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Flood Inundation Mapping in Medan Maimun, Medan City Using HEC-RAS 2D and the Nakayasu Synthetic Unit Hydrograph

Sarra Rahmadani*
Universitas Negeri Medan, INDONESIA

Dewi Fitria Marlisa
Universitas Malikussaleh, INDONESIA

Rumilla Harahap
Universitas Negeri Medan, INDONESIA

Siti Zulfa Yuzni
Universitas Negeri Medan, INDONESIA

Nanda Savira Ersa
Universitas Malikussaleh, INDONESIA

Cut Meuthia Rani
Universitas Negeri Medan, INDONESIA

Al Fatahillah
Universitas Negeri Medan, INDONESIA

Muh. Ilham Anggamulia
Universitas Muslim Indonesia, INDONESIA

Yusuf Aulia Lubis
Universitas Negeri Medan, INDONESIA

Anni Zahara Putri
Universitas Negeri Medan, INDONESIA

Wisnu Prayogo
Universitas Negeri Medan, INDONESIA

***Correspondence: E-mail:** sarra048@unimed.ac.id

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Abstract

Flood inundation mapping is a critical tool for urban flood risk assessment in tropical cities. This study investigates flood inundation extent in Medan Maimun Sub-district, Medan City, one of the most flood-prone areas in North Sumatra, Indonesia, where flood depths of approximately 3 meters were reported in February 2022 and December 2023. The study aims to: (1) determine design rainfall through frequency analysis and calculate design flood discharge for return periods of 2, 5, 10, 25, 50, and 100 years using the Nakayasu Synthetic Unit Hydrograph (SUH Nakayasu) method; (2) simulate flood routing using two-dimensional hydraulic modeling; and (3) map the resulting flood inundation extent for each return period. Rainfall frequency analysis used annual maximum rainfall data from two stations for the period 2014–2023, with the Log Pearson III method selected based on Chi-Square goodness-of-fit testing. Design flood discharges ranged from 383.403 m^3/s at the 2-year return period to 555.149 m^3/s at the 100-year return period. Flood routing and inundation mapping were performed using HEC-RAS version 5.0.7 integrated with RAS Mapper. Total inundation area increased from 110.982 ha at the 2-year return period to 126.581 ha at the 100-year return period, covering approximately 41.6% of the sub-district area at the 100-year return period. The model was not formally calibrated or validated against observed flood data; results should be interpreted as indicative of relative flood risk patterns rather than precise predictions. The flood inundation maps produced provide a useful scientific basis for flood mitigation planning in Medan city, Indonesia.

Keywords: flood modeling, medan maimun, hydrograph, hec-ras 2d, urban flood

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INTRODUCTION

Rapid urbanization in developing countries has significantly altered land use patterns, converting green open spaces into impervious built-up areas that reduce soil infiltration capacity and amplify urban flood risk (Salvadore et al., 2015). Land use change has been established as the dominant driver of increased surface runoff compared to other factors such as slope gradient, soil type, and vegetation cover, as densely vegetated land retains and infiltrates rainfall, whereas impervious surfaces redirect precipitation more directly toward drainage networks and rivers (Rahmadani, 2022). This phenomenon is particularly pronounced in rapidly developing Indonesian cities, where large-scale land conversion from agricultural and green spaces to built-up areas has significantly increased surface runoff and flood frequency (Surya et al., 2020).

In Indonesia, urban flooding remains one of the most frequently occurring and socioeconomically damaging natural disasters, particularly in densely populated cities where stormwater drainage infrastructure has not kept pace with rapid urban expansion (Budiyono et al., 2016). Medan City, the capital of North Sumatra Province, covers an area of 265.10 km² with a recorded population of 2,494,512 in 2022, yielding a population density of 9,410 persons/km² a 1.35% annual increase from the previous year. Despite its metropolitan status, Medan remains highly susceptible to recurrent flooding across multiple sub-districts, including Medan Sunggal, Medan Helvetia, Medan Barat, Medan Johor, Medan Maimun, Medan Polonia, Medan Baru, Medan Petisah, and Medan Selayang.

Among all affected sub-districts, Medan Maimun was selected as the study area based on a combination of physical and demographic exposure factors beyond its flood history alone. The sub-district covers only 3.04 km² yet supports a population of 52,591 residents as of December 2024, distributed across six urban villages (Aur, Hamdan, Jati, Kampung Baru, Sei Mati, and Sukaraja) yielding a population density of 17,312 persons/km² (Medan BPS, 2025), approximately 1.84 times higher than the average density of Medan City as a whole (9,410 persons/km²). This high settlement density, combined with a low elevation of only 28 meters above sea level and direct adjacency to the Deli River along an extended reach within the sub-district, results in substantial flood exposure for a large resident population within a confined area. These physical and demographic characteristics, together with the recurring severe inundation reported by local residents and government officials at depths of approximately 3 meters in February 2022 (Syahputra, 2022) and December 2023 (Aldi, 2023), underscore the urgent need for quantitative, spatially explicit flood assessment tools to support evidence-based mitigation planning in this densely populated, highly exposed sub-district.

Flood inundation modeling has evolved substantially over the past two decades, with two-dimensional (2D) hydraulic simulation now recognized as the most reliable approach for capturing complex urban surface flow dynamics. Several previous studies have applied HEC-RAS 2D for urban flood inundation mapping with considerable success. Moya et al., (2016) applied HEC-RAS 2D along the Bolivian Amazon river system and demonstrated that 2D modeling significantly outperforms 1D approaches in capturing lateral floodplain inundation extents. Dasallas et al., (2019) employed HEC-RAS 2D in an urban watershed in South Korea and found that high-resolution DEM integration substantially improved inundation depth accuracy compared to coarser terrain inputs. Teng et al., (2017) conducted a comprehensive review of flood inundation models and confirmed that 2D shallow water equation solvers, as implemented in HEC-RAS, provide superior spatial resolution of flood hazard zones for return-period-based scenario analysis by Cook & Merwade, (2009) further demonstrated that HEC-RAS flood inundation map accuracy is strongly sensitive to terrain data resolution and cross-sectional representation, particularly in low-gradient urban settings.

