HEC-RAS-BASED URBAN FLOOD SIMULATION FOR ENHANCING MITIGATION SCENARIOS IN THE GAJAHWONG RIVER, INDONESIA

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ABSTRACT

Rapid urban development in Yogyakarta, including increased impermeable surfaces and inappropriate land use, has intensified surface runoff and flood risks, particularly along highways and riverbanks. The study of flooding on the Gajahwong River is significant due to the urban residential areas situated along its banks. This research aims to analyze the peak discharge and flood inundation model and estimate the ideal embankment height for flood mitigation in the Gajahwong River section. The peak discharge is calculated using the rational method, employing daily maximum rainfall data from 2001 to 2021, and flood inundation modeling is conducted using the Hydrological Engineering Center River Analysis System (HEC-RAS) software with a one-dimensional (1D) model for steady flow analysis. The Gumbel distribution was selected in the maximum rainfall frequency analysis with the Gumbel probability plot results showing a very high level of fit (R^2 = 0.9792). The high peak discharge in the Gajahwong Watershed is primarily driven by extensive built-up land, which dominated by 48% of the watershed's area, generating the C-value of 0.57. The research results indicate that the inundation area increases for flood return periods of 2-, 5-, 10-, 25-, and 50-years respectively by 52,891.3 m^2; 62,142.1 m^2; 67,702.6 m^2; 74,269.8 m^2; and 79,396 m^2. To deal with flood disasters in the Gajahwong River section, a 4-meters embankment is required. The implementation of both scenarios should be accompanied by nonstructural mitigation, such as cliff erosion control using natural vegetation or additional protective structures.

Key-words: *Return period; Peak discharge; Flood inundation; Channel discharge capacity; River embankment.*

1. INTRODUCTION

Understanding hydrological processes in water resource planning and management requires an understanding of the watershed concept (Yu and Duffy, 2018). According to Suprayogi et al. (2013), watersheds are essential to the management of water resources. Accordingly, the watershed unit is usually used as the research region in hydrological models (Edwards et al., 2015). Watershed features are influenced by a number of factors, such as topography, soil type, land use, slope length, and slope steepness. These features influence how varying rainfall intensities impact a number of hydrological processes, such as evapotranspiration, infiltration, percolation, surface runoff, groundwater content, and discharge (Asdak, 2014). Sekaranom et al. (2021) claim that the number of hydrometeorological disasters, especially floods, has been rising yearly. There are known temporary causes of floods. As stated by Dawson et al. (2008), they include poor urban design, failure of urban drainage systems, changes in land use, and geomorphology. Flood susceptibility is strongly influenced by soil types and distance from fault lines (Tehrany et al., 2017). Flooding is more likely to occur in low-lying locations with a slope of 10% to 15% (Igovic et al., 2017). Furthermore, Permatasari et al. (2017) explained that land use has the greatest impact on hydrological functions, as evidenced by runoff and baseflow.

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Urbanized, highly inhabited, and other flood-prone locations are particularly affected by flooding (Samu and Kentel, 2018). To guarantee that the effects of floods can be reduced, an area's flooding has to be evaluated. An issue of growing worldwide importance is the frequency of flooding events and the risk they pose in metropolitan areas. It is crucial to pursue integrated flood risk management techniques that incorporate flood modeling, especially in light of current estimates of escalating future circumstances (Nkwunonwo et al., 2020). One technique to assess floods is to model the hydrology and hydraulics of the river, such as Hydrologic Engineering Center's River Analysis System (HEC-RAS).

The purpose of HEC-RAS is to carry out hydraulic calculations in both one and two dimensions for an entire system of man-made and natural channels. One hydraulic model that is effective and quick to compute is HEC-RAS (Sholikha et al., 2022). When comparing the simulation results with the inundation area captured on satellite photography, the modeling simulation performs admirably. HEC-RAS modelling simulations can provide additional information such as flood depth, flow velocity and duration. HEC-RAS modelling can simulate flows from water level profiles in man-made and natural channels or rivers by generating flood collection scenarios for each return period. By employing HEC-RAS modeling to map flood collection scenarios, peak discharge parameters, the Digital Elevation Model (DEM), and the manning roughness coefficient for each river segment (Haikal and Suprayogi, 2024) can be used to ascertain the flood inundation and its depth (Pratiwi et al., 2021). Quiroga et al. (2016) used HEC-RAS to study flood modeling in the Amazon River. The modeling has also been widely applied in other countries. Györi and Haidu (2011) and Mihu-Pintilie et al. (2019) studied flooding in a watershed in Romania and produced HEC-RAS modeling results that were more accurate than flood data provided by the local government. Hopefully, this research can be a valuable asset for local authorities in flood management in Yogyakarta City. The authority can use the simulation findings to determine whether to redesign and expand the capabilities of storm sewage systems in order to prevent flood damages (Hsu et. al., 2000).

Yogyakarta is one of the cities that is developing quickly in Indonesia. Abandoned land in Yogyakarta City is targeted by developers to be used as urban housing or infill development (Suradi and Setiawan, 2004). The region's growth will have a significant role in increasing surface flow to rainfall, which will shorten the concentration and recession periods (Fletcher et al., 2013). Flooding will therefore be more likely. Highways and riverbanks in Yogyakarta City are frequently flooded. The narrowing of rivers due to inappropriate land use is also one of the contributors to flooding in Yogyakarta City. Rather than allowing rainwater to seep into the soils, Yogyakarta's multi-story structures and impermeable surfaces convert the majority of it into surface runoff and even floods (Suprayogi et al., 2020). One of the watersheds that runs through Yogyakarta City is Gajahwong.

