereby limiting the natural drainage capacity of the land [2],[3]. In addition, Jakarta's relatively even terrain and proximity to the coast also enhance its susceptibility to flooding. Flat topography hinders the adequate flow of rivers, resulting in frequent flooding [4]. Furthermore, coastal areas experience backwater effects at high tides, which increase the risk of flooding when rivers overflow into the ocean [5].

Climate change exacerbates the frequency and intensity of flooding. Global temperatures have increased rainfall intensity and frequent extreme weather events [6]. Urban areas are greatly affected by this shift in climate patterns because it strains current drainage systems and leads to more runoff because of increased precipitation levels. The relationship between climate change and urban expansion creates a complicated problem for flood management [7].

Consequently, the occurrence of floods in urban settings is greatly affected by various factors related to the urban catchment region, such as use, surface permeability, drainage infrastructure, and meteorological conditions [8],[9].To address these issues, it is necessary to implement efficient flood management systems that can address both natural and human-induced variables. A practical approach is to build retaining walls along rivers susceptible to floods [10],[11]. Retaining walls are purpose-built structures engineered to withstand the force of water and prevent metropolitan areas from flooding. They serve as crucial components in flood control systems by acting as barriers to water and protecting the surrounding surroundings.

The size of the flood-controlled retaining walls was calculated using hydrological and hydraulic analyses to ascertain the maximum levels of rainfall and flood discharge. Flood elevation maps were generated using previously described levels [12]-[14]. The appropriate height of the retaining wall was determined based on these analyses [15],[16]. Furthermore, the stability of the retaining wall was evaluated by analyzing its capacity to withstand rolling and shearing pressures, considering safety issues, and assessing its economic feasibility [17],[18].

Various approaches can be employed in hydrological and hydraulic analyses; however, these analyses must adhere to the standard codes for flood discharge planning. Frequency analysis is a commonly used method [19],[20]. This approach analyzes the rainfall patterns in a region to predict the maximum rainfall for a specific return period based on the probability of occurrence [21]. The chosen method for analyzing the maximum flood discharge depends on the available data. When debit measurement data in a watershed are lacking, the synthetic-unit hydrograph method is often used [22]. This method converts rainfall data into direct runoff discharge data by leveraging watershed characteristics[23],[24].

2. Material and Method

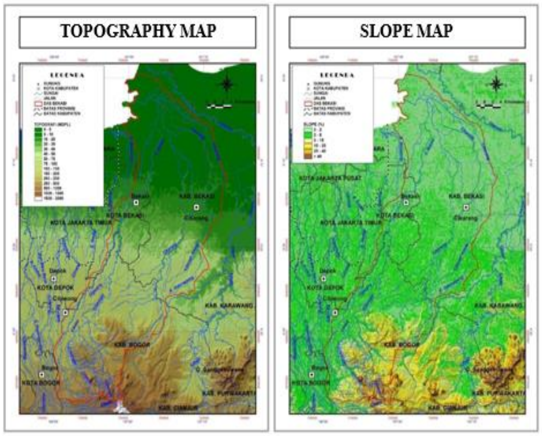
2.1. Study Area

This study was conducted on the Bekasi River. The Bekasi River watershed is located in the Ciliwung Cisandane River Basin in Jakarta, Indonesia (Fig. 1a). The Bekasi River watershed lies between 6°18'14.66″ S and 106°58'19.95″ E and has a catchment area of 170.59 km^2. The length of the Bekasi River from upstream to downstream was ± 33.84 km. The topography of the Bekasi River watershed is primarily at an elevation of 0-10 meters above sea level. The region has a very flat slope, with over 80% of the area having a gradient of less than 8%, classifying it as a Lower Watershed zone prone to flooding, as shown in Fig.1b. The Bekasi River watershed features a moderate width and relatively swift current upstream, which slows significantly downstream. Land use in the study area included 43.40% rice fields and 23.30% settlements, with forested areas being minimal and significantly below the recommended 30% for watershed forests (Fig. 1c).

2.2. Data Collection

The hydrological data collection for analyzing rainfall and flood discharge planning consisted of rainfall and discharge data obtained from observations using an automatic water-level recorder (AWLR). Several agencies performed hydrological data collection; previous studies related to planning the Kali Bekasi watershed are presented in Table 1.

(a)



(b) and (c)).

