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Spatial Evaluation of Land-Use Planning Directives Based on Flood Disaster Risk Assessment and HEC-RAS Modeling in the Rajabasa River Riparian Zone

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ABSTRACT

The area surrounding the Rajabasa River is among the areas most frequently affected by riverine flooding due to a combination of high rainfall intensity, inadequate drainage capacity, sedimentation, and the accumulation of domestic waste. The increasing demand for developed land in urban areas is accommodated through the spatial planning directives stipulated in the Bandar Lampung Detailed Spatial Plan (RDTR) for 2025-2045, which predominantly promotes the development of residential areas, commercial and service zones, and public service facilities. However, the flood hazard map derived from the disaster risk assessment (kajian risiko bencana (KRB)) for the Rajabasa River riparian zone indicates that 19.82% of the designated residential areas and 23.39% of the designated commercial and service areas are located within flood-prone zones. The Nakayasu Synthetic Unit Hydrograph (HSS) method was used to estimate design flood discharge, followed by Hydrologic Engineering Center–River Analysis System (HEC-RAS) 2D modeling to simulate flood inundation patterns along the Rajabasa River riparian zone. A spatial overlay analysis is subsequently conducted to compare the flood hazard map with the predicted inundation areas, providing a basis for evaluating and formulating recommendations for the spatial planning directives contained in the Bandar Lampung RDTR 2025–2045.

1. INTRODUCTION

The number of flood events recorded in Bandar Lampung City had reached 80 cases by June 2026, with a notable increase in flood occurrences between January and April [1]. Increased rainfall intensity contributes to higher river discharge, resulting in more frequent flooding during the rainy season [2, 3]. Rajabasa Subdistrict is among the areas most frequently affected by flooding, highlighting the need to strengthen community preparedness for flood hazards [4]. In general, flooding is triggered by rainfall exceeding normal levels, particularly during extreme weather events, when river and tributary systems are unable to accommodate the volume of runoff generated. Flood risk is further intensified by land-use changes that disregard environmental carrying capacity and by inadequate drainage systems, particularly in urban areas [5]. Based on the source of surface runoff, flooding can generally be classified into two types: upstream-induced flooding, which results from high rainfall in upstream catchment areas, and local flooding, which occurs when local rainfall exceeds the capacity of the drainage system [5, 6]. Both types of flooding occur in areas surrounding the Rajabasa River riparian zone.

The Rajabasa River is located within Rajabasa District, particularly across Rajabasa Raya, Rajabasa, and Rajabasa Nunyai Subdistricts, and extends toward Langkapura District. A previous study [7] conducted in the vicinity of the Rajabasa River indicated that flooding in Rajabasa District is predominantly caused by river overflow, with river water levels frequently exceeding the height of embankments constructed independently by local communities. Another research [8] in the Rajabasa watershed demonstrated that surface runoff follows the existing drainage and flow network, resulting in gradual and prolonged flood events. Flooding in Rajabasa District is therefore not solely attributable to solid-waste accumulation in drainage channels, but is also strongly influenced by runoff originating from upstream areas at higher elevations. This condition indicates a mismatch between the capacity of the existing drainage system and the volume of runoff received by the area [9]. Accordingly, flooding along the Rajabasa River riparian zone occurs primarily because the drainage system is unable to accommodate increased river discharge during periods of high rainfall, particularly when additional runoff is conveyed from upstream areas.

The consequences of flooding are multidimensional, encompassing not only structural damage to residential buildings and public infrastructure but also substantial disruptions to the social and economic activities of affected communities [10-12]. Flooding is one of the most destructive natural hazards, capable of causing extensive damage along its

path. Historical evidence from various regions worldwide demonstrates that flood events have resulted in widespread losses of human life and property and have accounted for approximately two-thirds of total losses associated with natural disasters, both in terms of frequency and economic damage [13-15]. Although various mitigation measures have been implemented to reduce flood impacts, flood-control interventions cannot provide complete protection because the potential scale of associated problems and losses continues to increase and evolve. Furthermore, flood-related losses are often difficult to identify and quantify comprehensively [16].

In the context of flood management, spatial planning plays a critical role. Adaptive and disaster-risk-informed spatial planning can serve as a strategic instrument for reducing flood risk. This includes regulating land use, protecting river riparian zones, and integrating ecological considerations and local knowledge into spatial management. Appropriate land-use planning can help reduce disaster losses and strengthen community resilience [17, 18]. Disaster-risk-based spatial planning should therefore become a fundamental principle for development in flood-prone areas, accompanied by the provision of sufficient green open spaces to function as water infiltration areas [19]. Land-use planning also contributes to strengthening resilience and reducing vulnerability and disaster risk by controlling the expansion of developed land and other land-cover classes into areas with high levels of hazard exposure [20-23].

The preparation of the Bandar Lampung Detailed Spatial Plan (RDTR) has incorporated the disaster risk assessment (kajian risiko bencana (KRB)) as one of its key planning parameters. KRB is conducted using a clearly defined methodology referring to Regulation of the Head of the Indonesian National Disaster Management Agency (BNPB) No. 02 of 2012 concerning the General Guidelines for KRB, as well as other relevant guidelines issued by national ministries and government agencies. The flood-related KRB is developed using spatial and physical datasets, including flood-hazard zoning, Shuttle Radar Topography Mission (SRTM) data, existing land-cover data, and socioeconomic information [24]. However, the KRB incorporated into the RDTR relies primarily on a geomorphological approach rather than hydrological modeling because of limited availability of baseline data and insufficient calibration data [25, 26]. In contrast, most flood-inundation mapping approaches incorporate hydrological analysis to estimate peak discharge, water-surface elevation, and the spatial extent of inundation [26, 27]. The geomorphological approach has generally been preferred because of the extensive spatial coverage of the planning area and the limitations of available hydrological data.

Although the spatial planning document has established land-use directives based on the KRB (KRB), the effectiveness of these directives in adequately accounting for flood hazards requires further evaluation. One approach is to apply hydraulic modeling using Hydrologic Engineering Center–River Analysis System (HEC-RAS) to generate flood-inundation maps, which can subsequently be used to conduct a spatial assessment of the consistency between planned land uses and simulated flood-hazard conditions. The study [28] has demonstrated a strong relationship between increasing river discharge and the extent of flood inundation, indicating that hydrological analysis and spatial modeling are important tools for supporting flood mitigation and sustainable watershed management. HEC-RAS can be used to analyze river flow, flooding, and water-related hydraulic conditions because it is designed to perform one- and two-dimensional hydraulic calculations for complete networks of natural and constructed channels, overbank and floodplain areas, leveed areas, and other hydraulic systems [29].

