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Flood Risk Analysis in Gajah Wong River, Yogyakarta City

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ABSTRAK

Evaluasi kejadian banjir di suatu wilayah perlu dilakukan agar dampak yang diakibatkan oleh banjir dapat diminimalisir, salah satunya dengan pemodelan hidrologi dan hidraulika sungai. Kejadian banjir di Sungai Gajah Wong pada tahun 2016 dan 2022 menyebabkan tanggul Sungai Gajah Wong jebol, akibatnya banjir terus meluap dan masuk ke permukiman warga setinggi 2 meter. Penelitian ini bertujuan untuk menganalisis risiko yang ditimbulkan dari banjir luapan Sungai Gajah Wong, serta mengidentifikasi elemen berisiko akibat bahaya banjir. Pemodelan skenario genangan banjir menggunakan HecRAS membutuhkan input debit puncak, DTM *(Digital Terrain Model)*, dan *koefisien manning.* Ekstraksi foto udara resolusi tinggi digunakan untuk menghasilkan DTM dan mengidentifikasi bangunan yang terdampak genangan banjir sesuai dengan pemodelan genangan. Perhitungan debit puncak menggunakan metode rasional dengan memanfaatkan data curah hujan maksimum harian dalam rentang tahun 2001 sampai tahun 2021. Hasil penelitian menunjukkan penambahan luas genangan untuk periode ulang banjir 25 dan 50 tahun sekitar 4.826 m^2. Sedangkan bangunan yang terdampak banjir seluas 30.350,68 m^2 untuk kala ulang 25 tahun dan 35.439,05 m^2 untuk kala ulang 50 tahun.

Kata kunci: Pemodelan Banjir, HecRAS, Gajah Wong

ABSTRACT

Evaluation of flood events in an area is essential to minimize its impacts by conducting hydrological and hydraulic river modeling. In 2016 and 2022, the events led to the breach of the Gajah Wong River levee, causing the floodwater to overflow and inundate residential areas, reaching a height of 2 meters. This study aims to analyze the risks posed by the Gajah Wong River overflow, while also identifying the elements at risk due to the potential of flooding. The flood inundation scenario modeling using Hec-RAS requires input such as peak discharge, Digital Terrain Model (DTM), and Manning's coefficient. High-resolution aerial photo extraction is employed to generate DTM and identify buildings affected by flood inundation, in accordance with the flood modeling. The rational method is used to calculate the peak discharge, utilizing the maximum daily rainfall data from 2001 to 2021. The results show that there was a significant expansion of inundation that reached 4.826 m^2 for the 2-year and 50-years flood return periods. However, in terms of the flood impact on buildings, an area of 30.350,68 m^2 is affected for the 2-year return period, and it expands to 35.439,05 m^2 for the 50-year flood.

Keywords: Flood Modelling, HecRAS, Gajah Wong

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1. INTRODUCTION

The watershed is a commonly used unit in water resource management that is divided into three sections: upstream, middle, and downstream. The watershed plays an important role in the management of water resources. (Suprayogi & Werdiningsih, 2014). The watershed is a concept that is fundamental to the understanding of hydrological processes for water resources planning and management (Yu X and Duffy C, 2018). Additionally, watersheds offer ecosystem services and regulate water-related functions due to their inherent ability to efficiently capture and retain rainfall while facilitating the flow of water resources. Moreover, watersheds provide benefits by serving as a resource to support the activities of living organisms within them. There are several components that influence watershed characteristics, e.g., soil type, land use, topography, slope steepness, and slope length. These characteristics play a role in responding to different rainfall intensities, influencing factors such as evapotranspiration, infiltration, percolation, surface runoff, groundwater content, and runoff (Asdak, 2014). The Opak Watershed is comprised of 12 sub-watersheds, namely Opak, Gawe, Buntung, Tepus, Kuning, Mruwe, Kedung Semerangan, Code, Winongo, Bulus, Belik, and Gajah Wong. The Gajah Wong sub-watershed is located in urban area which consists of Sleman Regency Yogyakarta City, and Bantul Regency. There is a segment of the Gajah Wong River, located in the Umbulharjo District, that experiences flooding every year. This river, which flows through the city of Yogyakarta, annually overflows and inundates residential areas during the high rainfall period. The Gajah Wong River levee was breached during the flood event in 2022, causing floodwater to overflow and inundate residential areas to a height of 2 meters. Furthermore, on March 18, 2021, a flood occurred in the Umbulharjo District due to heavy rainfall, and at least 50 households experienced losses as a result of the flood disaster (Tribun Jogja). According to the latest data from the Regional Disaster Management Agency of Yogyakarta City in 2022, a flood occurred in the Umbulharjo District on October 2-3, 2022. The flood was triggered by heavy rainfall, leading to the inundation of several houses.