At the national level, several studies in Indonesia have applied HEC-RAS for urban flood mapping with relevant findings. Cahyono & Rusli, (2024) conducted flood inundation mapping in the Kota Lama area of Semarang using HEC-RAS integrated with HEC-HMS and ArcGIS, finding that inundation area increased significantly from 406 ha at the 2-year return period to 796 ha at the 100-year return period. Rohmat et al., (2022) modeled urban flooding in Majalaya, Bandung using HEC-HMS and HEC-RAS 2D with DEMNAS and LiDAR data integration, obtaining a Nash-Sutcliffe Efficiency (NSE) value of 0.88, indicating very good model performance under densely populated urban conditions in Indonesia. Sukiyoto & Manurung (2025) integrated the SUH Nakayasu method with HEC-RAS 2D and LiDAR DEM for flood simulation in the ungauged Cipinang catchment, Jakarta, achieving a Nash-Sutcliffe Efficiency of 0.78 and demonstrating the reliability of Nakayasu-based discharge inputs for 2D hydraulic flood modeling in ungauged urban watersheds in Indonesia. Geographically closer to the study area, Zevri (2019) mapped flood inundation zones in the Sei Sikambing watershed; a sub-watershed of the Deli River in Medan City; using a Geographic Information System approach; however, that study did not apply full 2D hydraulic simulation and was limited to static spatial analysis without a comprehensive multi-return-period scenario (Rahmadani, 2022).

Despite the growing application of HEC-RAS 2D for urban flood inundation mapping in Indonesia, as demonstrated by Cahyono & Rusli, (2024) in Semarang and Rohmat et al., (2022) in Bandung, three specific gaps remain unaddressed in the context of Medan Maimun. First, no prior study has applied multi-return-period scenario analysis (spanning 2- to 100-year events) within a single integrated HEC-RAS 2D and RAS Mapper framework specifically for this sub-district. Second, the existing local study by Zevri, (2019) in the neighboring Sei Sikambing watershed relied on static GIS-based spatial analysis without dynamic 2D hydraulic simulation, limiting its capacity to represent depth-varying inundation patterns across return periods. Third, none of the available studies have explicitly linked simulated inundation depths to channel conveyance capacity constraints, which is essential for identifying the physical drivers of flood risk in narrow urban river channels such as the Deli River.

The scientific novelty of this study therefore lies in the integration of SUH Nakayasu-derived design flood hydrographs with HEC-RAS 2D hydraulic simulation to produce a spatially explicit, multi-return-period flood inundation dataset for Medan Maimun Sub-district, while explicitly linking simulated channel hydraulics to field-reported flood depths for indirect physical plausibility assessment. Beyond this methodological contribution, the practical significance of this study lies in providing local government agencies and disaster risk reduction institutions with quantitative flood hazard maps that can directly support spatial planning, infrastructure resilience assessment, and flood mitigation prioritization in Medan City. The objectives of this research are: (1) to determine design rainfall and rainfall intensity through frequency analysis, and to calculate the corresponding design flood discharge for return periods of 2, 5, 10, 25, 50, and 100 years using the Nakayasu Synthetic Unit Hydrograph (SUH Nakayasu) method; (2) to simulate flood routing in Medan Maimun Sub-district using two-dimensional hydraulic modeling; and (3) to determine flood inundation area resulting from the simulated flood routing for each return period scenario through spatial visualization using RAS Mapper. The findings are expected to provide a scientific basis for flood mitigation planning, spatial management, and drainage infrastructure development in Medan City, and to serve as a replicable methodological framework for flood inundation mapping in other densely populated urban sub-districts across Indonesia.

METHOD

Study Area

This study was conducted in Medan Maimun Sub-district, Medan City, North Sumatra Province, Indonesia. Medan Maimun Sub-district covers an area of 3.04 km^2 at an elevation of 28 meters above sea level and is administratively divided into six urban villages: Aur, Hamdan, Jati, Kampung Baru, Sei Mati, and Sukaraja (Medan BPS, 2025). The study area is directly bordered by the Deli River, which is part of the Deli River Watershed (DAS Deli) a nationally strategic river originating from Mount Pintau (1,400 m a.s.l.) and Mount Sibayak (1,800 m a.s.l.) in Karo Regency, flowing through Deli Serdang Regency, and discharging into the Strait of Malacca near Belawan. The Deli River Watershed has a total area of 351.90 km^2 with a main river length of 86.00 km and an average riverbed slope of 0.00611 (BWS Sumatera II, n.d.). It is divided into four sub-watersheds: Upper Deli (158.9 km^2), Babura (99 km^2), Sikambing (40 km^2), and Lower Deli (54 km^2). The study area location is presented in **Figure 1**.

Data

Data used in this study consisted of primary and secondary data. Primary data were obtained through field surveys using GPS instruments to record study area coordinates. Secondary data included: (1) monthly maximum daily rainfall data for the period 2014–2023 obtained from BBMKG Regional Station I Medan and Sampali Station, sourced from the BMKG; (2) the Deli River Watershed map including watershed boundaries, river length, watershed area, and river geometry, sourced from the Sumatera II River Basin Authority; (3) high-resolution Digital Elevation Model (DEM) data sourced from DEMNAS, Geospatial Information Agency, with a native spatial resolution of 0.27 arc-second (~8 m) (Geospasial, 2018). A summary of data sources is presented in **Table 1**.

Table 1. Research Data Summary

No.	Data Type	Source	Description
1	Maximum daily rainfall 2014–2023	BMKG	BBMKG Station I & Sampali
2	Deli River Watershed geometry	BWS Sumatera II	River length, watershed area, riverbed slope
3	Digital Elevation Model (DEM)	DEMNAS	High resolution
4	Land use map of the Deli River Watershed	BWS Sumatera II	Used to determine the runoff coefficient
5	Sub-district administrative and demographic data	Medan BPS, 2025	Area, population, density
6	Study area coordinates	GPS field survey	Primary data