Figure 1. Study Area (a) Watershed Map, (b) Topographic Maps, (c) Slope Map

Table 1. Research Data

No	Data	Sources	Year	Function
		Hydrology Data		
1	Observed Daily Rainfall, Land-use map	[25]	2011-2020	Hydrology analysis
2	Observed Daily Rainfall Data	Meteorological, Climatological and Geophysical Agency	2002-2012	Hydrology analysis
3	Discharge Observation Data	[25]	2001-2011	Hydrology analysis
4	Observation Daily Discharge	Public Works Regency and River Basin Authority of Ciliwung Cisadane Agency	2011-2022	Modellingcal ibration
		Spatial Data		
1	Digital Elevation Data	https://tanahair.indonesia.go.id/demnas/#/demnas	Resolution 0,27 arc-second	Watershed delineation
2	Watershed boundary	https://geoportal.menlhk.go.id/portal/home/	Scale: 1:50.000	Validation of watershed boundary
3	Soil type map	https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v20/en/	Scale 1:5.000.000	Determination of soil texture

2.3. Methodology

This research consisted of several stages: data collection, hydrological modeling, and hydraulic modeling using HEC-RAS [24],[26],[27]. In this study, we used HEC-RAS 6.2. The HEC-RAS application determined the water level profile along a river or across a water cross-section. The water level was calculated using the energy equation, which was solved using a technique known as the standard step method [28]. The equation is shown in Equation (1):

$$Y_2 + Z_2 + \frac{a_2 V_2^2}{2g} = Y_1 + Z_1 + \frac{a_1 V_1^2}{2g} + h_f \quad (1)$$

Where:

Y_n: height (m)
Z_n: Elevation (m)
V_n: velocity (m/s)
α_1: velocity distribution coefficient
g: gravity (m/s^2)
h_f: head loss

Spatial data analysis included watershed boundary delineation, soil texture, and land cover classification. Hydrological modeling, including rainfall data analysis, consists of consistency, homogeneity, correlation, and regression tests—calculationRegional average rainfall data were calculated using the Thiessen polygon method. Peak discharge modeling with a synthetic unit hydrograph used an average rainfall return period of 50 years and watershed characteristics.

The research stages are briefly presented as a flowchart in Fig.2.

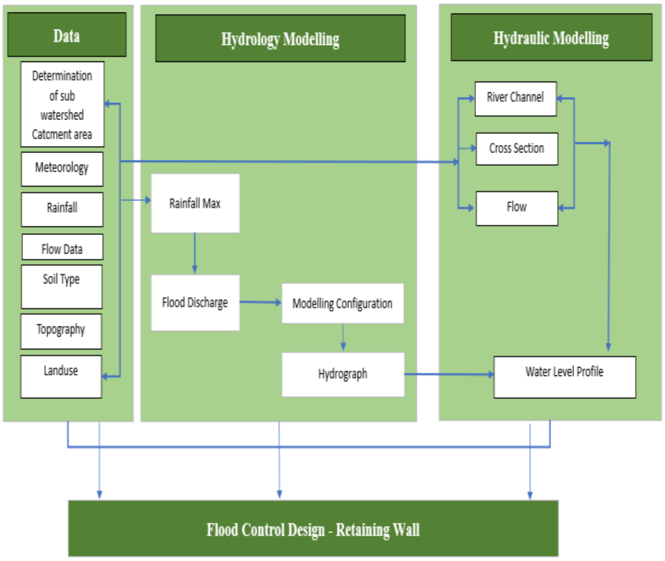


Figure 2. Research Flowchart

2.4. Development Model

2.4.1. Rainfall Analysis

The analysis of rainfall data began with a frequency analysis of hourly historical rainfall data. The annual maximum rainfall values were extracted from the dataset and ranked from the highest to the lowest. The rank-order (M) method was used to organize and plot the rainfall data, with the most significant value ranked one and the smallest ranked n. To determine the return period, which indicates the probability of a particular rainfall event being equal to or exceeding each year, the Weibull plotting position equation in Equation (2) was applied [29].

$$T = \frac{(y+1)}{M} \tag{2}$$

where T is the return period in years, y is the number of years of data, and M is the data rank in the time series.