Sekaranom (2021), the number of hydro-meteorological disasters, especially floods, is on the increase year by year. According to Ardiansyah (2020), the flood susceptibility interval is predominantly dominated by all zones of the Gajah Wong sub-watershed, ranging from the upstream to the downstream zones. Low-lying areas with a slope of 10%-15% are the most vulnerable to flooding (Igovic et al., 2017). The analysis of geological conditions and the determination of river distance using a Digital Elevation Model (DEM) has been identified as the most significant impact in mitigating flood risks (Lee et al., 2017). Temporary causes of flooding have been identified. These include changes in land use, geomorphology, failure of urban drainage systems and poor urban planning Dawson (2008). The distance from fault lines and soil types significantly influences flood susceptibility (Tehrany et al., 2017). Moreover, land use is also the most influential factor in hydrological functions, as represented by runoff and baseflow (Permatasari, 2017).

A flood hazard and flood risk map play an important role in managing flood risks. These instruments are utilized by the stakeholders to mitigate floods (Costabile, 2020). In a hydrological model, it is common to use a watershed unit as the study area (Edwards, et al., 2015). Spatial modeling can be employed to visualize the distribution of flood risk in the Gajah Wong River's segment. Hence, this research employed spatial modeling to simulate floods for both the 2-year and 50-year return periods using peak discharge data. The objective was to assess the potential risks posed by flooding in the Gajah Wong River. The identification of elements at-risk is conducted to understand the consequences of flood hazards on built-up land in both the present and future scenarios. This enables the implementation of flood mitigation measures to minimize losses and damages.

2. METHODS

2.1. Study Area

This study was conducted in the sub-watershed segment of Gajah Wong River, located in the Umbulharjo District of Yogyakarta City, as depicted in Figure 1. The selection of this sub-watershed as the research location was based on its urban setting, which is predominantly characterized by residential areas and a high susceptibility to flooding. Notably, there were several impacts of flood events, such as a levee breach in 2016, significant losses for at least 50 households in 2018, and the inundation of several houses from October 2nd to 3rd, 2022, as reported by the Regional Disaster Management Agency of Yogyakarta City. Disruptions to hydrological processes in urban areas escalate the risk of flooding, leading to both material and non-material losses.

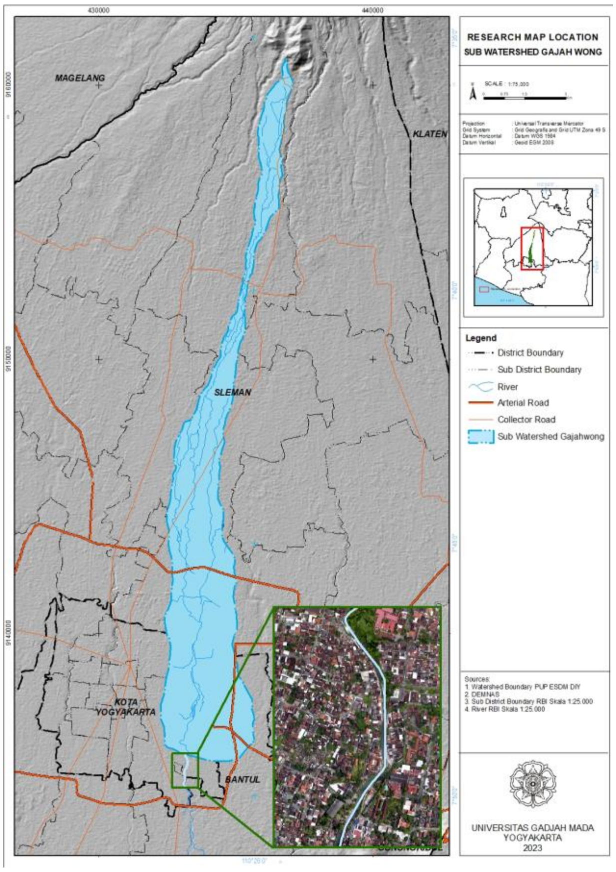

Figure 1. Location map of the study area

2.2. Peak Discharge

Water tends to remain within the watershed for an extended period during flood events (Suprayogi et al., 2022). Floods occur when the flow discharge reaches its peak. Flood evaluation using HEC-RAS modeling was conducted to assess the channel's capacity to convey flood discharge for each return period. The peak discharge was calculated using the equation below (Asdak, 2014):