Gajahwong Watershed, which is located upstream in Sleman Regency and downstream in Bantul Regency, is a component of the urban watershed that flows through Yogyakarta. Ardiansyah, et al. (2020) mentioned that the Gajahwong River segment in Umbulharjo District experiences annual flooding. The study shows that every subwatershed zone in Gajahwong is impacted by the flood vulnerability interval, from upstream to downstream zones. The Gajahwong River overflows and floods residential areas annually during heavy rainfall. The largest flooding event on record occurred in early and mid-2016, causing the river's dam to fail and resulting in the inundation of residential areas by up to 2 meters. On 18 March 2021, heavy rainfall caused a flood in Umbulharjo Regency, an area located on the banks of the Gajahwong River. At least 50 families suffered losses due to the flood. Heavy rains caused an overflowing flood on the Gajahwong River in Umbulharjo District on 3rd October 2022 and 4th January 2024. This resulted in many houses being affected by the overflowing flood, and in March 2023 there was another flood in a residential area. Therefore, it is necessary to conduct studies related to flood modelling and mitigation in the Gajahwong River segment.

Therefore, This research aims to analyze the peak discharge, model the inundation flood, and estimate the ideal embankment height for flood mitigation in the Gajahwong River section. The study utilises DEM and spatial data in the form of transverse and longitudinal profiles of the Gajahwong River to analyse floods. In order to forecast regions that would be impacted by floods of a specific size and volume, flood inundation modeling is developed utilizing hydrological factors. Areas at vulnerable of excess floods from the Gajahwong River segment can be mapped using spatial modeling for flood management. Maps of flood inundation zones are produced in this work using spatial modeling and annual peak discharge data for return periods of 2-, 5-, 10-, 25-, and 50-years. Disaster mitigation and policymaking can both benefit from these maps. Maps of flood hazards and risks are crucial for managing flood risk, and stakeholders utilize them to lessen the impact of floods (Costabile et al., 2020). Mapping flood-prone areas and modelling floods can be a valuable reference in spatial planning for riverine border areas (Yuniartanti, 2018). HEC-RAS models can be used in other flood-prone areas for real-time flood control management, with side channels as a preventive measure to reduce flooding and damage (Peker et al., 2024).

2. STUDY AREA

The latest information from the Public Works, Housing, Energy, and Mineral Resources Office of Special Region of Yogyakarta, Gajahwong Watershed (**Fig. 1**) has an area of ±37.12 km^2 with a main river length of 31.41 km and an average river slope of 0.066%. The river in Gajahwong Watershed is classified as a river with perennial type, which flows throughout the year. The slope in Gajahwong Watershed is dominated by flat relief. The area of slope for flat relief (28.06 km^2), gentle (7.64 km^2), steep (0.07 km^2), rather steep (1.35 km^2), and very steep (0.004 km^2) (Indonesian Geospatial Information Agency, n.d.). The Gajahwong Watershed flows from Mount Merapi through the landforms of volcanic slopes and alluvial plains. The alluvial plains are densely populated areas, especially in Yogyakarta City. Thus, this makes the Gajahwong Watershed hazardous to flooding. The authority implemented planning for the Gajahwong River via a river rejuvenation program extending to 2035, which includes the construction of river embankments (Central River Region of Serayu Opak, 2016).

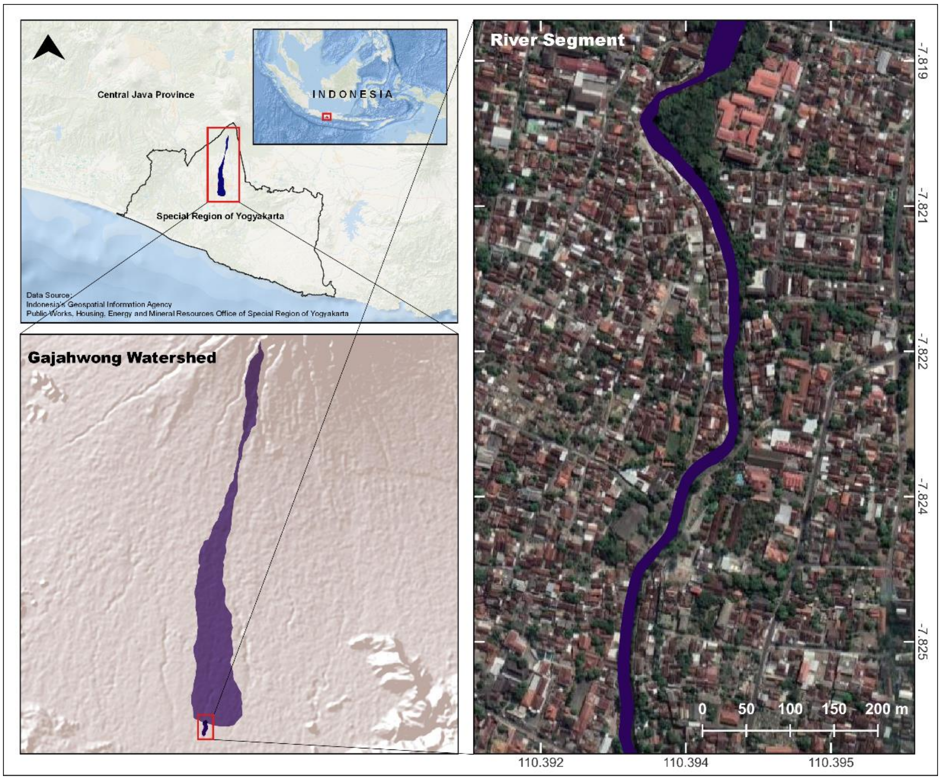


Fig. 1. Study area.

3. DATA AND METHODS

The data input process in flood modeling is carried out using HEC-GeoRAS. The data input in the HEC-GeoRAS extension of ArcGIS 10.4 includes spatially distributed geometric data such as Stream Centerlines, Bank Lines, Flow Path Centerlines, and XS Cross Sections. Subsequently, Manning's coefficients and peak flow data for several return periods, along with reach boundary conditions, are entered into the HEC-RAS 5.0.1 software. The stream centerlines in this study have a length of 1,008 meters and are used as the reference for creating the Bank Lines, Flow Path Centerline, and XS Cross Section layers.