Based on these considerations, this study aims to evaluate the spatial suitability of land-use planning directives within the Rajabasa River riparian zone by comparing the disaster-prone areas identified in the spatial planning document with the flood-inundation areas generated through HEC-RAS modeling.

2. METHODOLOGY

2.1 Study area

This study was conducted within the Rajabasa River riparian zone in Rajabasa District, Bandar Lampung City. The Rajabasa River extends for approximately 3.82 km and passes through Rajabasa Raya, Rajabasa, and Rajabasa Nunyai Subdistricts, as well as part of Langkapura District. The Rajabasa River riparian zone was delineated using the buffer function in ArcGIS, with the Rajabasa River polygon used as the primary spatial input.

The analyzed riparian buffer extended from 0 to 50 m from the river boundary, in accordance with the Regulation of the Minister of Public Works and Housing of the Republic of Indonesia No. 28/PRT/M/2015 concerning the Determination of River and Lake Riparian Boundaries.

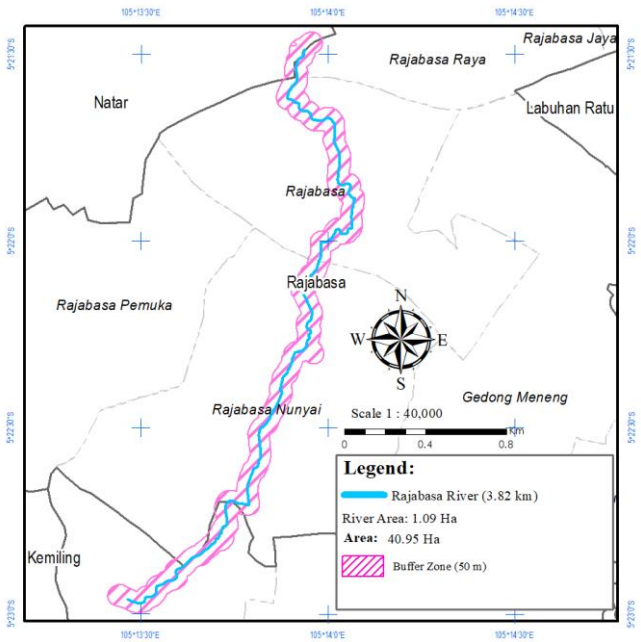


Figure 1. Map of the study area within the Rajabasa River riparian buffer zone

Figure 1 shows the Rajabasa River riparian buffer zone used as the study area. The 0–50 m buffer was used as the spatial unit for analyzing land use, RDTR directives, KRB, and flood inundation.

2.2 Nakayasu Synthetic Unit Hydrograph method

The Nakayasu Synthetic Unit Hydrograph (HSS) method

was used to estimate the design flood hydrograph of the Rajabasa River sub-watershed [30]. Design flood discharge is generally calculated using observed flood-event data or historical discharge records from a river or channel. However, when historical discharge data are incomplete or unavailable, a design rainfall approach is commonly applied as an alternative [31, 32]. In this study, the design flood discharge was estimated from design rainfall using the Nakayasu Synthetic Unit Hydrograph method.

Annual maximum rainfall data for the period 2016–2025 were analyzed using the Gumbel probability distribution to derive design rainfall for return periods of 2, 5, 10, 20, 25, 50, 100, and 200 years. The selection of the Gumbel distribution was based on the results of distribution fit tests and relevant previous references [33, 34].

The mean annual maximum rainfall was calculated using Eq. (1):

$$\bar{X} = \frac{1}{n}\sum_{i=1}^{n} X_i \tag{1}$$

The standard deviation of annual maximum rainfall was calculated using Eq. (2):

$$S = \sqrt{\frac{\sum_{i=1}^{n}(X_i - \bar{X})^2}{n-1}} \tag{2}$$

The reduced variate is calculated using Eq. (3):

$$Y_T = -\ln\left(-\ln\frac{T-1}{T}\right) \tag{3}$$

Calculate the maximum design rainfall and the Gumbel frequency factor using Eq. (4):

$$X_T = \bar{X} + k \times S_x \quad \text{Where, } K_T = (Y_T - Y_n)/S_n \tag{4}$$

Effective rainfall can be calculated using Eq. (5) [35]:

$$R_n = C \times R \tag{5}$$

where,

X_i = Annual maximum rainfall in year (i) (mm);
$\bar{X}$ = Mean annual maximum rainfall (mm);
n = Number of years of rainfall observations;
S_x = Standard deviation of annual maximum rainfall (mm);
T = Return period (years);
Y_T = Gumbel reduced variate for return period (T);
Y_n = Mean reduced variate;
S_n = Standard deviation of the reduced variate;
K_T = Gumbel frequency factor; and
X_T =Design rainfall (mm) corresponding to a return period of (T);
Rn = Effective rainfall (mm/hour);
C = Run off coefficient;
R = Design rainfall (mm/hour).

The analysis resulted in a mean annual maximum rainfall of 84.734 mm and a standard deviation of 28.737 mm. The Gumbel parameters used in the analysis were Y_n = 0.4952 and S_n = 0.9496. The resulting design rainfall values were 80.839, 115.140, 137.849, 159.633, 166.543, 187.830, 208.959, and 230.012 mm for the 2, 5, 10, 20, 25, 50, 100, and 200 year return periods, respectively.

The design rainfall was converted into effective rainfall using the composite runoff coefficient of the sub-watershed, as expressed in Eq. (6):

$$R_e = C \times X_T \tag{6}$$

where, R_e is effective rainfall (mm), C is the composite runoff coefficient, and X_T is the design rainfall (mm). The composite runoff coefficient obtained from the land-use characteristics of the Rajabasa River sub-watershed was 0.6811.

The effective rainfall was subsequently distributed into hourly rainfall depths to construct the design rainfall hyetograph. The rainfall intensity for duration T was calculated using Eq. (7):

$$I_t = \frac{X_T}{24}\left(\frac{24}{t}\right)^{2/3} \tag{7}$$

where, I_t is rainfall intensity for duration (t) (mm/hour), X_T is design rainfall (mm), and (t) is rainfall duration (hour). The resulting incremental rainfall depths were arranged into an hourly design hyetograph and subsequently converted into effective rainfall depths using the composite runoff coefficient.