$$Q = 0{,}278.\ C.\ I.\ A$$

where:

C = Runoff coefficient

I = Rainfall intensity (mm/hour)
A = Sub-watershed Area (Km^2)

a. Runoff Coefficient

The runoff coefficient can also be used to compare the response of each different land form in converting rain to surface runoff, according to Che, et al. (2018). The coefficient of surface runoff is a key concept in flood mitigation measures related to increasing surface runoff (Ramehiang, 2019). It serves as an indicator to assess whether a watershed has experienced disturbances. The C-value is influenced by the permeability and water-holding capacity of the soil, where a higher C-value indicates a greater proportion of rainfall turning into runoff. To calculate the runoff coefficient, information on land use, slope, soil type, and drainage density is utilized with Cook's method. The overlay mapping method is used to integrate information from multiple maps, allowing for a comprehensive determination of the runoff coefficient. The runoff coefficient is obtained through a weighted average calculation based on overlaid unit area values, as shown in the equation below:

$$C = \frac{(CaxLa) + (CbxLb) + \cdots + (CnxLn)}{La + Lb + \cdots + Ln}$$

where:
Cn = Runoff coefficient of the nth unit (%)
Ln = Area of the nth unit (ha)
C = Runoff coefficient (%)

b. Rainfall Intensity

The analysis of design rainfall is conducted by combining daily rainfall data processing with time concentration. The daily rainfall data used consists of maximum daily rainfall intensity recorded from 1991 to 2021, obtained from rain gauge stations around the Gajah Wong River, including the Angin-Angin, Beran, Bronggag, Gemawang, Karang Ploso, and Prumpung stations.

The obtained rainfall data is analyzed using various statistical parameters including mean (x), standard deviation (S), coefficient of variation (Cv), coefficient of skewness, and coefficient of kurtosis (Ck). The next step involves determining the appropriate distribution type based on these statistical parameters, which include normal distribution, log-normal distribution, Gumbel distribution, and log-Pearson Type III distribution. The chi-square test and Kolmogorov-Smirnov test are then performed to determine the best-fitting distribution.

To calculate the design rainfall for the 2-year and 50-year return periods, the following formula is used:

$$R_T = X_r + K_T S$$

where:
RT = Design rainfall for a T-year return period
Xr = Mean rainfall
S = Standard deviation
KT = Frequency factor for T-year return period

Afterwards, the design rainfall is used as an input in the Mononobe formula to determine rainfall intensity, as shown in the equation below:

$$\mathrm{I} = \frac{R24}{24} x \left(\frac{24}{tc}\right)^{2/3}$$

2.3. *Digital Terrain Model* (DTM)

According to Papaioannou, et al. (2016), the accuracy of river hydraulic models for flood inundation delineation is influenced by the accuracy of river geometric data. The flood modeling process involves the use of Digital Elevation Model (DEM) data and Manning's coefficient data. The DEM data is processed to generate the river cross-sectional geometry, which enables the modeling of flood inundation scenarios when the channel capacity is exceeded. The DEM data is obtained through aerial photo extraction, and the compilation of aerial photos and extraction of the DEM into a Digital Terrain Model (DTM) format is carried out using Agisoft software.

2.4. HecRAS

Hydrological modelling is a method used to simplify complex hydrological phenomena. The objectivity of researchers in conducting watershed modelling has a significant impact on the resulting hydrological model (Clark, et al., 2017). The input data for the analysis includes hydrological parameters, which consist of peak discharge for different return periods and reach boundary conditions. Steady flow analysis is employed for hydrological analysis in this study, as it specifically focuses on evaluating floods based on the peak discharge for each return period. Specifically, the peak discharge values for the 2-year and 50-year return periods are utilized as input data. The HEC-RAS modeling is then conducted, generating different flood inundation scenarios as the hydraulic calculations in the river respond differently to varying discharge values.