3.1. Goodness-of-Fit Test and Rainfall Intensity

Time focus and daily rainfall data processing are combined in the design rainfall analysis. Rain gauge stations around the Gajahwong Watershed, such as the Angin-angin, Beran, Bronggang, Gemawang, Karang Ploso, and Prumpung stations, provided the highest daily rainfall intensity data utilized between 2001–2021. Statistical measures including mean (x), standard deviation (S), coefficient of variation (Cv), coefficient of skewness, and coefficient of kurtosis (Ck) are used to examine the rainfall data. These parameters, which include the normal distribution, Gumbel distribution, Log-normal distribution, and log-Pearson III distribution, are then used to establish the proper distribution type. The best-fitting distribution was found using the Smirnov-Kolmogorov and Chi-Square tests. The selected distribution will be tested to match the empirical rainfall data with certain theoretical probabilities of the selected distribution. These probabilities are then transformed to the theoretical scale (reduced variate) according to the selected distribution type. The empirical data is plotted against the theoretical reduced variate value with the addition of the theoretical distribution fitting line. The fit is assessed through a correlation test of the empirical points with the theoretical line. The following formula is used to determine the design rainfall for many return periods.

$$XT = Xr + KT.S \tag{1}$$

where:

XT	-design rainfall for a T-year return period;
Xr	-average rainfall;
KT	-frequency factor for T-year return period;
S	-standard deviation

The following equation illustrates how the design rainfall is then used as an input in the Mononobe formula to determine rainfall intensity. A hyetograph requires the design rain to be distributed into hourly rainfall. The Tadashi Tanamoto rain distribution concept pattern can be used to create the rain distribution pattern. The distribution can be used in Java, the location of the Gajahwong watershed (Triatmodjo, 2009). The result of the rainfall distribution is used to calculate the design peak discharge.

$$I = \left(\frac{R}{24}\right)\left(\frac{24}{Tc}\right)^{\frac{2}{3}} \tag{2}$$

where:

I	-rainfall intensity (mm/hours);
R	-maximum rainfall per day (mm);
Tc	-concentration time (hours)

3.2. Peak Discharge

In flood mitigation strategies that address increasing surface runoff, the surface runoff coefficient is an essential component. The reaction of each distinct landform in transforming rainfall to surface runoff may also be compared using the runoff coefficient (Crăciun et al., 2009; Che et al., 2018). It serves as a marker to ascertain whether disruptions have occurred in a watershed. The soil's permeability and water-holding capacity have an impact on the C-value. A higher percentage of rainfall turning into runoff is indicated by a higher C-value. Cook's approach is used to compute the runoff coefficient, taking into account data on drainage density, slope, land use, and soil type (Chow, 1964). A thorough calculation of the runoff coefficient is then obtained by combining data from several maps using the overlay mapping technique. As demonstrated in the following equation, the coefficient is determined by calculating a weighted average using superimposed unit area values below.

$$C = \frac{(Ca \times La) + (Cb \times Lb) + \cdots + (Cn \times Ln)}{(La + Lb + \cdots + Ln)} \tag{3}$$

where:

C -runoff coefficient in percent where Cn ➔ Ci (i=a∼n);

Ln -area of the unit in hectare where Ln ➔ Li (i=a∼n)

The volume of water that flows through a cross-section of a canal in a certain amount of time is known as the peak discharge. A flood will happen if the waterway cannot handle the flood discharge. Water usually stays in the watershed for a long-time during flood occurrences (Suprayogi et al., 2024). When the flow discharge peaks, floods happen. Due to excessive rainfall, floods annually inflict catastrophic harm to society (Dutta and Deka, 2024). Peak discharge calculations were conducted using the rational method. Chow (1964) stated that the rational method is a method that can be used for urban flood planning. In simple terms, the technique involved designing drainage channels that could remove a specific proportion of the maximum daily rainfall that was measured (Biswas, 1970). In addition, the rational method can also be used to calculate the maximum discharge in a small watershed. According to Hadisusanto (2010), a watershed is classified as small if it has an area of <50 km^2.

$$Qp = 0.278\ C\ I\ A \tag{4}$$

where:

C -runoff coefficient;

I -rainfall intensity (mm/hour);

A -watershed area (km^2)

3.3. Digital Terrain Model (DTM)

Digital Elevation Model (DEM) data and Manning's coefficient data are used in the flood modeling procedure. The most important impact in reducing flood risks has been found to be the examination of geological conditions and the use of DEM to determine river distance (Haidu and Ivan, 2016a; Lee et al., 2017). The cross-sectional geometry of the river is created by processing the DEM data, allowing flood inundation scenarios to be modeled when the channel capacity is exceeded. Aerial photo extraction is used to collect the DEM data, and Agisoft software is used to compile the aerial photos and extract the DEM into a Digital Terrain Model (DTM) format. The DTM data in this study used aerial photographs using an unmanned aerial vehicle (UAV) aircraft with a spatial resolution of 1.18 m x 1.18 m.

3.4. HEC-RAS

The process of simplifying intricate hydrological processes is known as hydrological modeling. The final hydrological model is greatly influenced by the researchers' objectivity while modeling watersheds (Clark, 2017; Haidu and Ivan, 2016b). The HEC-RAS 1D model is utilized to create flood inundation scenarios. The consideration of using the HEC-RAS 1D model is that flood inundation modeling is carried out in well-defined channels, where it simulates water flow along a linear trajectory in a single direction. Peak discharge for various return durations and reach boundary conditions are among the hydrological metrics that were employed in the analysis. Using the findings of channel slope measurements, the normal depth boundary condition is applied in this study. Based on field observations, interviews with residents, and cross-checking information on flood events from the Yogyakarta Regional Disaster Mitigation Agency in 2023, the flood inundation model that best represents real conditions is the flood inundation model with a cross-section of 200 m (**Fig. 2** and **Fig. 3**).