The Thiessen method was employed [30]. This method uses a proportional approach to account for the area of influence of each rainfall station, accommodating non-uniform distances between them. The rainfall stations used in the analysis were as follows: (1) Sta. Cikeas, and (2) Sta. Bend. Bekasi, (3) Sta. Bekasi Irrigation Hall, (4) Sta. Cikarang, (5) Sta. Tunggilis, (6) Sta. Sumur Batu, (7) Sta. Gadog (8) Sta. Cibongas, (9) Sta. Cibinong and (10) Sta. Klapa Nunggal. The proportional analysis of the rainfall distribution in the Kali Bekasi watershed is illustrated in Fig. 3.

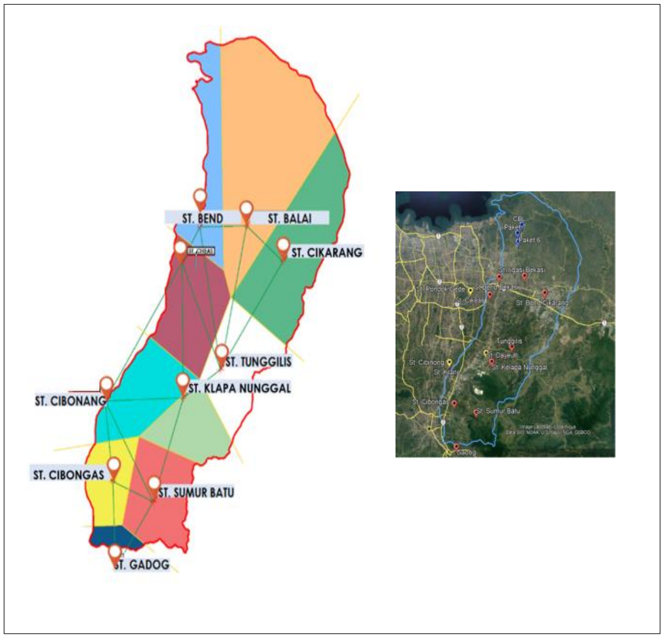


Figure 3. Area Proportion of Rainfall Station Distribution in Bekasi River Watershed

The widely recognized log-Pearson type III (LPT-III) distribution was used to analyze the probability distribution of rainfall events [31]. The LPT-III distribution applies a logarithmic transformation to calculate rainfall intensity for various durations and return periods. We analyzed the maximum annual rainfall events using LPT-III to determine the return period values for the dataset. The suitability of LPT-III for rainfall design analysis was validated in a recent comparison study, where it outperformed other methods such as the Normal, Gumbel, Pearson III, and Log-normal distributions. The study findings confirm that the LPT-III is appropriate for this analysis.

2.4.2. Flood Discharge Analysis.

Hourly rainfall data were required to analyze the planned flood discharge. Hourly rainfall calculations are required to estimate the design of a flood hydrograph later using a unit hydrograph at a certain interval. The Mononobe method was used to calculate the hourly rainfall using Equation (3).

$$R_t = \left(\frac{R_{24}}{T}\right) \tag{3}$$

Where:

R_t = Average rainfall (mm)
R_{24} = Maximum daily rainfall over 24 h (mm)
T = Rainfall duration (years)
t = Rainfall duration (h).

The rainfall duration in Indonesia ranges from 5-7 hours/day. In this study, this value was estimated as six h/d. After obtaining the hourly rainfall distribution, the rainfall distribution ratio was calculated using Equation (4).

$$R_t=(t \times R_T)-(t-1)\times R_{(T-1)} \quad (4)$$

3. Results

3.1. Hydrology Analysis

To obtain the return period rainfall at the study site, where the basis of the calculation is taken from the regional rainfall generated based on the analysis of the Thiessen method, the distribution method is used at the initial stage: (1) normal, (2) Log Normal, (3) Gumbel, and (4) Log Person III. The results were then tested for distribution suitability using the chi-square and Smirnov-Kolmogorov methods. Based on the calculation results, the best distribution is LPT-III (Table 2), based on the results of ΔD_{critis}, X^2_{Table}.

The LPT-III rainfall method was used to analyze the peak rainfall, which was converted to the hourly rainfall distribution using the Mononobe method. The results are presented in Table 3. To calculate the flood discharge design, the synthetic unit hydrograph (HSS) Nakayasu method was used, which uses the characteristics of the watershed in the study area in the form of (1) watershed area (A): 1383 km^2; (2) length of river (L): 157 km; (3) runoff coefficient (C): 0.326; (4) time concentration (t_c) and travel time (t_r): 9.5 hours, and (5) peak time (T_p): 17 h. The results of the peak discharge are shown in Fig.4.