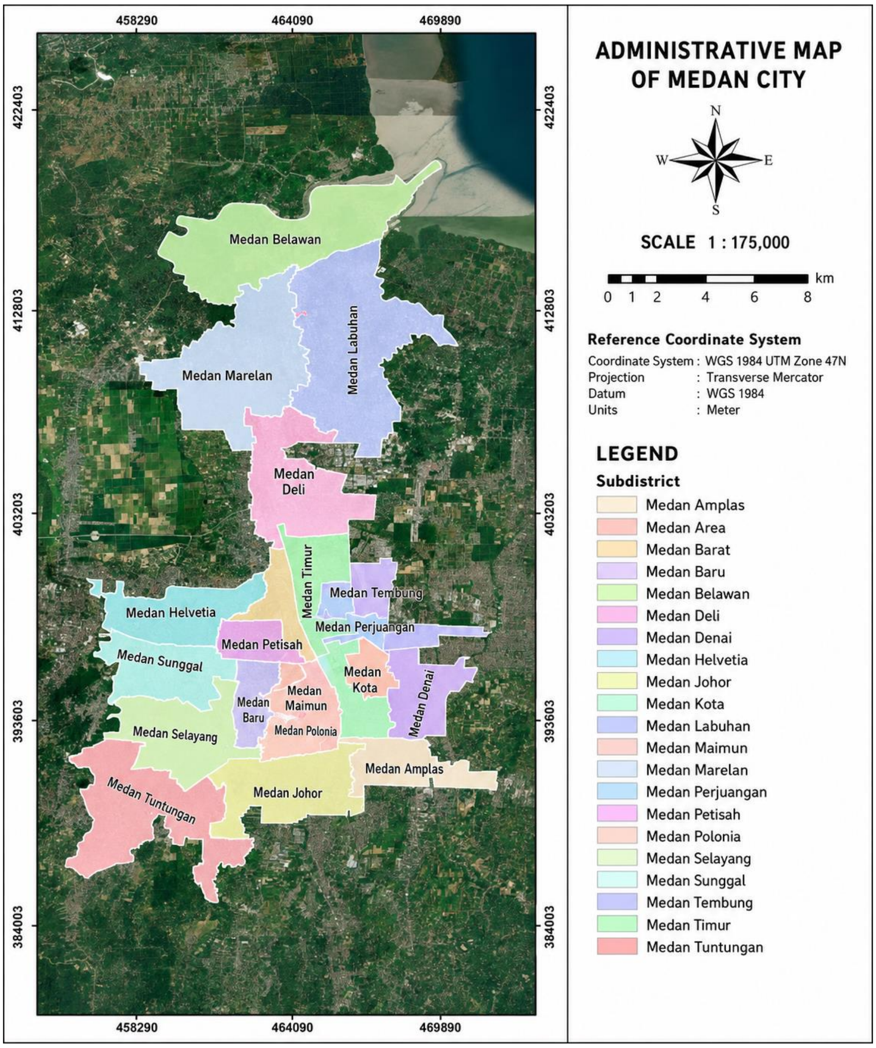

Figure 1. Study location of Medan Maimun Sub-district

Rainfall Frequency Analysis

Rainfall frequency analysis was conducted to estimate design rainfall depths for various return periods as the basis for flood discharge calculation. Annual maximum rainfall data from two observation stations BBMKG Regional Station I Medan and Sampali Station covering the period 2014–2023 were used. Areal rainfall was calculated using the Thiessen polygon method from both stations. Although the Thiessen polygon method is most commonly applied with multiple rainfall stations, it remains methodologically valid with two stations, where the catchment area is divided into two polygons separated by the perpendicular bisector of the line connecting the two stations;

each station's areal weight is proportional to the catchment area within its respective polygon. This approach was adopted due to the limited availability of long-term rainfall stations within and near the Deli River Watershed. Frequency analysis was performed using four distribution methods: Normal, Log Normal, Log Pearson III, and Gumbel (Suripin, 2004).

Statistical parameters calculated for each method include the mean ($\bar{X}$), standard deviation (S), skewness coefficient (Cs), kurtosis coefficient (Ck), and coefficient of variation (Cv), formulated as follows (Suripin, 2004). The mean is calculated using Equation (1):

$$\bar{X} = \frac{\sum_{i=1}^{n} X_i}{n} \qquad (1)$$

where $\bar{X}$ is the mean rainfall (mm), Xi is the i-th rainfall data value (mm), and n is the number of data points. The standard deviation is calculated using Equation (2):

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

where S is the standard deviation (mm). The skewness coefficient is calculated using Equation (3):

$$Cs = \frac{n \sum_{i=1}^{n} (X_i - \bar{X})^3)}{(n-1)(n-2)(S^3)} \qquad (3)$$

where Cs is the skewness coefficient. The coefficient of variation is calculated using Equation (4):

$$Cv = \frac{S}{\bar{X}} \qquad (4)$$

where Cv is the coefficient of variation. Selection of the most appropriate distribution method was based on conformity of statistical parameters with theoretical requirements and Chi-Square goodness-of-fit test results. The Chi-Square test compared the calculated Chi-Square value (X^2) against the critical value (X^2cr) at a 5% significance level and degrees of freedom $Dk = K - (p + 1)$, where K is the number of distribution classes and p is the number of parameters (Suripin, 2004). The acceptance criterion requires $X^2 < X^2$cr as formulated in Equation (5):

$$X^2 = \sum_{i=1}^{k} \frac{(O_i - E_i)^2}{E_i} \qquad (5)$$

where Oi is the observed frequency in class i and Ei is the theoretical frequency in class i. The selected distribution method was subsequently used to calculate design rainfall for return periods of 2, 5, 10, 25, 50, and 100 years. Rainfall intensity was then calculated using the Mononobe formula as presented in Equation (6) (Suripin, 2004):

$$I = \frac{R_{24}}{24} \left(\frac{24}{t}\right)^{2/3} \qquad (6)$$

where I is the rainfall intensity (mm/hour), R_{24} is the maximum 24-hour rainfall depth (mm), and t is the rainfall duration (hours). Hourly rainfall distribution patterns were subsequently derived using the Alternating Block Method (ABM) to produce design rainfall hyetographs for each return period as input for flood discharge calculation.

Design Flood Discharge Using SUH Nakayasu

Design flood discharge was calculated using the Nakayasu Synthetic Unit Hydrograph (SUH Nakayasu) method, as direct streamflow measurement data were unavailable at the study location while sufficient rainfall data were available. The SUH Nakayasu method was selected because it was developed based on watershed characteristics in Japan that share similarities with tropical watershed conditions in Indonesia and has been widely applied to watersheds in Sumatra (Sirait et al., 2021; Soemarto, 1999). Deli River Watershed parameters used in the calculation include: main river length (L) = 86.00 km, watershed area (A) = 351.90 km^2, unit rainfall (R_0) = 1 mm, average riverbed slope (Sb) = 0.00611, and watershed runoff coefficient (C) = 0.300. This composite runoff coefficient reflects the mixed land use composition of the Deli River Watershed, which includes substantial proportions of agricultural land, open space, and vegetated areas in its upper and middle reaches, despite dense urban development concentrated near the downstream sub-districts including Medan Maimun; the watershed-averaged value is therefore lower than coefficients typically reported for fully urbanized catchments.