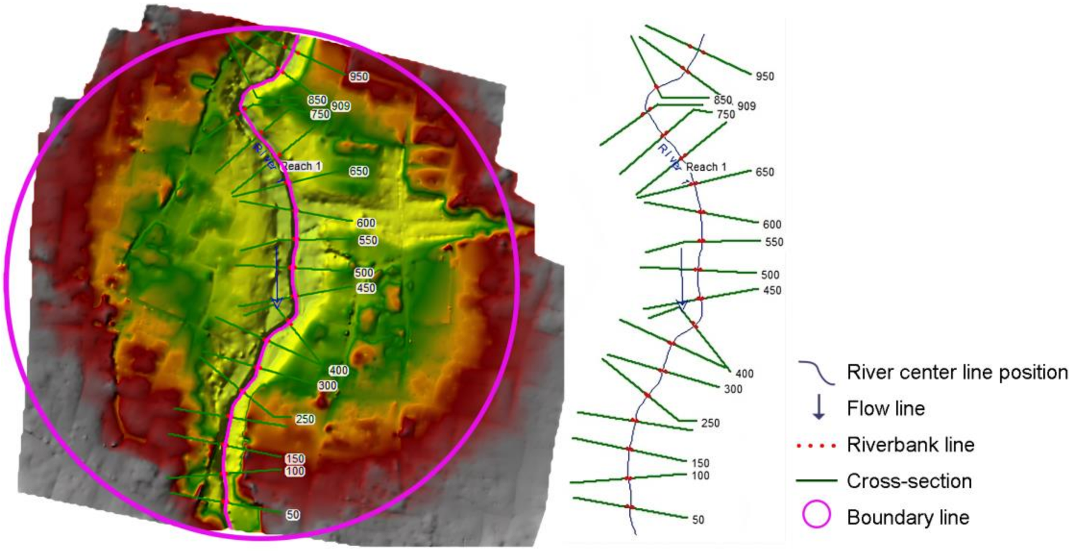


Fig. 2. Geometric data (cross-section) processing in HEC-RAS.

Selected Boundary Condition Locations and Types				
River	Reach	Profile	Upstream	Downstream
River 1	Reach 1	all		Normal Depth S = 0.03

Fig. 3. Reach Boundary Conditions Input.

For hydrological analysis, this study uses steady flow analysis, which assesses floods by calculating the peak discharge for each return period. In particular, the input data are the peak discharge values for the 2-, 5-, 10-, 25-, and 50-year return periods. Papaioannou et al. (2016) state that the precision of river geometric data affects the accuracy of river hydraulic models for flood inundation delineation.

3.5. Drainage Channel Design for River Embankment

Referring to the embankment design module of the Indonesian Ministry of Public Works and Housing (2016), the wet section to accommodate maximum discharge for the Gajahwong River segment using the formula below and visualized in **Fig. 4.**

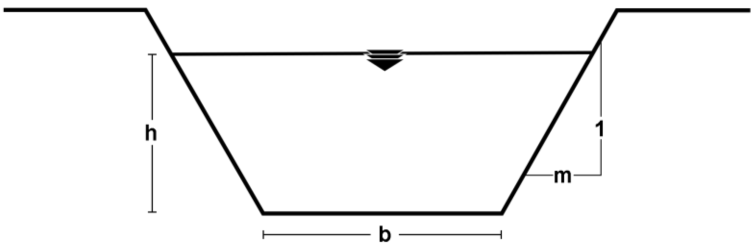


Fig. 4. Embankment design.

$$Ae = (b + m.h)h \tag{5}$$

$$P = b + 2h(\sqrt{1 + m^2}) \tag{6}$$

$$R = \frac{Ae}{P} \tag{7}$$

where:

b	-channel width (m);
h	-water depth (m);
m	-comparison of embankment slopes;
R	-hydraulic radius (m);
P	-wet cross-section of the channel (m);
Ae	-wet cross-sectional area (m^2)

The results of these variables are used in the calculation as the discharge of the Gajahwong River channel in the segment. The channel discharge is compared with the design peak discharge. Flooding will occur when the channel discharge cannot accommodate the design peak discharge so that river water will overflow onto land.

4. RESULTS AND DISCUSSIONS

4.1. Design Rainfall

The significance level used in this analysis is 5%. Based on Indonesian National Standardization Agency (2016), a confidence level of 95% is considered sufficient for use in the Goodness-of-fit test. Furthermore, in several hydrological analyses, a 5% significance level provides acceptable results with relatively high accuracy across different types of distributions (Zeng et al., 2015; Das, 2018). The Goodness-of-fit test shows that each of the four distributions utilized in this study is considered suitable for use because the test statistic values for each distribution are below the critical value (**Table 1**). Therefore, any kind of dissemination is acceptable. The Gumbel distribution was chosen as an example of a cautious flood mitigation strategy. Assuming the worst-case scenario, planning for flood mitigation will be more adaptable to future extreme conditions when maximum rainfall is assumed. This was predicated on the highest total rainfall. This allows for a more serious approach to mitigation.

Table 1.

Goodness-of-fit test.

Return Period (Years)	Normal	Gumbel	Log-Normal	Log-Pearson III
2	71.3	65.43	62.37	68.14
5	102.99	105.41	98.08	98.71
10	119.67	131.89	124.45	114.54
25	136.34	165.33	157.91	130.21
50	147.55	190.14	185.32	139.36
Chi-Square Statistic (Critical Value = 7.815)	5.57	1.57	4.43	7.29
D-Statistic (Critical D = 0.286)	0.22	0.22	0.18	0.18
Fit	Yes	Yes	Yes	Yes

In contrast to research by Mlynski et al. (2024) which showed that the Gumbel distribution produced the lowest results in a watershed in Poland. The study shows that the determination of design rainfall is influenced by the choice of method. In addition, the difference in climate types in Indonesia and Poland also shows that the frequency analysis results are opposite. The study also showed that there was no significant increase in rainfall. Meanwhile, the maximum rainfall in the Gajahwong watershed showed a significant increasing trend, as evidenced by the Mann-Kendall test which produced a p-value of 0.042 with a significance level of 5%.