Table 2. Rainfall Design using Frequency Distribution and Distribution Test

Period (T) (years)	**Normal** (mm)	**Log-Normal** (mm)	**Gumbel** (mm)	**Log Person III** (mm)
2	106	106	127	**126**
5	156	154	158	**153**
10	169	170	179	**171**
20	179	184	199	**187**
25	182	188	205	**195**
50	190	201	225	**214**
100	199	214	244	**233**
Smirnov- Kolmogorov				
ΔD_{Table}	0.30	0.30	0.30	0.30
ΔD_{critis}	0.22	0.43	0.19	**0.13**
Chi-Square				
X^2_{Table}	5.99	5.99	5.99	**5.99**
X^2_{critis}	1.79	0.74	1.79	1.79

Table 3. Hourly Rainfall Distribution – Mononobe Method

Time Hours	**Ratio (%)**	**Hourly Rainfall (mm/h)**				
		R_{10}	**R_{20}**	**R_{25}**	**R_{50}**	**R_{100}**
1	55.03	36.44	39.77	39.77	45.44	49.43
2	14.3	9.47	10.34	10.34	11.81	12.85
3	10.03	6.64	7.25	7.25	8.29	9.01
4	7.99	5.29	5.77	5.77	6.6	7.18
5	6.75	4.47	4.87	4.87	5.57	6.06
6	5.9	3.9	4.26	4.26	4.87	5.3
Daily rainfall (mm/d)		171	187	195	214	233
Adequate rainfall (mm/d)		66	72	75	83	90

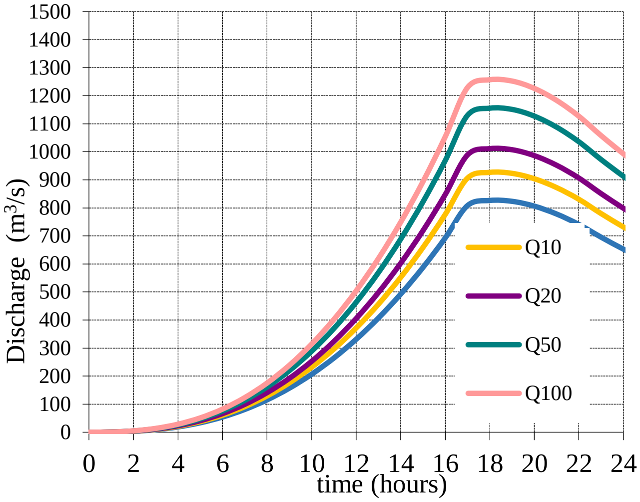


Figure 4. Flood Design Q_{50} using Nakayasu Hydrograph

3.2. Hydraulic Analysis

Hydraulic analysis was performed to determine the embankment height of the retaining wall, which in this model was performed using HEC RAS 6.2. Due to changes in the upstream discharge, the type of flow used in this model could be more stable. For the downstream section, the water level was modeled as an average depth with a river slope of 0.002 and a manning coefficient of 0.03 (channel material: natural stream channel).

To assess the capacity of a river as a rainfall reservoir, flood discharge determination follows the Public Work and Housing Regulation, which considers the catchment area, type of urban area (metropolitan city), the high risk involved, and the return period for the discharge ranged from Q_{25} to Q_{50}. In this study, we used a return period of Q_{50}. The modeling results indicate that almost all channels are overflowing, except near the Bekasi Dam (Fig. 5). Water levels range from 0 to 2 m above the riverbank because of the very flat slope (<8%), which is characteristic of downstream watersheds that are prone to flooding. This situation is worsened by land cover in the Bekasi River watershed, which is predominantly residential. According to the land use map, forest area was minimal, accounting for only 2.11% (Table 4).

Node	Q_{50}		
	Water Level Elevation	Riverbank	
		Left	Right
0	26.06	Overflow	Overflow
1	25.85	-	Overflow
2	25.44	Overflow	Overflow
3	25.14	Overflow	Overflow
4	24.43	Overflow	-
5	22.96	Overflow	Overflow
6	21.47	-	Overflow
7	19.68	-	Overflow
8	18.72	Overflow	Overflow
9	17.91	-	-
10	17.21	-	-
11	15.77	-	-
12	13.37	-	-
13	12.25	Overflow	Overflow
14	11.53	Overflow	-
15	11.39	Overflow	Overflow
16	10.56	Overflow	Overflow
17	9.16	Overflow	Overflow
18	8.51	Overflow	Overflow
19	6.92	Overflow	Overflow
20	6.21	-	Overflow
21	5.35	Overflow	-
22	4.02	-	-
23	2.42	-	-