2.5. Flood Risk

The objective of conducting flood disaster risk assessment is to identify, evaluate, and mitigate potential risks. To comprehensively understand disaster risk, it is essential to consider key risk indicators, such as threats and vulnerabilities. Additionally, in previous studies, researchers have identified three fundamental indicators of disaster risk: threats, vulnerabilities, and capacities (Rahman, 2018). In this study, the focus is on assessing the physical vulnerability of the affected buildings due to flooding in the study area. The results of this analysis will generate flood risk maps based on the selected return periods, enabling the estimation of potential losses for each return period.

2.6. Model Validation

The validation of flood modeling generated by HEC-RAS involves a crucial step to ensure its accuracy and reliability. The validation process aims to evaluate the reliability of the modeled outcomes by comparing them to real-world flood conditions. According to Wibowo's research (2017), one approach to validate HEC-RAS modeling is through interviews with residents residing in areas affected by flooding. By gathering insights and firsthand accounts from the local community, the validation process gains valuable information. Additionally, comparing previous flood event maps to the modeled results provides another means of validation. By employing these varied validation techniques, the reliability and credibility of the HEC-RAS flood modeling can be enhanced, ensuring its effectiveness in assessing and managing flood risks.

3. RESULTS AND DISCUSSION

3.1. Regional Rainfall

Regional rainfall calculations are carried out using the Polygon Thiessen method. This method was chosen due to the uneven distribution of rainfall gauging stations and topographical conditions that do not vary too much. There are five rainfall measurement points used as interpolation points. Each point produces its area of influence. Based on the interpolation results, the coverage area of Bronggang rain gauge is 1.55 km^2, Gemawang rain gauge is 17.84 km^2, Karangploso rain gauge is 4.77 km^2, Prumpung rain gauge is 9.42 km^2, and Angin-Angin rain gauge is 3.67 km^2.

Daily rainfall in the Gajah Wong sub-basin ranges from 23.91 mm/day to 170.55 mm/day. The maximum daily rainfall in 2017 was much higher than in other years because of the occurrence of Cyclone Cempaka in 2017, so Yogyakarta experienced the influence of extreme rainfall (T. Kurniawan, 2017).

Frequency analysis calculations were performed on the maximum daily rainfall data. Frequency analysis is used to determine the appropriate type of probability distribution for calculating the design rainfall. The design rainfall then becomes the basis for calculating the design rainfall intensity. The results of the frequency analysis calculations using the normal and Gumbel distribution methods show that the coefficient of variation (cv) is 0.53, the coefficient of skewness (cs) is 0.97 and the coefficient of kurtosis (ck) is 0.52.

A goodness of fit test is then performed on the designed rainfall data. The goodness of fit test is carried out to determine the suitability of the frequency distribution of the data samples with the calculated results. Goodness of fit tests were performed using Chi-Square and Smirnov-Kolmogorov. Based on the results of calculating several statistical parameters, it was concluded that all types of distributions were acceptable. The type of distribution used to calculate the design rainfall is the Gumbel distribution, as the total rainfall value using the Gumbel distribution is higher than the other types of distribution.

3.2. Run-off Coefficient

Flow discharge is influenced by various factors, including topography, soil infiltration, vegetation cover, and surface storage. After weighting, the runoff coefficient value for the Gajah Wong River segment is determined to be 0.57 as shown in Table 1.

Based on the calculation results, it was found that the flow coefficient in the Gajah Wong sub-watershed was 0.57. This indicates that the area has a relatively high flow coefficient and a poor ability to store and channel rainfall that falls below the surface.