The SUH Nakayasu calculation begins with determining time parameters; lag time (t_g), effective rainfall duration (T_r), watershed characteristic coefficient (α), time to peak (t_p), and time for discharge to decline to 30% of peak discharge ($T_{0.30}$); formulated in Equations (7) through (11). For river length L > 15 km, tg is calculated as follows (Soemarto, 1999):

$$t_g = 0.21 \times L^{0.70} \quad (7)$$

$$T_r = 0.75 \times t_g \quad (8)$$

$$\alpha = \frac{0.47 \times (A \times L)^{0.25}}{t_g} \quad (9)$$

$$t_p = t_g + 0.80 \times T_r \quad (10)$$

$$T_{0.30} = \alpha \times t_g \quad (11)$$

The peak discharge of the synthetic unit hydrograph (Qp) is then calculated using Equation (12) (Soemarto, 1999):

$$Q_p = \frac{C \times A \times R_0}{3.6 \times (0.3 \times t_p + T_{0.3})} \quad (12)$$

where Qp is the peak discharge (m^3/s), C is the runoff coefficient, A is the watershed area (km^2), and R_0 is the unit rainfall (mm). Unit hydrograph ordinates for the rising limb and recession limb are calculated using Equations (13) through (15):

$$Q_t = Q_p \times \left(\frac{t}{t_p}\right)^{2.4} ; 0 < t \leq t_p \quad (13)$$

$$Q_t = Q_p \times 0.30^{\left(\frac{t - t_p}{T_{0.30}}\right)} ; t_p < t \leq t_p + T_{0.30} \quad (14)$$

$$Q_t = Q_p \times 0.30^{\left(\frac{t - t_p + 0.50 \times T_{0.30}}{1.5 \times T_{0.30}}\right)} ; t > t_p + T_{0.30} \quad (15)$$

where Q_t is the discharge at time t (m^3/s). Effective rainfall (Re) was obtained by multiplying the hourly hyetograph rainfall by the watershed runoff coefficient as presented in Equation (16):

$$Re = C \times R_t \quad (16)$$

where Re is the effective rainfall (mm) and Rt is the hourly hyetograph rainfall (mm). It should be clarified that the unit rainfall (R_0 = 1 mm) used in the peak discharge formula (Equation 12) represents a unit of effective rainfall by definition in the SUH Nakayasu method, rather than total rainfall. The runoff coefficient (C) in Equation 16 is therefore used to convert the hourly design rainfall hyetograph into the effective rainfall series required for convolution with the unit hydrograph ordinates, and does not constitute a duplicate application of the runoff coefficient (Soemarto, 1999). Design flood hydrographs for return periods of 2, 5, 10, 25, 50, and 100 years were obtained through convolution of SUH Nakayasu ordinates with hourly effective rainfall, with base flow (Qb) subsequently added to produce total discharge at each time interval.

HEC-RAS 2D Modeling and RAS Mapper

Surface flow modeling and flood inundation mapping were performed using HEC-RAS 2D (Hydrologic Engineering Center's River Analysis System), developed by the U.S. Army Corps of Engineers. HEC-RAS 2D simulates two-dimensional unsteady flow by numerically solving shallow water equations on a terrain-based computational domain (Brunner, 2016). The 2D approach was selected because it produces more accurate spatial representation of flow depth and velocity compared to one-dimensional approaches, particularly in urban floodplain (Teng et al., 2017).

The model domain was georeferenced using the Universal Transverse Mercator (UTM) Zone 47N coordinate system with the WGS 1984 horizontal datum and the EGM2008 vertical datum, with linear units in meters. DEMNAS terrain data were reprojected to UTM 47N using the Project Raster tool in ArcGIS 10.8, exported to ESRI BIL format, and imported into RAS Mapper as a RAS Terrain layer. River cross-section geometry, including bank lines delineating the left and right channel banks, was obtained from BWS Sumatera II. The 2D Flow Area perimeter was delineated to encompass the Deli River corridor within Medan Maimun Sub-district, with a computational mesh cell size of 10 m × 10 m. Manning's roughness coefficient was set at n = 0.03 for the river channel.

The upstream boundary condition was defined as a flow hydrograph using the SUH Nakayasu design flood discharges for each return period, while the downstream boundary condition was defined using the normal depth method based on the river's longitudinal bed slope. Simulations were conducted using the Unsteady Flow Analysis feature for two-dimensional flow computation over a 24-hour period for each return period scenario, with a computational time step of 10 seconds and hydrograph and mapping output intervals of 10 minutes. Model stability was monitored through the Computations Summary window, confirming a complete simulation status for all scenarios, together with review of error and warning messages in the cross-section output, which indicated a maximum water surface elevation error of 3.092 m across the analyzed cross-sections. No hydraulic structures such as bridges, culverts, weirs, or junctions were incorporated into the model, consistent with the unobstructed channel conditions of the studied reach.

Simulation results were subsequently visualized using the RAS Mapper feature in HEC-RAS to produce flood inundation maps displaying the spatial distribution of inundation depth and area for each return period scenario. Inundation areas were calculated spatially from RAS Mapper outputs for all analyzed return period scenarios. Several aspects of the model setup warrant acknowledgment as limitations. Breaklines were applied only along the main channel bank lines, without additional breaklines along roads, embankments, or floodplain boundaries, which may affect the resolution of overland flow paths in densely built-up areas. The specific computational solver (full Saint-Venant momentum equations versus diffusion wave approximation) was not explicitly recorded, and Courant number values were not directly extracted from the simulation logs. The Manning's roughness coefficient was applied uniformly without site-specific calibration or documented justification of its source. Hydrological conditioning of the DEM, such as stream burning or breaching of artificial obstructions, was not explicitly performed, which may affect flow path representation in flat urban terrain. These limitations are further discussed in the Conclusion section.

RESULTS AND DISCUSSION

Annual maximum rainfall data from the Deli River Watershed for the period 2014–2023 were obtained from two observation stations. The mean annual areal rainfall calculated using the Thiessen polygon method from both stations was 452.85 mm, with the highest values recorded in 2018 at 602 mm at BBMKG Regional Station I and in 2016 at 614 mm at Sampali Station. Statistical parameter analysis using four frequency distribution methods produced the results presented in **Table 2**.

Table 2. Summary of Statistical Parameters for Frequency Distribution Methods

Parameter	Normal	Log Normal	Log Pearson III	Gumbel
Mean ($\bar{X}$)	464.6	2.664	2.664	464.6
Standard Deviation (S)	63.876	0.058	0.058	63.876
Skewness Coefficient (C_s)	0.920	0.551	0.551	0.920
Kurtosis Coefficient (C_k)	5.235	4.572	4.572	5.235
Coefficient of Variation (C_v)	0.137	0.0218	0.0218	0.137

Based on the theoretical parameter requirements, only the Log Pearson III method satisfied both criteria, with C_s = 0.551 and C_k= 4.572 (requirements: 0 <C_s < 9 and 0 < C_k < 9). Chi-Square goodness-of-fit test results showed that all methods satisfied the test criterion with calculated X^2 values less than the critical value X^2cr = 5.991; however, based on conformity with theoretical statistical parameter requirements, the Log Pearson III method was selected as the most appropriate distribution (Suripin, 2004). A complete summary of statistical parameter conformity and goodness-of-fit test results for all distribution methods is presented in **Table 3**.