The fit of the empirical rainfall data to the Gumbel distribution was tested through the Gumbel reduced variate. The majority of data points constantly follow the fitted line, indicating a solid fit between the theoretical Gumbel fit and the empirical data of annual maximum rainfall as seen by the Gumbel probability plot in **Fig. 5.** They have a very high level of fit ($R^2 = 0.9792$), which supports this. This demonstrates that the Gumbel distribution is appropriate for simulating periods of intense precipitation in the research region. Further perspective is given by the reference line for mean rainfall (71,3 mm), which emphasizes how much exceptional events differ from normal circumstances. The top tail has a little divergence, especially for incredibly few rainfall events. However, this is a typical feature of extreme value modeling and has little bearing on the model's dependability. Based on the results of the entire distributions, the following is the estimated maximum rainfall for a given return period.

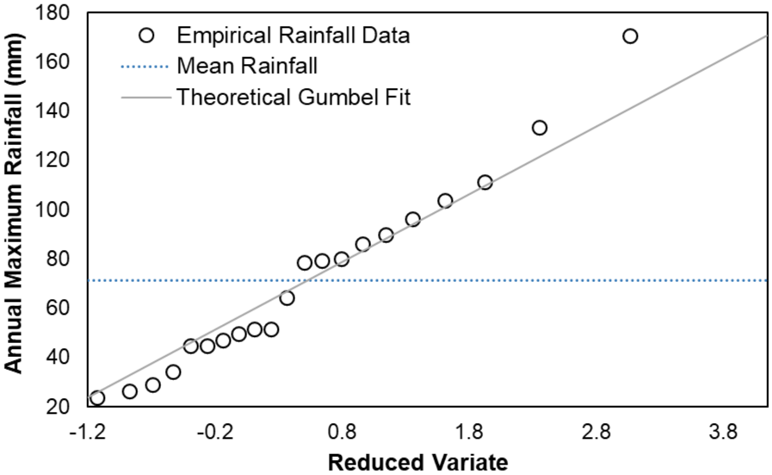


Fig. 5. Gumbel probability plot.

The rainfall (Gumbel distribution) is 65.43 mm for a 2-year return period and 190.14 mm for a 50-year return period. This rise suggests that although heavy rainfall events are occurring less frequently, their effects are more significant. This rise indicates that while the frequency of intense rainfall events is decreasing, their impact is increasing. Actual rainfall may exceed the projected Gumbel distribution due to land use change, which can intensify intense rainfall. The Gajahwong River may receive more flow from upstream regions, specifically Sleman Regency, hence this needs to be monitored. Surface runoff will become more likely if urban expansion extends upstream into the Gajahwong watershed. As a result, the river will receive more rainfall.

4.2. Peak Flood Discharge

The watershed parameters or features are assumed to be largely constant in calculations for peak discharge with return periods of 2-, 5-, 10-, 25-, and 50-year. Tadashi Tanimoto's rainfall distribution pattern calculation results indicate that the distribution of rainfall rises with the length of the return period. The occurrence of intense rainfall is linked to this, and it rises with longer return times. The probability that the rainfall will return is equal to the rise in the rainfall distribution values. This happens because the design rainfall distribution is still followed by the probability values at each distribution point. Since the rainfall distribution values are still exactly proportionate to the design rainfall values, the probability values have an impact on them. Input data for the design discharge calculation is the rainfall distribution results. The Tadashi Tanamoto rainfall distribution (**Fig. 6**) was used to identify the peak discharge of each return period.

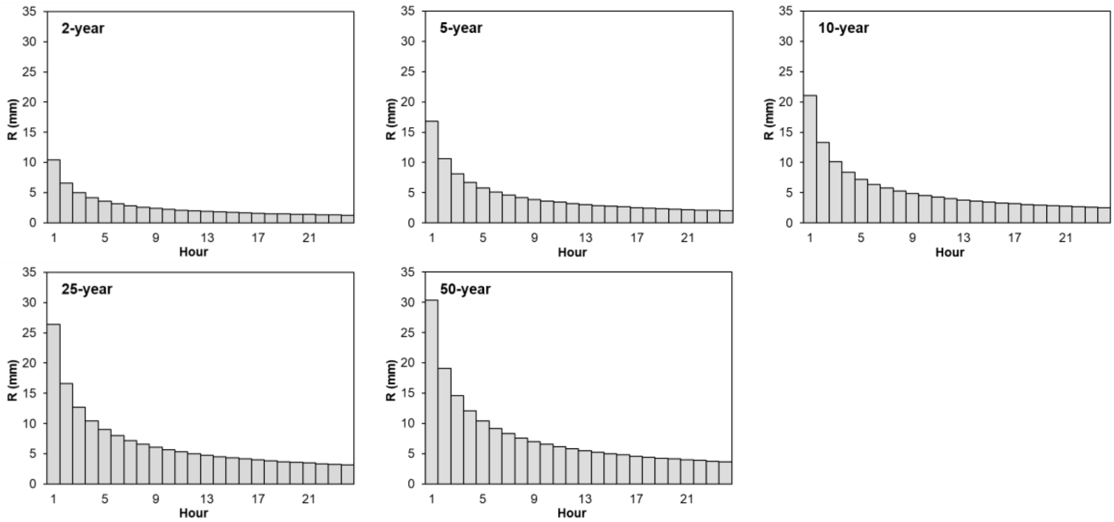


Fig. 6. The Tadashi Tanamoto rainfall distribution for earch return period.

Every return period uses the same flow coefficient value. A design rainfall intensity value that is uniformly distributed across the watershed is produced by combining the design rainfall data with the concentration time. With a composite C-value of 0.57 from Cook's approach, the concentration time (the amount of time needed for water to move from the farthest point to the observation site) in the Gajahwong Watershed is roughly 2.74 hours (2 hours 44 minutes). C-value indicates that the area has a fairly high flow coefficient and has a poor ability to store and drain rainfall that falls to the subsurface. Because of the huge variation in design rainfall values between the two periods, there is a significant divergence in the peak flood discharge between the 2- and 50-year return periods (**Table 2**). This is compatible with the concept of probability and the effect of large-design rainfall levels on peak discharge (**Fig. 7**).