Table 1. Runoff coefficients in the study area

Watershed charactersitics	Characteristics that generate flow				Weight x Area	Total Area (km^2)	C	
	Extreme (100)	High (75)	Moderate (50)	Low (25)			Cn	Ct
Topography	Steep (>40%)	Hilly (10-40%)	Undulating (5-10%)	Flat (0-5%)				
Weight	0,4	0,3	0,2	0,1	5,5		0,17	
Area (Km)	0,007	5,126	11,504	16,602				
Soil infiltration	Rock with thin soil layer cover	Clay	Sandy Silt, Dusty Sandy Silt, Silt, Silty Clay	Sand, Sandy Silt	3,21		0,1	
Weight	0,2	0,15	0,1	0,05				
Area (Km)	0	0	31,025	2,214				
Vegetation	Settlements, vacant land	Irrigated rice fields, rainfed rice fields, and dryland fields	Mixed gardens, sparsely forested areas	Dense forests	5,27	33,24	0,16	0,57
Weight	0,2	0,15	0,1	0,05				
Area (Km)	18,545	1,927	12,742	0,024				
Surface storage	Negligible, strong slope, no lakes	Few, good slope, no lakes	Moderate, moderate to good slope, 2% of the area consists of lakes	Abundant, poor slope, many lakes	4,98		0,15	
Weight	0,2	0,15	0,1	0,05				
Area (Km)	0	33,22	0,018	0				

3.3. Peak Discharge

Peak flow calculations with 25-year and 50-year return periods are carried out assuming that the catchment parameters or characteristics are relatively the same or have not changed. The flow coefficient value used is the same for all return periods. The rainfall intensity and sub-catchment area used are also the same as in the previous calculation. The design rainfall data is then combined with the concentration time to give a design rainfall intensity value that is evenly distributed over the sub catchment. The peak discharge value of the Gajah Wong sub-watershed at return period 25 is 80.5 m^3/second, while for the 50-year return period, it reaches 92.5 m^3/second.

3.4. Flood Inundation Modeling

The HecRAS modeling results reveal a notable increase in flood from 76.763,85 m^2 in 25-year to 81.590 m^2 in 50-year return period floods, resulting in an additional area of approximately 4.826 m^2 being inundated which is shown in Table 2 and visualized in Figure 2 and 3. This variation in flood extent can be attributed to the calculated design discharge using the rational method, which plays a significant role in flood assessment. Specifically, the design discharge for the 25-year return period amounts to 80.5 m^3/second, while for the 50-year return period, it reaches 92.5 m^3/second. The peak discharge holds great importance in flood evaluation as it indicates the volume of water passing through a given channel section per unit of time, thereby impacting its capacity to accommodate the floodwaters. In this study, the estimation of peak discharge involved the rational method, which considers data on the runoff coefficient, rainfall intensity, and catchment area.

Table 2. Flood inundation area in the Gajah Wong River

Return Period (year)	C	I (mm/h)	A (km^2)	Q (m^3/ s)	Indundation Area (m^2)
25	0,57	15.27	33,24	80,5	76.763,85
50	0.57	17.56	33,24	92.5	81.590

3.5. Flood-affected Area

The quality of urban buildings has an impact on flood vulnerability as urban settlements consider flood risk reduction in their construction (Darabi et al., 2019). One example of adaptation is the construction of elevated house foundations to mitigate flood impacts (Thanvisitthpon, 2017). However, despite these efforts, certain residential areas remain susceptible to flooding caused by the overflowing Gajah Wong River. Using HEC-RAS flood inundation modeling, the data analysis reveals several elements at risk that are affected by the river's overflow, including parks, educational facilities such as schools and campuses, residential neighborhoods, and places of worship such as mosques and prayer rooms.