Table 3. Chi-Square Goodness-of-Fit Test Summary for All Distribution Methods

Method	C_s	C_k	Parameter	X^2 Cal	X^2cr	Chi-Square	Selected
Normal	0.920	5.235	Not fulfilled	3	5.991	Fulfilled	No
Log Normal	0.551	4.572	Not fulfilled	4	5.991	Fulfilled	No
Log Pearson III	0.551	4.572	Fulfilled	1	5.991	Fulfilled	Yes
Gumbel	0.920	5.235	Not fulfilled	2	5.991	Fulfilled	No

Based on the selected Log Pearson III distribution, rainfall intensity for each return period was calculated using the Mononobe formula across durations ranging from 5 minutes to 24 hours. The resulting Intensity-Duration-Frequency (IDF) curves for all six return period scenarios are presented in **Figure 2**. The curves confirm that rainfall intensity decreases with increasing duration and increases with increasing return period, consistent with the convective rainfall pattern typical of tropical urban watersheds in Sumatra (Rohmat et al., 2022). Peak intensity at a 1-hour duration ranges from 157.834 mm/hour at the 2-year return period to 229.558 mm/hour at the 100-year return period. Design rainfall values derived from the Log Pearson III analysis for each return period are presented in **Table 4**.

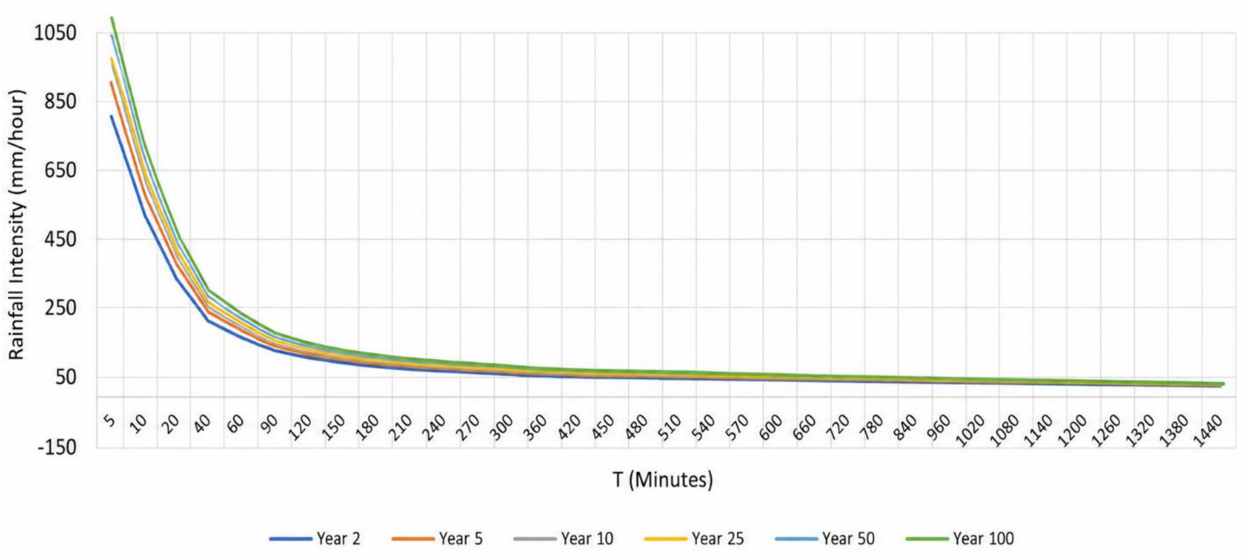

Figure 2. Intensity–Duration–Frequency (IDF) curves for the Deli River Watershed for return periods of 2, 5, 10, 25, 50, and 100 years

Table 4. Design Rainfall Results Using Log Pearson III Method

Return Period (Years)	KT	$XT\ (mm)$
2	-0.091	455.272
5	0.804	512.921
10	1.326	549.827
25	1.925	595.513
50	2.335	628.998
100	2.721	662.160

Design rainfall values showed a consistent increasing trend with increasing return period, from 455.272 mm at the 2-year return period to 662.160 mm at the 100-year return period, thereby indicating progressively greater hydrological risk. Rainfall intensity was subsequently calculated using the Mononobe formula and hourly rainfall distribution patterns were derived using the Alternating Block Method (ABM) to produce design hyetographs for each return period as input for flood discharge calculation, to ensure realistic temporal storm representation. This finding is consistent with Teng et al., (2017), who established that Log Pearson III-based frequency analysis is the most representative approach for tropical watershed conditions characterized by high rainfall variability, particularly where catchment responses vary strongly. Effective rainfall for each return period was determined by applying the composite runoff coefficient of the Deli River Watershed (C = 0.300), while accounting for spatial land-use heterogeneity, derived from weighted land use classification sourced from BWS Sumatera II. Hourly rainfall distribution patterns were subsequently derived using the Alternating Block Method (ABM), producing design hyetographs as direct input to the SUH Nakayasu convolution, to support subsequent hydrological model convolution. The resulting hyetograph values for all return period scenarios are summarized in **Table 5**, while the hyetograph pattern for the 100-year return period is illustrated in **Figure 3**, for clearer interpretation of results.

Table 5. Hourly Design Rainfall Hyetograph for Each Return Period

Hour	Q2	Q5	Q10	Q25	Q50	Q100
1	30.711	34.599	37.089	40.171	42.429	44.666
2	45.682	51.466	55.169	59.753	63.113	66.441
3	250.546	282.271	302.582	327.724	346.151	364.400
4	65.122	73.368	78.647	85.182	89.972	94.715
5	36.367	40.972	43.920	47.570	50.244	52.893
6	26.845	30.244	32.420	35.114	37.088	39.044
Total	455.272	512.921	549.827	595.513	628.998	662.160

The hyetograph pattern consistently places peak rainfall at hour 3 across all return period scenarios, reflecting the characteristic short-duration high-intensity convective storm pattern of tropical equatorial regions in Sumatra. At the 100-year return period, peak hourly rainfall reaches 364.400 mm, representing 55.0% of the total design rainfall depth of 662.160 mm, confirming the internal consistency of the rainfall analysis. Based on the Deli River Watershed morphological parameters, the following time parameter values were obtained: lag time tg = 5.388 hours, effective rainfall duration Tr = 4.041 hours, watershed characteristic coefficient α = 1.151, time to peak tp = 8.621 hours, $T_{0.30}$ = 6.199 hours, and base flow Qb = 5.462 m^3/s. The peak discharge of the synthetic unit hydrograph (Qp) was calculated at 3.334 m^3/s. Convolution of SUH Nakayasu ordinates with hourly effective rainfall for each return period produced the design flood discharge summary presented in **Table 6**.