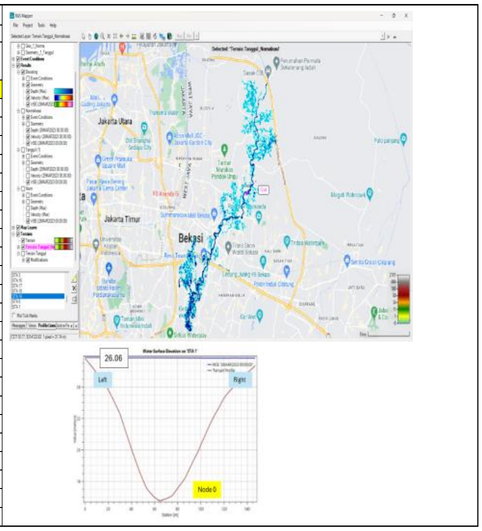


Figure 5. Hydraulic ModellingResult using Q_{50} (Existing Condition)

Table 4. Land-use of Bekasi River Catchment Area

Land-use	Area (Hectar)	Percentage (%)
Industrial plantations forestry	3056	2.11
Plantation	6785	4.69
Housing	33751	23.32
Dry agriculture	33257	22.98
Rice fields	62785	43.38
Shrubs	228	0.16
Ponds	3642	2.52
Open space	832	0.58
Waterbody	400	0.28

3.3. Retaining Wall Design

To address the flooding issue, the solution is to increase the channel capacity and reinforce the riverbank with retaining walls [32]. To determine the retaining wall's height, we identified the highest possible water level in the river. Next, we ascertained the necessary freeboard distance (1 m) above the highest water level. The retaining wall height is computed by adding the maximum water surface elevation to the required freeboard. The next step involved conducting the hydraulic modeling. The results of this model are shown in Fig. 6 and Fig.7. Fig. 6 shows the condition of the riverbank at each node. In contrast, Fig. 7 presents the cross-section of several nodes, comparing the existing conditions with the flood reduction achieved through riverbank restoration by enhancing the storage capacity and constructing retaining walls.

Node	Q_{50}		
	Water Level Elevation	Riverbank	
		Left	Right
0	24.39		
1	24.07		
2	23.61		
3	22.89		
4	21.81	Overflow	
5	20.87		
6	19.92		
7	19.02		
8	18.44	Overflow	
9	17.63		
10	16.7		
11	15.37		
12	13.36		
13	12.15	Overflow	
14	11.53		
15	11.39		
16	10.56		
17	9.09		
18	8.21	Overflow	
19	6.92		
20	6.12		
21	5.35		
22	4.02		
23	2.41		

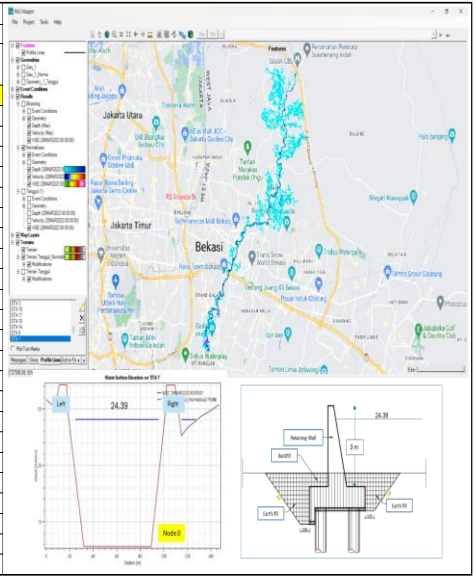
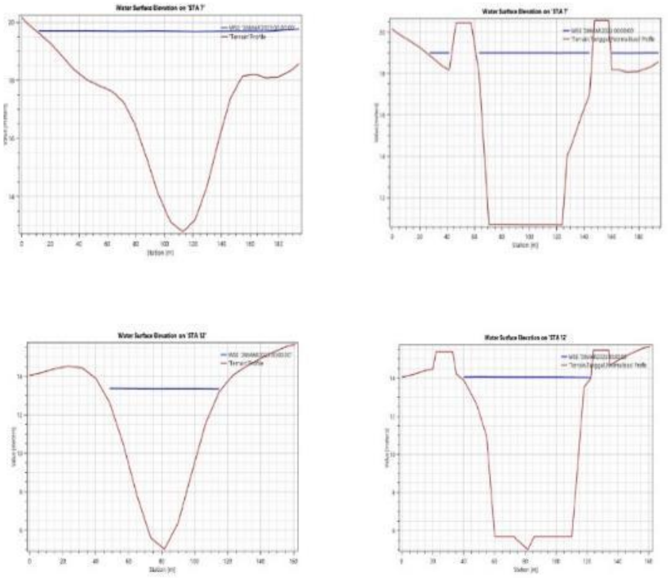