Table 2.
Peak discharge in Gajahwong River segment.

Return Period (Year)	Peak Discharge (m^3/s)
2	61.41
5	98.94
10	123.79
25	155.18
50	178.46

The high composite C-value is the cause of the high peak discharge. The predominance of built-up land use (48%) over other land use types is the cause of this rating. Land used for settlements is not vegetated. Nothing can lower the velocity of surface runoff on the ground when there is no vegetation present (Hidayah et al., 2022). Surface runoff rises as a result of built-up areas like settlements. Because there is no chance for infiltration, rainwater will quickly discharge as it hits the surface of built-up land. Water enters the river system more quickly as a result. Increased surface flow from impervious areas such as roads, parking lots, and rooftops results in peak discharges during rain events that destabilize river flows (Bell et. al, 2016). Therefore, the Gajahwong Watershed's increased peak discharge is largely caused by built-up land. The peak discharge will rise as the extent of built-up land increases, influencing the possible frequency and severity of floods in the Gajahwong Watershed.

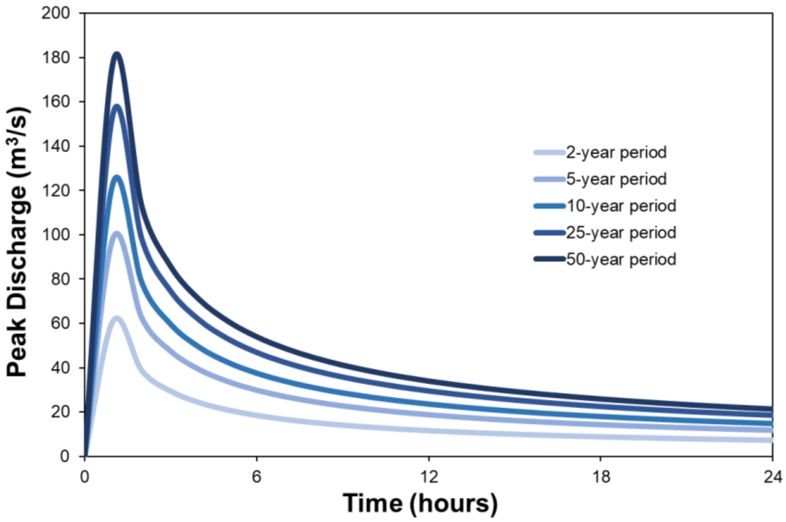
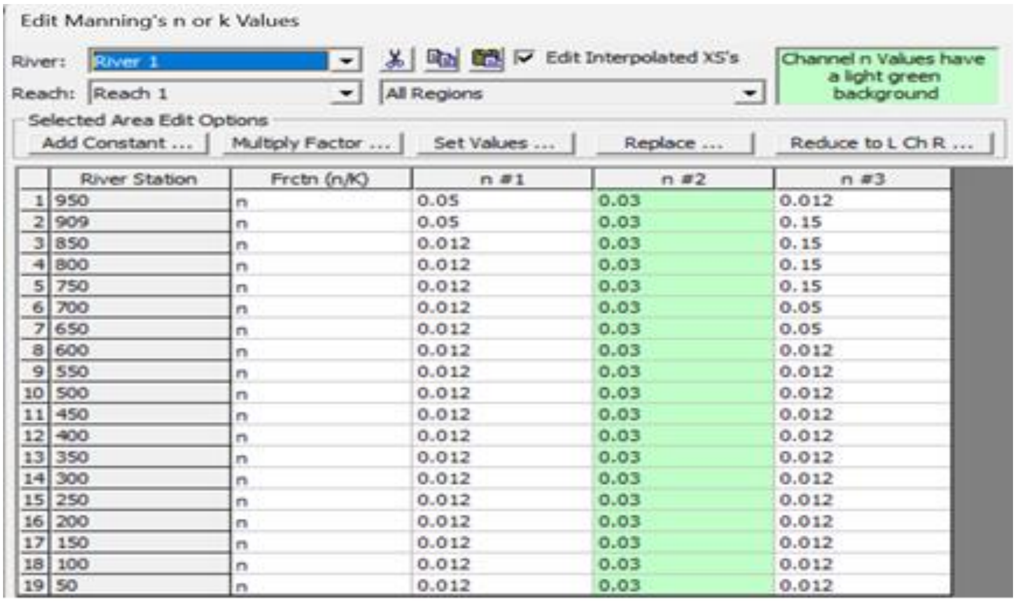


Fig. 7. Peak discharge design.

4.3. Flood Inundation Simulation

The modelling will result the region of flooding depends on the magnitude of the peak discharge. It causes a wider inundation when the peak discharge value is higher. There are both general, non-significant variances and similarities in the inundation distribution patterns for all return times. Inundation is simulated using HEC-RAS modelling in a 200 m cross-section. Data from past flood events in the Gajahwong River segment is used to calculate the cross-section's breadth.



Edit Manning's n or k Values

River: River 1 | Edit Interpolated XS's | Channel n Values have a light green background

Reach: Reach 1 | All Regions

Selected Area Edit Options: Add Constant ... | Multiply Factor ... | Set Values ... | Replace ... | Reduce to L Ch R ...

	River Station	Frctn (n/K)	n #1	n #2	n #3
1	950	n	0.05	0.03	0.012
2	909	n	0.05	0.03	0.15
3	850	n	0.012	0.03	0.15
4	800	n	0.012	0.03	0.15
5	750	n	0.012	0.03	0.15
6	700	n	0.012	0.03	0.05
7	650	n	0.012	0.03	0.05
8	600	n	0.012	0.03	0.012
9	550	n	0.012	0.03	0.012
10	500	n	0.012	0.03	0.012
11	450	n	0.012	0.03	0.012
12	400	n	0.012	0.03	0.012
13	350	n	0.012	0.03	0.012
14	300	n	0.012	0.03	0.012
15	250	n	0.012	0.03	0.012
16	200	n	0.012	0.03	0.012
17	150	n	0.012	0.03	0.012
18	100	n	0.012	0.03	0.012
19	50	n	0.012	0.03	0.012

Fig. 8. Manning coefficient.