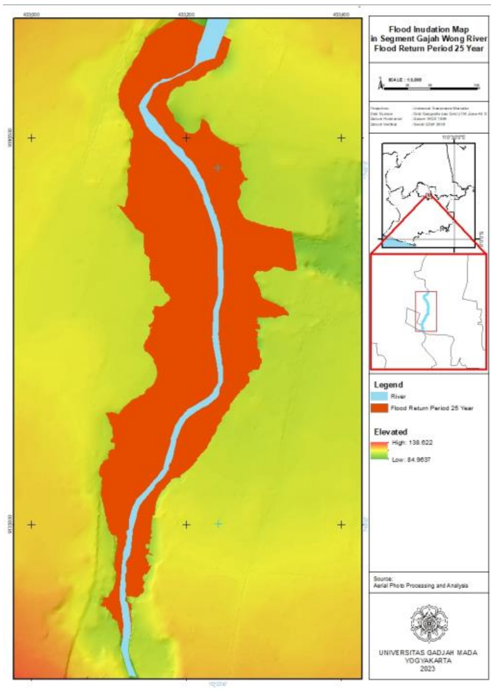

Figure 2. Inundation modeling 25-year return period

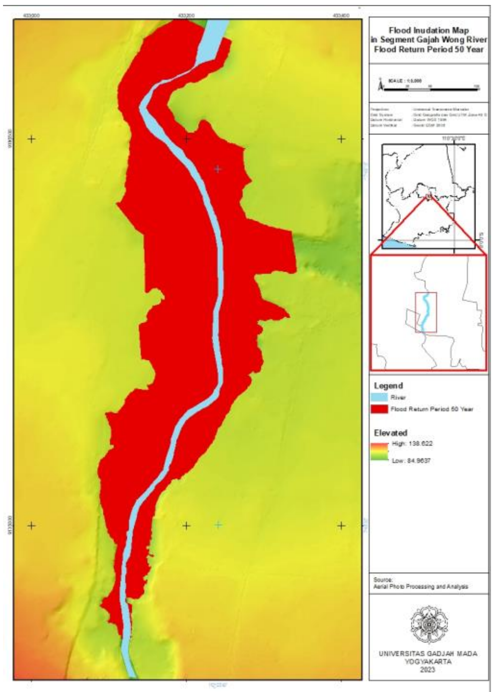

Figure 3 Inundation modeling for 50-year return period

In general, there is an expansion in the affected flood area for both the 25-year and 50-year return periods, totaling 81.590 m^2 as shown in Table 3. Based on Figure 5 and 6, which illustrates the comparison of affected areas for each element at risk, it is evident that the residential area has the highest level of impact along the Gajah Wong River for both the 25-year and 50-year return periods. This area also contributes significantly to the expansion of the affected areas, accounting for a total increased inundation area of approximately 5.088,37 m^2 for the 25-year and 50-year return periods. These expansions are visualized in Figure 4.

Table 3. Buildings affected by flood inundation in Gajah Wong River

Element at Risks	Affected area for 25-year return period (m^2)	Affected area for 50-year return period (m^2)
Park/Public Facilities	852,41	852,41
Educational Facilities	2.732,77	2.732,77
Residential Area	26.308,18	31.396,57
Mosque	457,3	457,3
Total	30.350,6	35.439