The Nakayasu Synthetic Unit Hydrograph was then constructed based on the physical characteristics of the Rajabasa River sub-watershed. The watershed area used in the calculation was 2.611 km², while the river length used for the Nakayasu calculation was 3.162 km. Because the river length was less than 15 km, the watershed lag time (T_g) was calculated using Eq. (8):

$$T_g = 0.21L^{0,7} (L < 15km) \tag{8}$$

where, L is the river length (km). Based on the characteristics of the study area, the calculated value of T_g was 0.470 hours.

The effective rainfall duration (T_r) was determined as:

$$T_r = 0.5 \times T_g \tag{9}$$

Resulting in T_r = 0.235 hours.

The time to peak discharge T_p was calculated using:

$$T_p = T_g + 0.8T_r \tag{10}$$

Resulting in T_p = 0.658 hours.

The Nakayasu recession coefficient α was calculated as:

$$\alpha = \frac{[0.47(LA)]^{0.25}}{T_g} \tag{11}$$

where, α is the watershed area (km²). L is the main river length (km). T_g is the lag time (hours). The resulting recession coefficient was α = 2.986.

The recession time corresponding to 30% of the peak discharge was calculated using:

$$T_{0,3} = \alpha t_g \tag{12}$$

Resulting in $T_{0,3}$ = 1.403 hours.

The peak discharge of the 1 mm unit hydrograph was calculated using:

$$Q_p = \frac{1}{3.6} \cdot \frac{A\, R_0}{0.3T_p + T_{0.3}} \quad (13)$$

where, R_0 is the unit effective rainfall depth of 1 mm. The calculated peak discharge of the 1-mm unit hydrograph was 0.453 m³/s.

The rising limb of the Nakayasu unit hydrograph was calculated using:

$$Q_t = Q_p \left(\frac{t}{T_p}\right)^{2.4} 0 < t \leq T_p \quad (14)$$

For the recession limb after the peak, the discharge was calculated using:

$$Q_t = Q_p (0.3)^{\frac{t-T_p}{T_{0.3}}} T_p < t \leq T_p + T_{0.3} \quad (15)$$

For the subsequent recession period, the discharge was calculated according to the Nakayasu recession relationship until the hydrograph approached zero. The resulting unit hydrograph was normalized to represent 1 mm of effective rainfall.

The design flood hydrograph was then obtained by convolution of the normalized Nakayasu unit hydrograph with the hourly effective rainfall hyetograph for each return period. The resulting design flood discharges were 0.91, 1.38, 1.65, 1.91, 1.99, 2.25, 2.51, and 2.76 m³/s at the first hour, and the peak discharges occurred at approximately the third hour, reaching 8.00, 12.11, 14.50, 16.79, 17.52, 19.76, 21.98, and 24.19 m³/s for the 2, 5, 10, 20, 25, 50, 100 and 200 year return periods, respectively. The resulting design flood hydrographs were subsequently used as inflow boundary conditions for the HEC-RAS hydraulic model.

2.3 Hydrologic Engineering Center–River Analysis System modeling

HEC-RAS was used to simulate river hydraulics using the design flood discharges derived from the HSS as boundary conditions. The model calculates water-surface profiles, flow velocities, and channel conveyance capacity, thereby enabling an assessment of potential river overflow and flood inundation associated with the design flood discharge.

Flood inundation modelling was conducted using the two-dimensional (2D) hydrodynamic model in HEC-RAS. The computational domain was developed using a Digital Elevation Model (DEM) as the terrain source, with the river geometry represented by the available cross-section data. A 2D flow area and computational mesh were generated to represent the floodplain, while Manning's roughness coefficient (n) was assigned according to the land-use characteristics within the modelling area. The design flood hydrograph obtained from the HSS Nakayasu analysis was applied as the upstream inflow boundary condition, while the downstream boundary condition was defined based on the hydraulic characteristics of the river outlet.

The unsteady flow simulation was performed using an appropriate computational time step based on the model stability and flow characteristics. The simulation results were evaluated based on water depth and spatial distribution of inundation. The maximum water depth generated during the simulation was subsequently used to delineate the flood inundation extent. The resulting inundation area was exported and spatially analyzed in a Geographic Information Systems (GIS) environment to identify the areas affected by flooding.

HEC-RAS simulations were conducted for several return periods, namely 2, 5, 10, 20, 25, 50, 100, and 200 years, to represent different levels of flood hazard. The resulting inundation areas, initially generated in KML format, were converted into shapefile (SHP) format and subsequently processed in ArcGIS. The integration of HEC-RAS and ArcGIS can facilitate the identification of flood-prone areas and provide a spatial basis for flood-mitigation planning and implementation [36, 37].

The HEC-RAS modeling results were subsequently compared with the spatial pattern directives stipulated in the RDTR for 2025-2045. Although the RDTR has a 20-year planning horizon, return periods of up to 200 years were included to evaluate the exposure of the study area to extreme flood events and to provide a basis for long-term flood-risk mitigation considerations.

2.4 Spatial data

The spatial data used in this study consisted of the 2025–2045 RDTR shapefile, which contains spatial planning directives and KRB classifications. The HEC-RAS modeling outputs, initially generated in KML format, were converted into shapefile format and subsequently overlaid with the RDTR spatial data for further analysis.

2.5 Geographic Information Systems analysis

The overlay method is a widely used spatial analysis technique in GIS, in which multiple spatial data layers within a common coordinate system are integrated to identify relationships among variables and delineate areas with overlapping characteristics, such as the spatial correspondence between disaster-prone areas and developed land [38, 39].

In this study, the overlay analysis integrated the planned residential area map, the flood KRB map derived from the 2025-2045 RDTR within the Rajabasa River riparian zone, and the flood inundation map generated through HEC-RAS simulation. This process aimed to identify areas designated for residential development that are simultaneously located within flood-risk zones according to the spatial planning document and predicted to experience inundation based on the HEC-RAS simulation results.

The overlay results were subsequently used to evaluate the spatial suitability of planned land use and the level of flood risk within areas designated for residential development.

2.6 Evaluation of land-use planning directives against potential flood inundation

The evaluation of land-use planning directives against potential flood inundation was conducted using an overlay analysis. The spatial datasets overlaid in this process included the RDTR land-use planning directives, KRB categories, and HEC-RAS modeling results representing inundation areas for the 20-year return period. The results were then used to develop an evaluation matrix. As part of the regulatory framework, the government has strengthened procedures for

the preparation, review, revision, and issuance of substantive approval for Detailed Spatial Plans (RDTR) to ensure that spatial planning remains adaptive to updated data and changing investment dynamics [40].