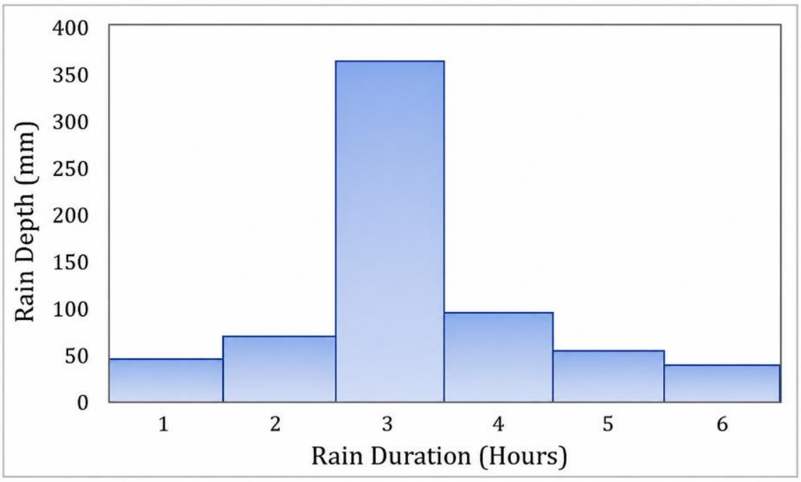

Figure 3. Design rainfall hyetograph for the 100-year return period using the Alternating Block Method

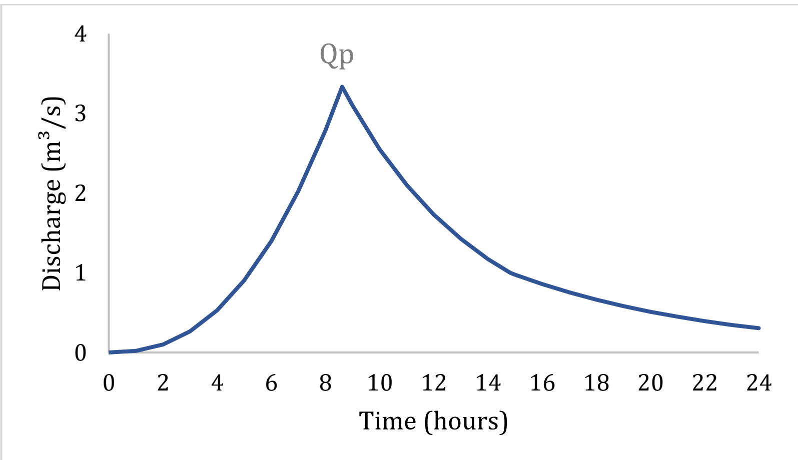

Figure 4. Nakayasu Synthetic Unit Hydrograph for the Deli River Watershed

Peak flood discharge increased consistently from 383.403 m^3/s at the 2-year return period to 555.149 m^3/s at the 100-year return period, with time to peak occurring uniformly at hour 9 across all scenarios. The most significant increase in peak discharge occurred between the 2-year and 5-year return periods, reflecting the high sensitivity of the Deli River Watershed system to changes in design rainfall intensity. This result is consistent with the findings of Rohmat et al., (2022), who demonstrated that urban watersheds in Indonesia with high runoff coefficients generate rapid discharge responses to increasing design rainfall intensity. The resulting SUH Nakayasu unit hydrograph curve is presented in **Figure 4**. The **Figure 4** presents the SUH Nakayasu unit hydrograph computed for a unit rainfall of 1 mm (R_0 = 1 mm), yielding a unit peak discharge of 3.334 m^3/s at hour 8.621, which was subsequently convolved with effective rainfall hyetographs to produce design flood discharges for each return period scenario. The shape of the hydrograph reflects the relatively fast response time characteristic of the Deli River Watershed, consistent with its small drainage area of 351.90 km^2 (< 500 km^2) and moderate average riverbed slope of 0.00611 (Soemarto, 1999). The convolution of this unit hydrograph with the effective rainfall hyetograph produced design flood discharges for all six return period scenarios, confirming that the SUH Nakayasu method is applicable for ungauged tropical watersheds in Sumatra (Soemarto, 1999), consistent with findings by Ansori et al., (2023) who demonstrated that Nakayasu peak discharge deviations from HEC-RAS 2D numerical modeling remain within 10%.

Table 6. Summary of Design Flood Discharges Using SUH Nakayasu

Return Period (Years)	Peak Discharge (m^3/s)	Time to Peak (Hours)
2	383.403	9
5	431.259	9
10	461.897	9
25	499.823	9
50	527.620	9
100	555.149	9

HEC-RAS 2D surface flow simulation using SUH Nakayasu design flood hydrographs as upstream boundary conditions produced flood inundation maps for each return period scenario. It is important to note that the HEC-RAS 2D model in this study was not formally calibrated or validated against systematically observed flood depth, discharge, or inundation extent data, as continuous field monitoring records were unavailable for the Deli River at the study location. However, an indirect form of comparison is provided by the agreement between the simulated flow depths in the main channel (approximately 2.8–3.4 m, as discussed above) and flood depths of approximately 3 m reported by local residents and government officials following major flood events in February 2022 (Syahputra, 2022) and December 2023 (Aldi, 2023) in Kampung Aur. While this agreement lends partial physical credibility to the simulation results, it should be noted that these reported depths originate from field-based eyewitness estimates rather than systematic instrumental measurement, and therefore do not constitute formal model validation. The absence of continuous field monitoring; such as automated water level records, surveyed high-water marks, or remote sensing-derived inundation extents; remains a significant limitation of this study.

Several sources of uncertainty should be considered when interpreting the results of this study. First, the rainfall record used for frequency analysis spans only 10 years (2014–2023), which is relatively short for reliably estimating design rainfall at long return periods such as 50 and 100 years. Second, although DEMNAS provides nationally consistent terrain data, its spatial resolution and vertical accuracy in densely built-up urban areas such as Kampung Aur may introduce uncertainty in the representation of microtopography and building footprints that influence overland flow paths. Third, the Manning's roughness coefficient (n = 0.03) was applied uniformly to the river channel without site-specific field calibration. Fourth, the river cross-section geometry and 2D mesh resolution (10 m × 10 m) represent simplifications of the actual channel and floodplain morphology, particularly in narrow alleyways and densely built urban blocks. Fifth, the downstream boundary condition, based on the normal depth assumption, may not fully represent backwater effects from tidal influence or downstream channel constrictions. Finally, design discharges for the 50- and 100-year return periods involve inherent statistical extrapolation uncertainty given the limited rainfall record length. Collectively, these factors suggest that the flood inundation maps produced in this study should be interpreted as indicative of relative flood risk patterns rather than as precise predictions of absolute inundation extent or depth.