Manning's coefficient data was determined for each cross section. Manning's coefficient can affect the kinetic energy of river flow. Rough surface conditions cause the flow to be turbulent and the flow is slow. The condition of the banks of the Gajahwong River segment in this study is dominated by built-up land in the form of settlements. This dense built-up land is found on both the right and left of the perpendicular and sloping riverbanks with a height of 2.5–3 meters. The coefficient values assigned to the floodplain on the right and left of the river are 0.012, 0.05, and 0.15 (**Fig. 8**), while the cross sections that show straight and unobstructed river flow have a coefficient of 0.03.

The greater the probability of a return period, the larger the flooded region. In particular, the inundation area is 52,891.3; 62,142.1; 67,702.6; 74,269.8; and 79,396 m^2 for return period of 2-, 5-, 10-, 25-, and 50-years, respectively. Each return period has an additional inundation area. The inundation area has increased by an average of 6,626.2 m^2 for each return period. However, the additional area is spread out with a pattern that tends to be uniform. It can be said that there is a continued inundation area from the increase in return period. Meanwhile, an increase in flood inundation depth occurs as the flood return period increases. This can be seen in both cross-section samples in **Fig. 9.**, which show different free profiles for each return period, with the highest depth occurring during the 50-year return period (**Table 3**).

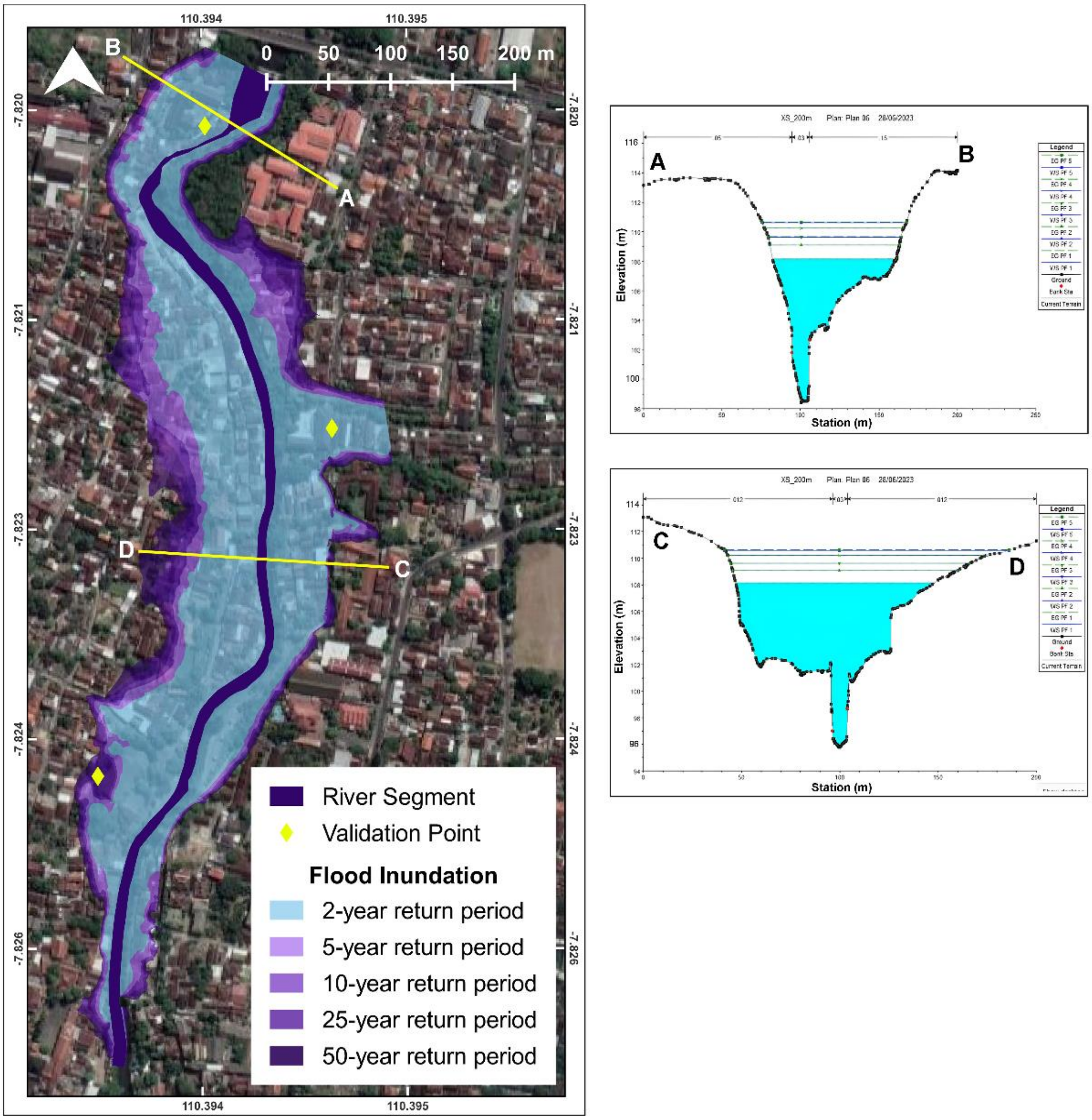


Fig. 9. Flood inundation simulation.

Table 3.

Area inundation from modeling in the Gajahwong River segment.