Previous reference [41] on the importance of law enforcement and spatial planning regulations in flood management has emphasized that spatial planning regulations may impose restrictions on development activities in areas exposed to high levels of flood risk. The government has also established a responsive legal framework capable of accommodating changing conditions and emerging challenges related to flood risk, including periodic reviews and adjustments of spatial planning regulations to ensure their continued relevance and sustainability.

This approach is reflected in Regulation of the Minister of Agrarian Affairs and Spatial Planning/Head of the National Land Agency of the Republic of Indonesia No. 9 of 2017 concerning Guidelines for Monitoring and Evaluation of Spatial Utilization. Accordingly, the evaluation matrix developed in this study consists of four recommendation categories: (1) consistent with the RDTR directives, (2) consistent with the RDTR directives with mitigation measures, (3) requiring spatial plan review, and (4) requiring revision.

The RDTR directives were further classified into two broad categories. The first category comprises directives associated with developed land, including residential areas, commercial and service areas, and public service facilities. The second category consists of non-developed land uses, including water bodies, road areas, and locally protected zones. Table 1 presents the RDTR evaluation matrix based on KRB and HEC-RAS inundation modeling results.

Table 1. Bandar Lampung Detailed Spatial Plan (RDTR) evaluation matrix

RDTR Spatial Planning Directive	Disaster Risk Assessment (KRB)	HEC-RAS Flood Modeling Result	Recommendation
Commercial and Service Area, Residential Area, Public Service Facilities	Present (Flood)	Inundated	Revision Required
Commercial and Service Area, Residential Area, Public Service Facilities	Absent	Inundated	Requires Reassessment
Commercial and Service Area, Residential Area, Public Service Facilities	Present (Flood)	Not Inundated	
Water Body, Road Network, Green Belt, Riparian Protection Area	Absent	Inundated	Consistent with the Spatial Planning Directive, Supported by Mitigation Measures
Commercial and Service Area, Residential Area, Public Service Facilities	Present (Other disaster)	Not Inundated	
Commercial and Service Area, Residential Area, Public Service Facilities	Absent	Not Inundated	Consistent with the Spatial Planning Directive
Water Body, Road Network, Green Belt, Riparian Protection Area	Absent	Not Inundated	

Source: Authors' own analysis based on RDTR spatial planning data, disaster risk assessment (KRB), and Hydrologic Engineering Center–River Analysis System (HEC-RAS) flood modeling results.

3. RESULTS AND DISCUSSION

3.1 Rainfall analysis

The following is a summary of the area of influence and C values for the three stations, as shown in Table 2.

Table 2. Summary of the area of influence and Thiessen coefficient

Weather Station	Area (ha)	Area (%)	Thiessen Coefficient (C)
Sidosari	132.93	50.91	0.51
Sukarame	43.25	16.57	0.17
Sumber Rejo Sejahtera	84.91	32.52	0.32
Total	261.09	100.00	1.00

Source: Authors' own analysis based on Thiessen polygon analysis of the rainfall station network.

The catchment area of each rainfall station was determined using the Thiessen method. The average regional rainfall was obtained by weighting the maximum rainfall recorded at each station using the corresponding Thiessen coefficients. The resulting average regional rainfall represents the rainfall distribution over the catchment area. The annual maximum regional rainfall for the 2016–2025 observation period is presented in Table 3.

Table 3. Annual maximum regional rainfall for the 2016-2025 observation period

Year	Xi max	Year	Xi max
2016	58.55	2021	71.75
2017	113.36	2022	73.93
2018	62.57	2023	42.45
2019	95.23	2024	119.89
2020	80.19	2025	129.42

Source: Authors' own analysis based on annual maximum regional rainfall data for 2016–2025.

Based on the annual maximum regional rainfall presented in Table 3, a frequency analysis was conducted using the Gumbel probability distribution to determine design rainfall for return periods of 2, 5, 10, 20, 25, 50, 100, and 200 years.

The resulting design rainfall values are presented in Table 4.

The goodness-of-fit tests indicated that the Gumbel probability distribution was suitable for the rainfall frequency analysis. The Chi-square test resulted in a calculated value of 3, which was lower than the critical value of 5.991. The Smirnov–Kolmogorov test also indicated that the Gumbel distribution satisfied the required acceptance criterion.

The design rainfall was subsequently converted into effective rainfall using the composite runoff coefficient of 0.6811. The resulting effective rainfall values were 55.061, 78.423, 93.891, 108.728, 113.434, 127.933, 142.325, and 156.664 mm for the 2, 5, 10, 20, 25, 50, 100, and 200 year return periods, respectively. These effective rainfall values were then distributed into hourly rainfall depths to construct the design rainfall hyetograph for the Nakayasu Synthetic Unit Hydrograph analysis. Table 4 presents the design and effective rainfall for each return period.

Table 1. Design and effective rainfall based on the Gumbel probability distribution

Probability	Return Period (Years)	Design Rainfall (mm)	Effective Rainfall (mm)
0.500	2	80.839	55.061
0.200	5	115.140	78.423
0.100	10	137.849	93.891
0.050	20	159.633	108.728
0.040	25	166.543	113.434
0.020	50	187.830	127.933
0.010	100	208.959	142.325
0.005	200	230.012	156.664

Source: Authors' own analysis based on Gumbel frequency analysis and effective rainfall calculation using the composite runoff coefficient.

3.2 Flood discharge analysis

The design flood discharge was calculated using the Nakayasu Synthetic Unit Hydrograph method based on the Rajabasa River sub-watershed area of 261.09 ha. The calculated flood discharges (Q) for return periods of 2, 5, 10, 20, 25, 50, 100, and 200 years are presented in Table 5.

The Nakayasu Synthetic Unit Hydrographs for the different return periods exhibit similar hydrograph shapes, with the primary difference occurring in the magnitude of the peak discharge. Figure 2 presents the hydrographs for all return periods considered in this study, ranging from 2 to 200 years.

Table 2. Design flood discharge for different return periods in the Rajabasa River sub-watershed

Return Period (Years)	Flood Discharge (m^3/s)					
	Hour 1	Hour 2	Hour 3	Hour 4	Hour 5	Hour 6
2	0.91	1.63	8.00	4.48	3.07	2.28
5	1.38	2.48	12.11	6.78	4.65	3.45
10	1.65	2.96	14.50	8.12	5.57	4.14
20	1.91	3.42	16.79	9.40	6.45	4.79
25	1.99	3.57	17.52	9.81	6.73	4.99
50	2.25	4.03	19.76	11.06	7.59	5.63
100	2.51	4.48	21.98	12.30	8.44	6.27
200	2.76	4.93	24.19	13.54	9.29	6.90

Source: Authors' own calculations based on the Nakayasu Synthetic Unit Hydrograph analysis.