Figure 6. Hydraulic ModellingResult using Q_{50} (after Riverbank Restoration)



(a) **(b)**

Figure 7. Comparison of Cross Section (a) existing condition (b) after retaining wall construction

4. Conclusions

This paper explored hydraulic and hydrological modeling to mitigate the consequences of floods by implementing effective flood management strategies, such as constructing riverbank retaining walls. The optimal height and stability of the retaining walls were established by performing hydrological and hydraulic analyses using the HEC-HMS and HEC-RAS, respectively. A case study is The Bekasi River, located in the Ciliwung Cisandane River Basin, Jakarta, Indonesia. The area's topography is very flat (<8%), with the characteristics of the watershed in the study area being 1383 km^2 and the length of the river 157 km. Hydrological analysis was performed using rainfall design using Log Person type III to analyze the peak rainfall, Mononobe to convert to the hourly rainfall distribution, and Nakayasu to calculate the flood discharge design. The result of the rainfall design was 214 mm, with the hourly rainfall distribution in the first hour being 45.44 mm/h. The flood design with a 50-year return period is 1155.6 m^3/s, causing the Bekasi River to overflow. The solution to flood mitigation is riverbank restoration, and constructing a retaining unit approximately 3 m high (including a 1-meter m freeboard) is required. This paper is limited by the use of historical hydrological data from 2011 to 2020. This limitation can impact the calibration of the models and reduce their predictive accuracy. Future work will model various scenarios of the nature-based solution (NbS) approach to address flooding in urban areas.

Acknowledgments

The authors gratefully acknowledge the financial support of Bina Nusantara University under the scheme of Penelitian International Binus (PIB) with contract number No: 069C/VRRTT/III/2024

Conflict of interest

The authors (s) declare that the publication of this article has no conflicts of interest.

Author Contribution Statement

Authors Yuliastuti Juliastuti: Conceptualization, methodology, validation, original draft preparation, writing, review, and supervising the findings of this work.

Author Yureana Wijayanti: Methodology, validation, and editing.

Author Muhamad Fajar: Conceptualization, methodology, data curation and computation.

Author Martin Anda: Conceptualization, validation, data curation

All the authors have read and agreed to the published version of the manuscript.

Data Availability

https://zenodo.org/records/13752411

References

[1] S. Du, P. Shi, A. Van Rompaey, and J. Wen, “Quantifying the impact of impervious surface location on flood peak discharge in urban areas,” *Natural Hazards*, vol. 76, pp. 1457–1471, 2015, https://doi.org/10.1007/s11069-014-1463-2

[2] H.-K. Chang, Y.-C. Tan, J.-S. Lai, T.-Y. Pan, T.-M. Liu, and C.-P. Tung, "Improvement of a drainage system for flood management with an assessment of the potential effects of climate change," *Hydrological Sciences Journal*, vol. 58, no. 8, pp. 1581–1597, 2013, https://doi.org/10.1080/02626667.2013.836276

[3] W. Sohn, S. D. Brody, J.-H. Kim, and M.-H. Li, “How effective are drainage systems in mitigating flood losses?,” *Cities*, vol. 107, p. 102917, 2020, https://doi.org/10.1016/j.cities.2020.102917

[4] N. Vercelli, M. Varni, B. Lara, I. Entraigas, and M. G. Ares, “Linking soil water balance with flood spatial arrangement in an extremely flat landscape,” *Hydrol Process*, vol. 34, no. 1, pp. 21–32, 2020, https://doi.org/10.1002/hyp.13567

[5] A. Cappato, E. A. Baker, A. Reali, S. Todeschini, and S. Manenti, “The role of modellingscheme and model input factors uncertainty in the analysis and mitigation of backwater induced urban flood-risk,” *J Hydrol (Amst)*, vol. 614, p. 128545, 2022, https://doi.org/10.1016/j.jhydrol.2022.128545