Source: Data Analysis, 2023

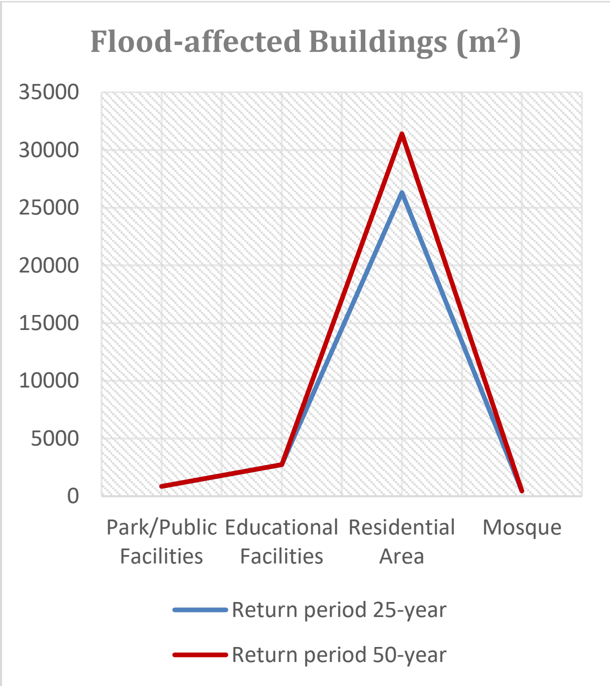

Figure 4. Flood-affected buildings

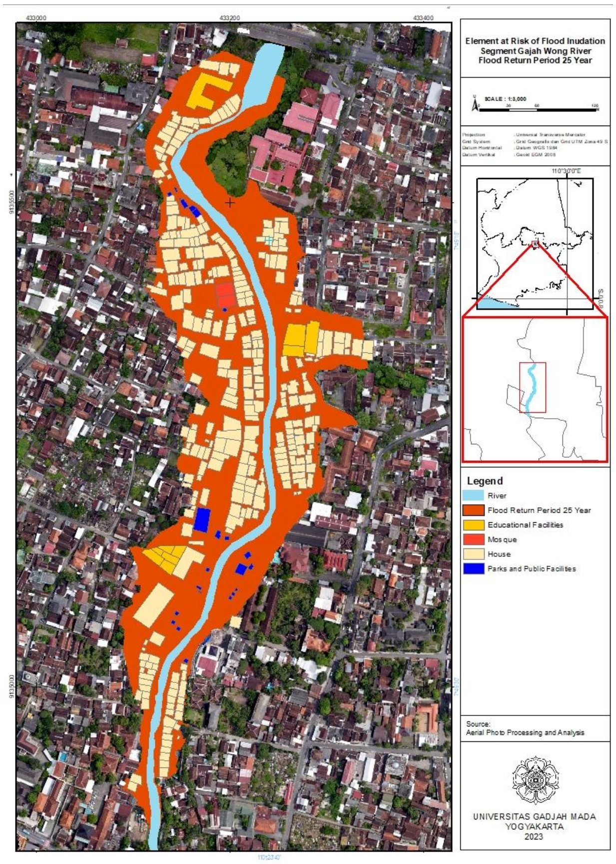

Figure 5. Flood-affected buildings map

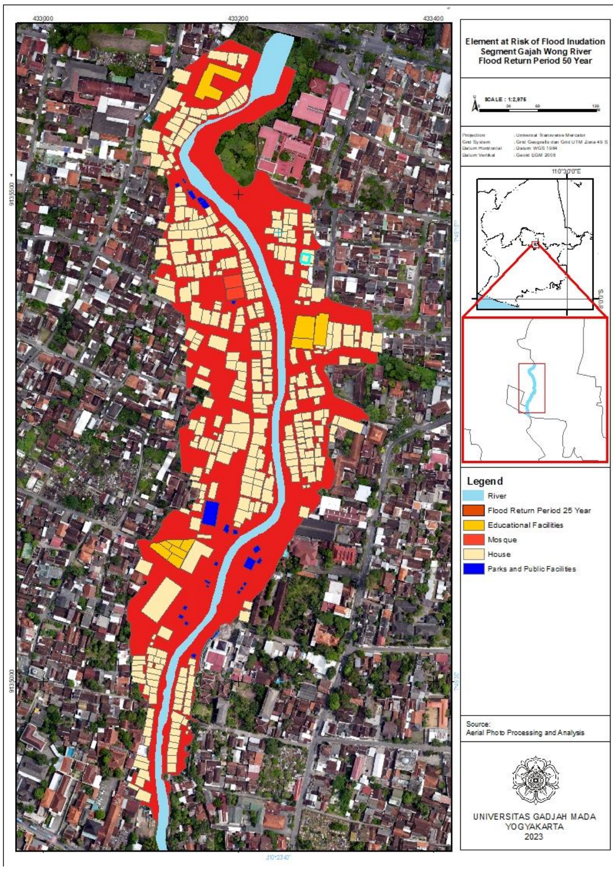

Figure 6. Flood-affected buildings map

3.6. Model Validation

(a) (b)

Figure 7. Validation of Flood Height in Affected Houses

Figure 7a represents a snapshot of the flood-affected area in 2023. In the modeling results, the area experiences flooding in the 25-year and 50-year flood scenarios. During the validation process, interviews with the local community confirmed that the river indeed overflowed, reaching a height of 1 meter. Moving on to Figure 7b, it illustrates the condition of house walls constantly exposed to flooding, resulting in cracks due to continuous water seepage.

4. CONCLUSION

Flood risks in the Gajah Wong River, as presented by the HecRas modeling, reveal an increase in the inundated area from 76.763,85 m^2 for a 25-year return period to 81.590 m^2 for a 50-year return period. During both periods, the most affected area is residential, reaching approximately 5.088,39 m^2. Other facilities impacted include parks, educational facilities, and places of worship, with a total affected area of about 30.350,6 m^2 for the 25-year return period and 35.439 m^2 for the 50-year return period.

The validation of this research, conducted by interviewing local people, confirmed the HecRas modeling results. Despite community validation, comparing the results with other modeling methods is necessary. Therefore, it is recommended for further study to employ other modeling methods to strengthen and complement the results of flood risk modeling in Gajah Wong River.

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