Return Period (Years)	Flood Area (m^2)	Increase in Inundation Area (m^2)
2	52,891.3	-
5	62,142.1	9,250.8
10	67,702.6	5,560.5
25	74,269.8	6,567.2
50	79,396	5,126.2
Average increase in inundation area		6,626.2

Residential areas, including various types of buildings such as mosques, parks, elementary schools, and campuses, dominate the land use in inundated areas. The built-up area around rivers is categorized as an element at risk, which increases the risk of flood hazards due to the large number of elements at risk. The influence of human activity through built-up land causes an increase in the surface runoff coefficient so that surface runoff production will also increase along with the presence of humans (Budiman and Suprayogi, 2024). Therefore, it is essential to implement adaptation and mitigation measures for flood disasters in this region. Given the scenario of continuously changing land use due to city growth, it can be said that there is a probability of wider flood inundation for peak events with a higher return period (Thakur et al., 2017). The yellow rhombus on **Fig. 9.** shows that points 1, 2, and 3 are drowned due to floods in the Gajahwong River. The 2010 Mount Merapi eruption, which flooded residences along the riverbanks, was the most severe flooding in the previous 20 years, according to interviews. This was due to the fact that there was no permanent embankment built along the river at that time. The river's capacity could not keep up with the increasing water output, and in the absence of an embankment, the river spilled, flooding residential areas.

4.4. River Embankment Evaluation

River embankments must be evaluated using concentration time and river slope data. The amount of time it takes for river water to move from upstream to the inlet section of the study area is known as the concentration time. The formula was used to determine river flow concentration time (Tc). It was determined that the Gajahwong Watershed River flow had a concentration-time of 2.74 hours and a river slope of 3%.

Table 4.

Embankment characteristic.

River Characteristics	Embankment Scenario	
	3-meters	4-meters
Channel wet cross-section area (Ae)	14.5 m^2	18 m^2
Surrounding wet channel (P)	16.708 m	18.944 m
Hydraulic radius (R)	0.868 m	0.95 m
Manning coefficient (plastered river stone)	0.012	0.012
Water velocity in channel	8.91 m/s	11.835 m/s
Channel discharge capacity	106.97 m^3/s	213.042 m^3/s

Table 5.

Simulation status.

Return Period (years)	Peak Discharge (m^3/s)	3-meters scenario		4-meters scenario	
		Channel Capacity Discharge (m^3/s)	Simulation Status	Channel Capacity Discharge (m^3/s)	Simulation Status
2	61.41		No Flood		No Flood
5	98.94		No Flood		No Flood
10	123.79	106.97	Flood	213.042	No Flood
25	155.18		Flood		No Flood
50	178.46		Flood		No Flood

Within the table over, it can be seen that if the peak discharge is lower than the channel capacity discharge then flooding will not occur, but if the peak discharge value is greater than the channel capacity discharge then flooding will occur. The design for a 3-meters embankment is displayed in **Table 4.** The data indicates that 106.97 m^3/s is the channel discharge capacity. The river will be unable to handle the flow if the peak discharge is more than the channel discharge, which will produce flooding as the river overflows. 3-meters tall embankments can lessen flood inundation during 2- and 5-year return intervals. However, an embankment higher than 3 meters is required for return times of 10-, 25-, and 50-years.

Given an embankment height of 4-meters for the Gajahwong River segment, calculations reveal a channel discharge capacity of 213.04 m^3/s (**Table 5**). If the peak discharge is below the channel discharge, the river can handle the flow and prevent flooding. By building 4-meters embankments along the Gajahwong River exertion, flood inundation can be prevented. In order to reduce flooding in the study area caused by the Gajahwong River's overflow, the embankment height along the river section must be raised to 4-meters.

Nevertheless, the planning of these embankments requires consideration. Each of the 3- and 4-meter embankment has different consequences in terms of flood control effectiveness, environmental impacts, construction costs, and technical risks. The 3-meter embankment is estimated to be unable to accommodate the design discharge at 10-, 25- and 50-year return periods. Flood risks to settlements and infrastructure are also higher. However, a 3-meter embankment is more advantageous than a 4-meter embankment in terms of construction costs and environmental impacts. A higher increase in flow capacity could potentially increase the risk of cliff erosion. In addition, there is a greater possibility of river profile changes occurring. However, a 4-meter embankment would be more resistant to peak discharge. The implementation of both scenarios should be accompanied by nonstructural mitigation, such as cliff erosion control using natural vegetation or additional protective structures.

5. CONCLUSIONS

The HEC-RAS models can be employed in other flood-prone areas to manage flood control through real-time simulation and guarantee dependability. Creating side channels is preventative steps that can lessen damage and the likelihood of flooding. For flood return periods of 2-, 5-, 10-, 25-, and 50-year, the peak flood discharge in the Gajahwong River segment obtained using the rational technique is 61.41 m^3/s, 98.94 m^3/s, 123.79 m^3/s, 155.18 m^3/s, and 178.46 m^3/s, respectively. The five return periods' design rainfall values differ significantly, according to the principle of probability and in accordance with the rising design rainfall value that affects the peak discharge, which explains the significant differences in peak flood discharges between the two return periods of 2- and 50-years. In line with the Gajahwong River's flood inundation modelling results using HEC-RAS, the area grows steadily as the peak discharge rises for every return period. The flood inundation area is 52,891.3 m^2, 62,142.1 m^2, 67,702.6 m^2, 74,269.8 m^2, and 79,396 m^2 for each of the following return periods: 2, 5, 10, 25, and 50 years. There is a probability of wider flood inundation as the consequences of the city's growth. To manage flood disasters in the Gajahwong River section, a 4-meters embankment is necessary because the 3-meters embankment design is unable to handle the river flow when the peak discharge is surpassed. Flood control efficacy, environmental effects, construction costs, and dangers must all be balanced when designing 3- and 4-meter embankments. The 4-meter option offers superior peak discharge resistance, but its best execution necessitates nonstructural techniques like erosion management.

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AUTHORS' CONTRIBUTIONS

Research conceptualization: SPS, SS; data collection and processing: SPS; statistical analysis: SPS; result interpretation: SPS, SS, SB; manuscript preparation: SPS, SB; literature review: SPS, SB.

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