[6] C. J. M. Hewett, M. E. Wilkinson, J. Jonczyk, and P. F. Quinn, “Catchment systems engineering: An holistic approach to catchment management,” *Wiley Interdisciplinary Reviews: Water*, vol. 7, no. 3, p. e1417, 2020, https://doi.org/10.1002/wat2.1417

[7] C. Lashford, T. Lavers, S. Reaney, S. Charlesworth, L. Burgess-Gamble, and J. Dale, “Sustainable catchment-wide flood management: A review of the terminology and application of sustainable catchment flood management techniques in the UK,” *Water (Basel)*, vol. 14, no. 8, p. 1204, 2022, https://doi.org/10.3390/w14081204

[8] J. Xia and J. Chen, “A new era of flood control strategies from the perspective of managing the 2020 Yangtze River flood,” *Sci China Earth Sci*, vol. 64, no. 1, pp. 1–9, 2021, https://doi.org/10.1007/s11430-020-9699-8

[9] A. A. R. R. Wangsa, Im. Nada, and I. B. Suryatmaja, “Efficiency of Infrastructure Planning of Retaining Wall as Flood Control in Bangin River Pecatu Badung Bali,” in *International Conference on Emerging Smart Cities*, Springer, 2022, pp. 693–706, https://doi.org/10.1007/978-981-99-1111-0_59

[10] F. Panini, P. Cambuli, M. Giordanella, I. Marquez, and G. Odetto, “Stability of a retaining wall in severe hydraulic conditions (Northern Italy),” 2020.

Available on https://www.sertec-engineering.com/wp-content/uploads/2020/05/04-02.pdf

[11] K. H. Yang, T. S. Nguyen, Y. H. Li, and B. Leshchinsky, “Performance and design of reinforced slopes considering regional hydrological conditions,” *Geosynth Int*, vol. 26, no. 5, pp. 451–473, 2019, https://doi.org/10.1680/jgein.19.00031

[12] U. M. Kannapiran and A. S. Bhaskar, “Flood inundation mapping of upstream region in the Adyar River basin: Integrating hydrologic engineering centre’s river analysis system (HEC-RAS) approach with groundwater considerations,” *Groundw Sustain Dev*, vol. 24, p. 101085, 2024, https://doi.org/10.1016/j.gsd.2024.101085

[13] T. Wijaya and Y. Wijayanti, “Flood Mapping Using HEC-RAS and HEC-HMS: A Case Study of Upper Citarum River at Dayeuhkolot District, Bandung Regency, West Java,” in *IOP Conference Series: Earth and Environmental Science*, IOP Publishing, 2024, p. 012103, https://doi.org/10.1088/1755-1315/1324/1/012103

[14] M. Hayati and F. Agustina, “The Impact of the Krueng Keureuto Dam and Reservoir on Flood Management in Aceh Utara Regency and Surrounding Areas: A Literature Review,” in *Proceeding of International Conference on Multidisciplinary Research*, 2024, pp. 238–244, https://doi.org/10.32672/picmr.v6i2.1227

[15] M. A. Salim and K. Wibowo, “Rob Flood Control on the North Coast of Java (Study on coastal areas of Pekalongan and Semarang),” in *IOP Conference Series: Earth and Environmental Science*, IOP Publishing, 2024, p. 012026, https://doi.org/10.1088/1755-1315/1321/1/012026

[16] N. W. Pinasti, E. Wijayanti, W. Nurfaida, M. Sulaiman, and A. Kurniawan, “Flow patterns at river bends and its response to surrounding infrastructures,” in *IOP Conference Series: Earth and Environmental Science*, IOP Publishing, 2024, p. 012002, https://doi.org/10.1088/1755-1315/1311/1/012002

[17] Z. Qin *et al.*, “Stability behavior of the Lanxi ancient flood control levee after reinforcement with upside-down hanging wells and grouting curtain,” Journal of Mountain Science, vol. 21, no. 1, pp. 84–99, 20, 2024, doi: https://doi.org/10.1007/s11629-023-8239-7

[18] L. Jin, P. Liu, W. Yao, J. Wei, and Z. Li, “Safety assessment of existing subgrade retaining wall based on a combined Weighting-TOPSIS evaluation method,” *Developments in the Built Environment*, vol. 18, p. 100420, 2024, https://doi.org/10.1016/j.dibe.2024.100420