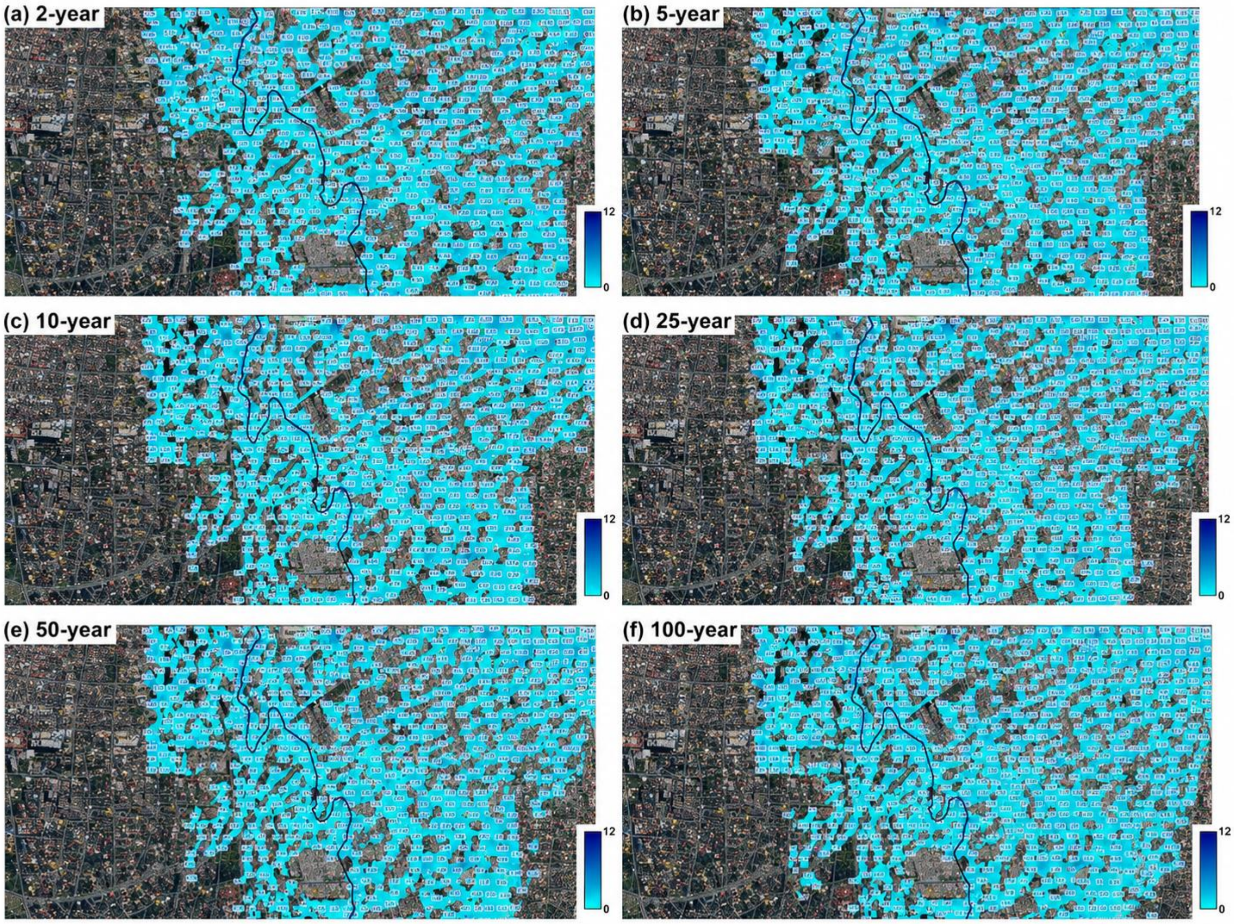

Figure 5. Spatial distribution of simulated flood inundation in Medan Maimun Sub-district based on HEC-RAS 2D modeling for different rainfall return periods: (a) 2-year, (b) 5-year, (c) 10-year, (d) 25-year, (e) 50-year, and (f) 100-year return periods.

Simulation results indicate that Deli River overflow consistently directed toward the right bank of the river, specifically toward the Kampung Aur area, Sei Mati Village, and Aur Village in Medan Maimun Sub-district. At the 100-year return period, inundation began to extend toward the left bank of the Deli River, indicating that flood risk at this return period is no longer confined to the Kampung Aur area alone but has expanded to cover a wider area of Medan Maimun Sub-district. One-dimensional cross-section simulation results across 21 cross-sections of the Deli River (STA 0 – STA 1000, at 50 m intervals) showed continuously increasing flood water levels with increasing return period. Average flow velocities across all cross-sections ranged from 5.62 to 7.03 m/s, with Froude numbers approaching 1.0, indicating critical flow conditions across nearly all river cross-sections. These high velocities and near-critical Froude numbers were observed specifically within the main channel rather than across the floodplain, where the channel cross-sectional area ranged from approximately 53 to 65 m^2. The narrow channel geometry approximately 19–20 m wide between banks with a bank height of only 1.0–1.5 m above the thalweg constrains flow before overtopping occurs. Conveying the design discharges (383–555 m^3/s) within this confined cross-section requires computed flow depths of approximately 2.8–3.4 m, which is consistent with the historical flood depth of 3.0 m recorded in Kampung Aur in December 2023. This agreement between simulated and historically observed flood depths lends physical plausibility to the simulated velocities, although the absence of field-measured velocity data remains a limitation, and future studies should incorporate direct field verification. Flood inundation maps produced from HEC-RAS 2D simulation for all return period scenarios are presented in **Figure 5 (a–f)**.

Inundation area results were classified into four depth categories: 0–0.5 m, 0.5–1.0 m, 1.0–2.0 m, and >2.0 m. This classification aligns with urban flood risk depth thresholds established in previous studies, where inundation depths exceeding 1 m are associated with high risk to urban buildings and infrastructure (Madhuri et al., 2021; Rangari et al., 2019). The spatial distribution of flood inundation for each return period scenario is summarized in **Table 7**.