Based on the results of the Nakayasu Synthetic Unit Hydrograph analysis, the design flood discharge increases with longer return periods. Peak discharge occurs at the third hour for all return periods, with a value of 8.00 m^3/s for the 2-year return period and increasing to 24.19 m^3/s for the 200-year return period. Although the general hydrograph shape remains relatively similar across the return periods, the increase in peak discharge indicates that less frequent flood events have the potential to generate substantially greater runoff and consequently higher hydraulic loading on the river system.

These results indicate that the return period strongly influences the magnitude of design flood discharge and, consequently, the potential depth and extent of inundation simulated using the HEC-RAS model. Therefore, the use of multiple return periods in this study is necessary to represent variations in flood hazard levels and to provide a basis for evaluating the suitability of the spatial pattern directives contained in the Bandar Lampung RDTR 2025–2045.

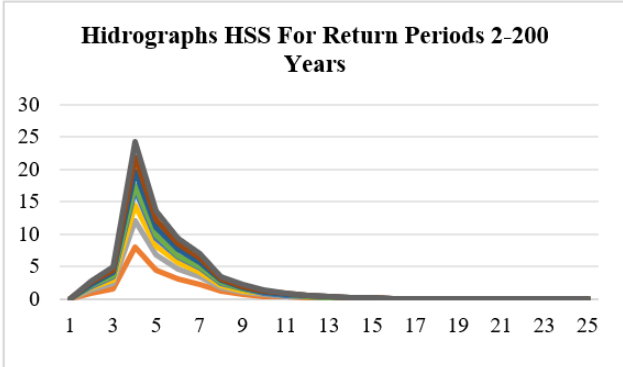


Figure 2. Nakayasu Synthetic Unit Hydrographs for the 2, 5, 10, 20, 25, 50, 100, and 200 year return periods

3.3 Qualitative validation for Hydrologic Engineering Center–River Analysis System simulation result

A qualitative validation of the flood inundation simulation was conducted by comparing the simulated inundation areas with historical flood occurrences in the study area. The validation covered five administrative areas along the Rajabasa River, namely Rajabasa Raya, Rajabasa, Rajabasa Nunyai, Langkapura, and Hajimena. Historical flood information, including the occurrence and frequency of flood events, was used as a reference to assess whether the areas identified as inundated by the HEC-RAS 2D model were generally consistent with areas where historical flood occurrences had been recorded. Table 6 compares historical flood occurrences with the HEC-RAS 2D simulation results.

The comparison between historical flood occurrences and the HEC-RAS 2D simulation results shows a general qualitative agreement between the recorded flood events and the simulated inundation conditions. Rajabasa Raya, Rajabasa, Rajabasa Nunyai, and Hajimena recorded 2, 6, 11, and 6 flood occurrences, respectively, and all four areas were identified as inundated by the HEC-RAS 2D model. This qualitative agreement indicates that the areas identified as inundated by the model are generally consistent with administrative areas where historical flood events have been recorded.

In contrast, Langkapura recorded no historical flood occurrences and was also classified as not inundated in the HEC-RAS 2D simulation. The agreement between the historical records and model results provides qualitative support for the model's representation of flood-prone

conditions in the study area. However, this comparison should be interpreted as a qualitative validation based on historical flood occurrences, because the available historical data represent the number of recorded events rather than spatially detailed inundation boundaries or measured flood depths.

Table 6. Comparison between historical flood occurrences and Hydrologic Engineering Center–River Analysis System (HEC-RAS) 2D simulation results

Administrative Area	Flood Occurrences	HEC-RAS 2D Simulation Result	Agreement
Rajabasa Raya	2	Inundated	Consistent
Rajabasa	6	Inundated	Consistent
Rajabasa Nunyai	11	Inundated	Consistent
Langkapura	0	Not Inundated	Consistent
Hajimena	6	Inundated	Consistent

Source: Authors' own analysis based on historical flood occurrence records and Hydrologic Engineering Center–River Analysis System (HEC-RAS) 2D simulation results.

3.4 Flood inundation based on Hydrologic Engineering Center–River Analysis System modeling

In this study, the 20-year return period was selected as a temporal representation consistent with the planning horizon of the 2025–2045 spatial plan. This scenario was used to assess flood inundation conditions that may potentially occur within the current planning period. In addition, the 100-year and 200-year return periods were applied to represent major and extreme flood scenarios, respectively, providing a broader assessment of potential flood hazards under less frequent but more severe hydrological conditions.

The HEC-RAS modeling results were used to identify and compare the spatial extent of flood inundation within the Rajabasa River riparian buffer zone under each return-period scenario. The resulting inundation maps for the 20-year, 100-year, and 200-year return periods are presented in Figures 3, 4, and 5, respectively, and were subsequently used to evaluate the exposure of existing land use and RDTR spatial planning designations to flood hazards.

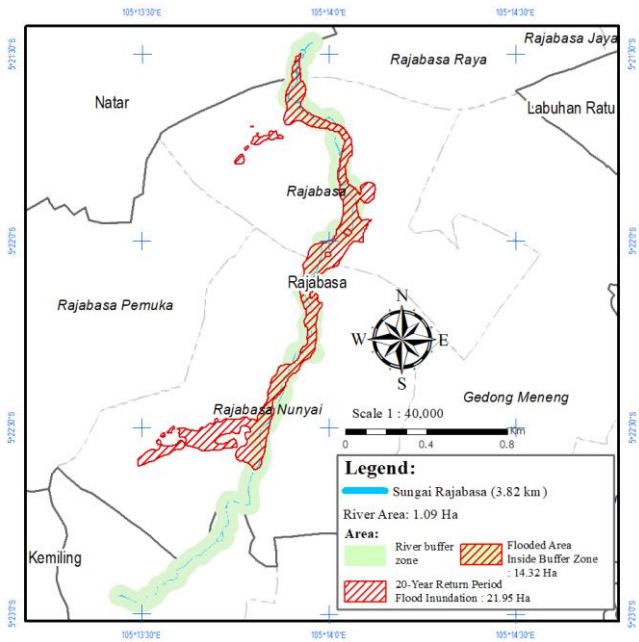


Figure 3. Flood inundation for the 20-year return period

The HEC-RAS simulation results for the 20-year return period indicate that flood inundation extends longitudinally along the river corridor, from the upstream area through Rajabasa Raya, Rajabasa, and Rajabasa Nunyai Subdistricts, covering approximately 34.97% of the total river riparian buffer area. In Rajabasa Nunyai, the inundation extends westward, which may be influenced by the surrounding topographic conditions.