[19] S. A. Mathias, “Hydrology and Frequency Analysis,” in *Hydraulics, Hydrology and Environmental Engineering*, Springer, 2024, pp. 253–279, https://doi.org/10.1007/978-3-031-41973-7_11

[20] C. T. Vidrio-Sahagún, J. He, and A. Pietroniro, “Multi-distribution regula-falsi profile likelihood method for nonstationary hydrological frequency analysis,” *Stochastic Environmental Research and Risk Assessment*, vol. 38, no. 3, pp. 843–867, 2024, https://doi.org/10.1007/s00477-023-02603-0

[21] H. O. Adebayo and A. O. Ogunlela, “Flood frequency analysis of Asa River, Ilorin, Nigeria,” *Int J Hydro*, vol. 8, no. 1, pp. 15–19, 2024, DOI: https://doi.org/10.15406/ijh. 2024.08.00368

[22] F. Alia, S. Y. Iryani, L. P. Putri, “Comparison analysis of measured unit hydrograph of Buah watershed,” *AIP Proceeding*, vol. 2689, no. 040025, 2023, https://doi.org/10.1063/5.0114303

[23] B. Yi, L. Chen, and T. Xie, “On the Influence of Spatial Heterogeneity of Runoff Generation on the Distributed Unit Hydrograph for Flood Prediction,” *Hydrology and Earth System Sciences Discussions*, vol. 2024, pp. 1–41, 2024, https://doi.org/10.5194/hess-2024-51

[24] İ. B. Peker, S. Gülbaz, V. Demir, O. Orhan, and N. Beden, “Integration of HEC-RAS and HEC-HMS with GIS in Flood Modelling and Flood Hazard Mapping,” *Sustainability*, vol. 16, no. 3, p. 1226, 2024, https://doi.org/10.3390/su16031226

[25] Y. I. Sihombing, A. Rizaldi, M. Farid, N. F. Januriyadi, and I. R. Moe, “Jakarta’s 2020 New Year Flood Assessment with a Rainfall–Runoff–Inundation (RRI) Model,” MDPI AG, May 2023, p. 100. doi: https://doi.org/10.3390/ecws-7-14317

[26] S. Moghim, M. A. Gharehtoragh, and A. Safaie, “Performance of the flood models in different topographies,” *J Hydrol (Amst)*, vol. 620, p. 129446, 2023, https://doi.org/10.3390/rs16020320

[27] A. Yusuf, R. Ojo, M. O. Idrees, A.-L. Balogun, I. B. Salami, and O. S. Sani, “Modelling flood hazards impacted by ungauged river in urbanised area using HEC-RAS and GIS,” *Nigerian Journal of Technological Development*, vol. 20, no. 2, pp. 83–92, 2023, https://doi.org/10.4314/njtd.v20i2.1405

[28] V. Te Chow, *Open Channel Hydraulic*. New York: McGraw-Hill 1959. Available on https://heidarpour.iut.ac.ir/sites/heidarpour.iut.ac.ir/files/u32/open-chow.pdf

[29] M. S. Shama *et al.*, “Modified generalized Weibull distribution: theory and applications,” *Sci Rep*, vol. 13, no. 1, p. 12828, 2023, https://doi.org/10.1038/s41598-023-38942-9

[30] J. Lee, S. Kim, and H. Jun, “A Study of the Influence of the Spatial Distribution of Rain Gauge Networks on Areal Average Rainfall Calculation,” *Water (Basel)*, vol. 10, no. 11, p. 1635, Nov. 2018, doi: https://doi.org/10.3390/w10111635.

[31] R. Montes-Pajuelo, Á. M. Rodríguez-Pérez, R. López, and C. A. Rodríguez, “Analysis of Probability Distributions for Modelling Extreme Rainfall Events and Detecting Climate Change: Insights from Mathematical and Statistical Methods,” *Mathematics*, vol. 12, no. 7, p. 1093, Apr. 2024, doi: https://doi.org/10.3390/math12071093

[32] A. Pathan, K. Kantamaneni, P. Agnihotri, D. Patel, S. Said, and S. K. Singh, “Integrated Flood Risk Management Approach Using Mesh Grid Stability and Hydrodynamic Model,” *Sustainability*, vol. 14, no. 24, p. 16401, Dec. 2022, doi: https://doi.org/10.3390/su142416401