Table 7. Flood Inundation Area in Medan Maimun Sub-district by Return Period

Inundation Depth (m)	Q2 (ha)	Q5 (ha)	Q10 (ha)	Q25 (ha)	Q50 (ha)	Q100 (ha)
0 – 0.5	25.181	24.847	24.940	25.050	24.785	24.199
0.5 – 1	22.951	24.101	24.706	25.396	25.780	26.378
1 – 2	32.418	34.202	35.572	37.020	38.024	38.915
> 2	30.432	32.544	33.546	35.077	36.023	37.089
Total	110.982	115.694	118.764	122.543	124.612	126.581
% of area	36.5	38.1	39.1	40.3	41.0	41.6

Total inundation area increased progressively from 110.982 ha at the 2-year return period to 126.581 ha at the 100-year return period, representing a 14.05% increase across the analyzed return period range. The 1.0–2.0 m inundation depth category consistently dominated inundation area across all return period scenarios, reaching a maximum of 38.915 ha at the 100-year return period. The >2.0 m inundation depth category also demonstrated a significant increasing trend, from 30.432 ha at the 2-year return period to 37.089 ha at the 100-year return period, representing a 21.9% increase. Given that Medan Maimun Sub-district consists predominantly of dense residential and urban land use, with minimal remaining open or vegetated land, the simulated inundation is inferred to predominantly affect built-up areas; however, this inference is based on the sub-district's known land use composition rather than a formal land use overlay analysis within the HEC-RAS simulation, and should be considered a qualitative observation rather than a quantified result. As shown in Table 7, the proportion of inundated area relative to the total sub-district area (304 ha) increases progressively from 36.5% at the 2-year return period to 41.6% at the 100-year return period, indicating an extremely high level of flood vulnerability even at low return periods. Furthermore, inundation depths exceeding 1 m account for 76.004 ha or 60.0% of total inundated area at the 100-year return period, suggesting that a substantial proportion of urban structures in Medan Maimun are exposed to high flood risk.

These findings are consistent with Moya et al., (2016), who demonstrated that 2D modeling captures the spatial distribution of inundation in urban floodplains, particularly in flat and highly urbanized areas, thereby improving interpretation of localized flood exposure in dense settlements. Compared to Cahyono & Rusli (2024) in Kota Lama Semarang, which recorded an inundation area of 406 ha at the 2-year return period, the inundation area in Medan Maimun is smaller because the sub-district covers only 3.04 km^2; however, the proportional flood coverage of 41.6% at the 100-year return period exceeds that of comparable urban sub-districts, indicating disproportionate flood vulnerability. In contrast to Zevri (2019), who produced static flood mapping for the Sei Sikambing watershed without multi-return-period scenario analysis, this study provides a quantitative, spatially explicit flood inundation dataset for Medan Maimun across six return period scenarios using 2D hydraulic simulation, while linking simulated channel hydraulics to field-reported flood depths for physical plausibility assessment. This condition is exacerbated by degradation of the Deli River channel due to riverbank damage and deterioration of river protection structures, which reduces flood discharge capacity (Budiyono et al., 2016). The flood inundation maps are applicable to spatial planning, infrastructure resilience assessment, and disaster risk reduction in Medan City, Indonesia.

CONCLUSION

This study successfully modeled surface flow and generated flood inundation maps for Medan Maimun Sub-district, Medan City using HEC-RAS 2D and RAS Mapper across six return period scenarios. Rainfall frequency analysis using the Log Pearson III method selected as the most appropriate distribution based on Chi-Square goodness-of-fit testing yielded mean annual areal rainfall of 452.85 mm for the Deli River Watershed, with design rainfall increasing from 455.272 mm at the 2-year return period to 662.160 mm at the 100-year return period. Design flood discharges calculated using the SUH Nakayasu method showed a consistent increase in peak discharge from 383.403 m^3/s at the 2-year return period to 555.149 m^3/s at the 100-year return period, with time to peak occurring uniformly at hour 9 across all scenarios. HEC-RAS 2D simulation results demonstrated that Deli River overflow consistently directed toward the right bank, specifically toward Kampung Aur, Sei Mati Village, and Aur Village, with inundation extending to the left bank at the 100-year return period. Total flood inundation area increased progressively from 110.982 ha at the 2-year return period to 126.581 ha at the 100-year return period, representing a 14.05% increase across the analyzed range. The 1.0–2.0 m inundation depth category consistently dominated while the >2.0 m category increased by 21.9% over the same range. Proportionally, inundated area relative to the total sub-district area increased from 36.5% at the 2-year return period to 41.6% at the 100-year return period, indicating an extremely high level of flood vulnerability in Medan Maimun Sub-district even under relatively frequent flood events, indicating an extremely high level of flood vulnerability in Medan Maimun Sub-district. These findings should be interpreted with caution, as the model was not formally calibrated or validated against observed flood data, and uncertainties associated with the limited rainfall record length, terrain resolution, and uniform roughness coefficient may affect the absolute accuracy of the simulated results. Based on these findings, several mitigation measures are recommended for consideration by relevant stakeholders. Normalization and rehabilitation of the Deli River channel should be prioritized, particularly along the segment passing through Medan Maimun Sub-district (STA 0–STA 1000), given that existing channel capacity is insufficient to accommodate flood discharge even at the 2-year return period. Flood control structures such as levees or flood retention basins should be planned with a minimum design return period of 25 years, given that inundation in the >2 m depth category at this return period has already reached 35.077 ha; this recommendation should nonetheless be further justified through cost-benefit analysis and reference to applicable Indonesian drainage design standards before implementation. The flood inundation maps produced in this study can be directly integrated into the Medan City Spatial Planning Document (RTRW) as a scientific basis for designating flood-prone zones and controlling land use conversion in Medan Maimun Sub-district. Future research is recommended to include structural and non-structural flood mitigation scenario analysis, as well as model validation using observed water level data to further improve inundation prediction accuracy.

AUTHOR CONTRIBUTIONS

Conceptualization, SR, DFM, and RH; methodology, SR, DFM, SZY, and NSE; software, AF, MIA, YAL, and WP; validation, DFM, RH, and WP; formal analysis, SR, NSE, AF, and MIA; investigation, SR, SZY, CMR, and YAL; resources, SR, DFM, and RH; data curation, NSE, CMR, AF, and AZP; writing—original draft preparation, SR, SZY, and NSE; writing—review and editing, DFM, RH, CMR, and WP; visualization, AF, MIA, YAL, and AZP; supervision, DFM and RH; project administration, SR and AZP; funding acquisition, SR, DFM, and RH.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest concerning the publication of this article. The authors also confirm that the data and the article are free of plagiarism.

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