The spatial distribution of the simulated inundation is consistent with the findings of previous reference [12, 42], which reported that Rajabasa Raya, Rajabasa Nunyai, and Rajabasa experience flooding since 2020 and classified as flood prone area. The drainage channels are relatively shallow and are frequently obstructed by accumulated solid waste and sediment, resulting in overflow during periods of high-intensity rainfall. The three inundated subdistricts exhibit similar physical conditions, particularly narrow drainage channels, sediment accumulation, and the accumulation of domestic solid waste.

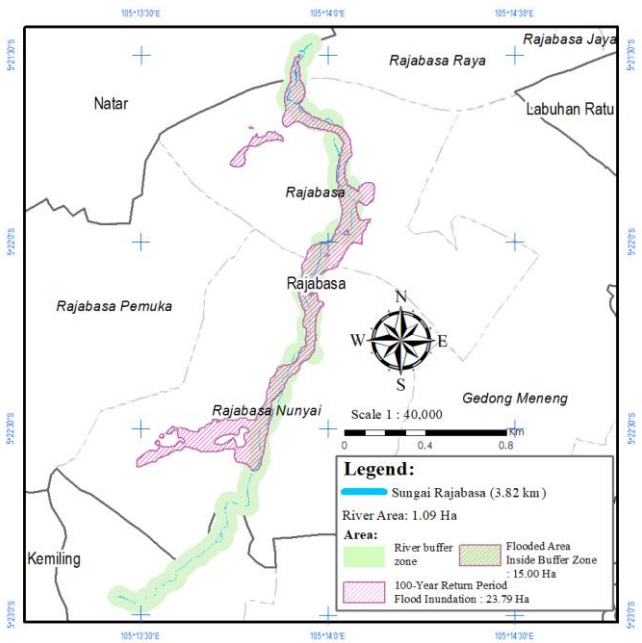


Figure 4. Flood inundation for the 100-year return period

The HEC-RAS simulation results indicate that the total flood inundation area increases by 1.80 ha between the 20-year and 100-year return periods. In comparison, the increase between the 100-year and 200-year return periods is relatively smaller, at 0.61 ha. Within the Rajabasa River riparian zone specifically, the inundated area increases by 0.68 ha from the 20-year to the 100-year return period and by a further 0.20 ha

from the 100-year to the 200-year return period.

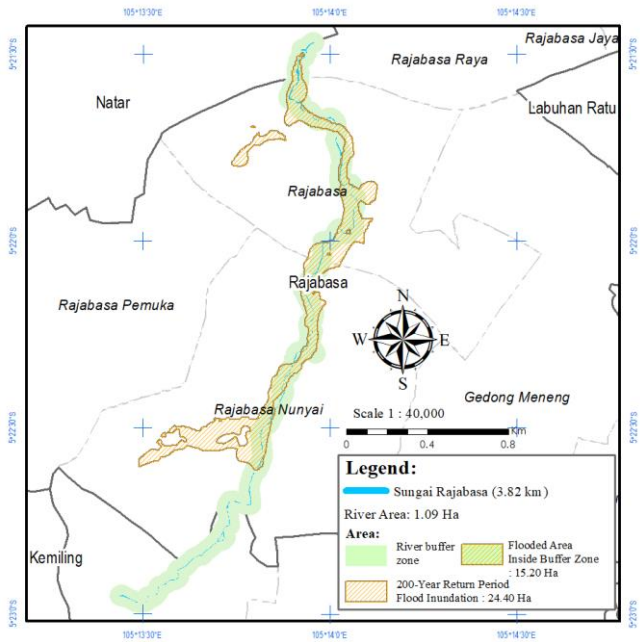


Figure 5. Flood inundation for the 200-year return period

The HEC-RAS simulations for different return periods indicate the potential for flood inundation within the study area. Under actual field conditions, the extent and severity of flooding may be exacerbated by the limited capacity of the drainage system, as well as by sedimentation and blockage within drainage channels, which reduce their ability to convey surface runoff effectively.

The relatively small differences in inundation extent among the three return-period scenarios indicate that an increase in the return period does not necessarily result in a substantial expansion of the inundated area. Thus, although the magnitude of flood discharge increases, the spatial extent of the affected area tends to remain relatively stable. The consistency between the simulated inundation areas and historical flood observations reported in the study [42] provides supporting evidence for identifying areas potentially exposed to flooding along the Rajabasa River riparian zone.

Nevertheless, as emphasized in the research [43], flood-inundation maps generated using HEC-RAS 2D combined with the Nakayasu Synthetic Unit Hydrograph method should be interpreted as representations of relative flood-risk patterns rather than as highly precise predictions of actual flood extent.

Overall, the HEC-RAS results indicate that flood exposure along the Rajabasa River riparian zone is spatially persistent across all modeled return periods. These findings provide a basis for subsequent evaluation of RDTR spatial planning directives, particularly in areas where planned land uses overlap with flood-prone zones.

3.5 Bandar Lampung Detailed Spatial Plan land-use planning directives

The land-use planning directives within the Rajabasa River riparian buffer are presented in Figure 6, while the area associated with each land-use category is summarized in Table 7. The RDTR designates a substantial proportion of the river riparian zone which ideally should remain free from permanent development for residential, commercial and service, and public service facility uses. Consequently, the spatial planning directives within the study area are predominantly oriented toward developed land uses. Overall, land-use directives associated with developed areas account for 88.48% of the total Rajabasa River riparian zone.

As visually illustrated in Figure 6, the river riparian zone, which should ideally be dominated by green areas representing riparian vegetation and protective functions, is instead predominantly designated for residential and commercial uses, represented by yellow, orange, and pink areas, as well as public service facilities, represented in purple. This condition is consistent with previous studies [44-47], which indicate that riparian buffer zones are increasingly threatened by human development activities and pressures from agricultural and urban expansion. Such pressures have been associated with inappropriate spatial planning practices in many countries over recent decades. These findings indicate that the protective function of the river riparian zone as an ecological buffer has not been adequately incorporated into the land-use planning directives established by the local government.

Table 7. Land-use planning directives within the Rajabasa River riparian zone

RDTR Spatial Planning Directive	Area (ha)
Water Body	0.78
Road Network	2.45
Green Belt	0.05
Commercial and Service Area (SWP Scale)	1.05
Commercial and Service Area (WP Scale)	1.64
Local Protection Area	1.43
Medium-Density Residential Area	31.39
Public Service Facilities (City Scale)	2.14
Public Service Facilities (Neighborhood Scale)	0.02
Total Area	40.95

Note: Bandar Lampung Detailed Spatial Plan (RDTR). Authors' own analysis based on RDTR spatial planning data for the Rajabasa River riparian zone.

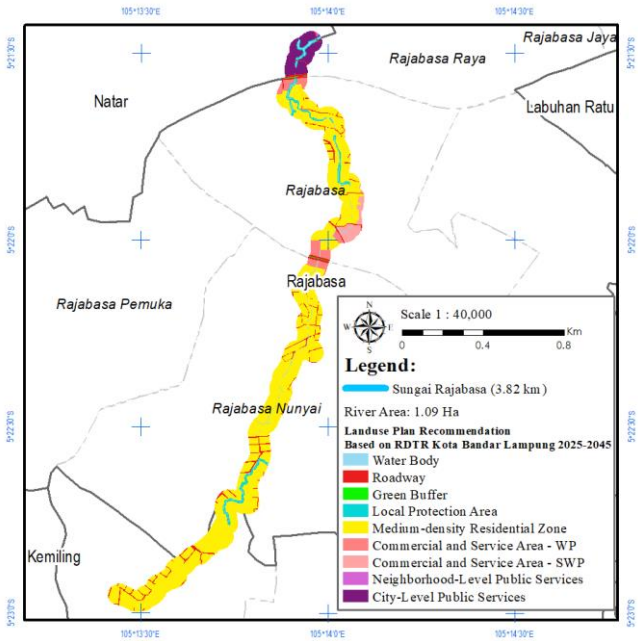


Figure 6. Spatial planning directives in the Bandar Lampung Detailed Spatial Plan (RDTR) 2025-2045

Locally protected areas and green belts should ideally constitute a substantial proportion of the Rajabasa River

riparian zone. However, under the RDTR directives, only 1.43 ha is designated for these functions, representing a relatively small proportion of the total riparian area. The predominance of residential, commercial, and service development within the river riparian zone may reduce the area's natural capacity to accommodate and attenuate surface runoff, potentially increase flood inundation, and increase the exposure of both residents and economic activities to flood hazards.

3.6 Flood disaster risk assessment in the Bandar Lampung Detailed Spatial Plan

To minimize flood disaster risk through non-structural measures, land-use control and monitoring are recommended, particularly in areas classified as having moderate to high flood risk [48]. The RDTR has incorporated the KRB as one of its planning parameters, with the KRB data derived from assessments conducted by the BNPB.

Within the Rajabasa River riparian study area, as shown in Figure 7, zones classified as having moderate and high flood hazard are predominantly distributed in the upstream section of the river. Other parts of the study area are also exposed to different types of natural hazards, including earthquakes. Table 8 summarizes the hazard classifications within each RDTR land-use designation.

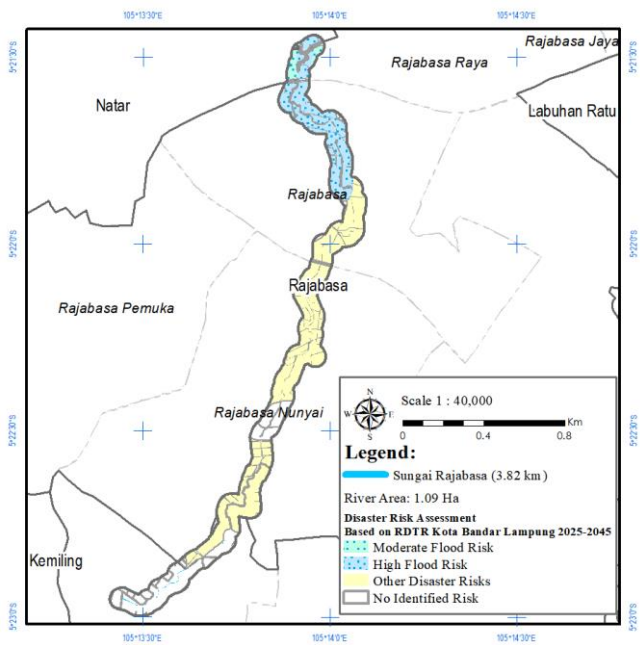


Figure 7. Flood hazard distribution within the Rajabasa River riparian zone

The KRB incorporated into the RDTR 2025-2045 indicates that 19.82% of the areas designated for residential development are located within high flood-hazard zones. All areas designated for public service facilities are classified as being exposed to flood hazards, while 23.39% of the areas designated for commercial and service activities are located within high flood-hazard zones. The residential, commercial and service, and public service facility areas identified as being exposed to flood risk were subsequently overlaid with the HEC-RAS modeling results to evaluate whether these planned development areas also have the potential to experience flood inundation.

3.7 Recommendations for evaluating land-use planning directives against potential flood inundation

Figure 8 presents the spatial distribution of areas in which the approved RDTR directives should be revised, reviewed, or maintained for implementation. Areas requiring revision are predominantly located in the northern part of Rajabasa Subdistrict, where the same locations are classified as flood-hazard areas in the KRB and are also predicted to be inundated based on the HEC-RAS simulation. Table 9 summarizes the recommendations for each RDTR land-use designation.

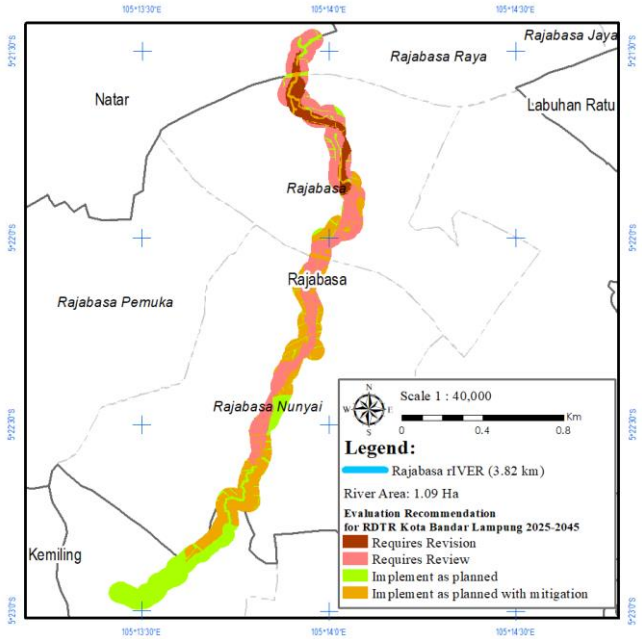


Figure 8. Recommended evaluation of the Bandar Lampung Detailed Spatial Plan (RDTR) within the Rajabasa River riparian zone

The largest proportion of the study area falls within the category requiring further review. These areas are predominantly designated for residential and commercial and service uses, are also exposed to other types of disaster hazards, and include several locations predicted to experience flood inundation. These findings indicate the need for a more detailed reassessment of the existing spatial planning directives before further development is implemented.

Residential areas are one of the land-use categories that require review, as they are directly linked to the level of exposure of the population and built assets to flooding. The review of spatial plans represents an important form of intervention in regulating spatial utilization by various development sectors and stakeholders [49]. Meanwhile, several other land-use directives may still be maintained, provided that they are accompanied by strengthened mitigation strategies, including controls on development intensity, the implementation of flood-control infrastructure, and the protection of river riparian zones. These findings indicate that the RDTR should be evaluated adaptively by incorporating flood-hazard information derived from hydraulic modeling, thereby ensuring that urban development during the 2025–2045 planning period does not increase flood risk.

For areas recommended for revision, a subsequent overlay analysis was conducted using existing land-cover data to

identify current activities and land-use conditions, particularly already-developed residential areas. The results of this overlay analysis are presented in Table 10.

Table 8. Distribution of flood-prone areas within the Rajabasa River riparian buffer zone

RDTR Designation	Moderate Flood	High Flood	Other Disasters	None
Water Body	-	-	-	0.78
Road Area	-	-	-	2.45
Green Belt	-	-	-	0.05
SWP-Scale Trade and Services	-	-	1.05	-
WP-Scale Trade and Services	-	0.53	1.20	-
Local Protection Zone	-	-	-	1.43
Medium-Density Residential Zone	-	6.22	18.46	8.71
City-Scale Public Service Facilities (SPU)	0.98	1.16		-
RW-Scale Public Service Facilities (SPU)	-	0.02		-

Note: Bandar Lampung Detailed Spatial Plan (RDTR). Authors' analysis based on RDTR spatial planning data and disaster risk assessment (KRB) for the Rajabasa River riparian buffer zone.

Table 9. Distribution of recommendations for land-use planning directives within the Rajabasa River buffer zone

RDTR Designation	Requires Reassessment	Requires Revision	In Accordance with the Designation	In Accordance with the Designation with Mitigation Measures	Total
Water Body	-	-	0.35	0.42	0.78
Road Area	-	-	1.57	0.88	2.45
Green Belt	-	-	0.02	0.03	0.05
SWP-Scale Trade and Services	0.78	-	-	0.27	1.05
WP-Scale Trade and Services	1.29	0.19	-	0.16	1.64
Local Protection Zone	-	-	0.82	0.61	1.43
Medium-Density Residential Zone	11.21	2.61	7.53	10.04	31.39
City-Scale Public Service Facilities (SPU)	1.90	0.24	-	-	2.14
RW-Scale Public Service Facilities (SPU)	0.02	-	-	-	0.02
Total	15.20	3.04	10.29	12.41	40.95

Source: Authors' analysis based on RDTR spatial planning data, disaster risk assessment (KRB), and flood modeling results for the Rajabasa River buffer zone.
Note: Bandar Lampung Detailed Spatial Plan (RDTR).

Table 10. Distribution of existing land-cover areas within land-use planning zones recommended for revision

Existing Land Cover	RDTR Designation			Total
	WP-Scale Trade and Services	Medium-Density Residential Zone	City-Scale Public Service Facilities (SPU)	
Water Body	0.00	0.25	0.09	0.34
Built-Up Land	**0.10**	**0.85**	**0.00**	**0.95**
Unbuilt Land	0.08	1.52	0.15	1.75
Grand Total	0.19	2.61	0.24	3.04

Source: Authors' analysis based on existing land-cover data and RDTR spatial planning zones recommended for revision.
Note: Bandar Lampung Detailed Spatial Plan (RDTR).

Table 10 indicates that 0.95 ha of existing developed land is currently consistent with the applicable RDTR land-use directives. However, the HEC-RAS simulation shows that this area is potentially inundated and is also classified as flood-prone according to the KRB. Therefore, it is strongly recommended that the spatial designation of this area be revised toward alternative land uses, particularly those associated with protection and ecological functions. If the RDTR is subsequently revised, the existing developed area may consequently be classified as a spatial-use conflict.

One strategy for reducing flood risk is to decrease human exposure within flood-prone areas by relocating settlements farther from river corridors or toward areas at higher elevations [50-52]. Accordingly, restoration of the developed riparian area represents a preferable long-term strategy. This approach is consistent with reference [53], which states that where river riparian zones have already been occupied or privately controlled by communities, their functions should gradually be restored to those of protected river setbacks. Meanwhile, areas that remain as water bodies or undeveloped land should retain their existing ecological functions, allowing future RDTR directives to be adjusted accordingly. A more detailed assessment should also be undertaken for areas classified as "requiring further review," particularly where maintaining or restoring ecological functions may generate greater long-term environmental benefits than the potential costs associated with land-use adjustment.

4. CONCLUSIONS

Based on the HEC-RAS modeling results, the design flood hydrograph reaches its peak at approximately the third hour, while the magnitude of peak discharge increases with longer return periods. For the 20-year return period, which was selected to correspond with the 2025-2045 planning horizon of the Bandar Lampung RDTR, the simulated flood inundation covers approximately 34.97% of the analyzed Rajabasa River riparian zone. The 100-year and 200-year return-period scenarios, representing major and extreme flood events, show relatively limited additional expansion of the inundated area, indicating that the spatial extent of flood-prone areas tends to remain relatively stable despite increases in flood discharge.

The existing RDTR directives within the study area are predominantly oriented toward developed land uses, including residential, commercial and service, and public service facility areas, several of which are located within flood-prone zones identified by the KRB. The spatial overlay between the RDTR directives, KRB flood-hazard areas, and HEC-RAS inundation results demonstrates that several existing spatial planning directives require further review or revision. In particular, development directives located within areas that are simultaneously identified as flood-prone by the KRB and predicted to be inundated by HEC-RAS should be reconsidered and, where appropriate, redirected toward protective and ecological functions.

These findings demonstrate the importance of integrating hydraulic flood modeling into the evaluation and future revision of detailed spatial plans. Such integration can strengthen disaster-risk-informed spatial planning and reduce the likelihood that future urban development within the Rajabasa River riparian zone will increase population, asset, and economic exposure to flood hazards.

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