HEC-RAS Based Modeling for the Flood Mitigation Analysis of the Karema River

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ABSTRACT

The Karema River, located in the Karema Watershed (DAS Karema) in the West Sulawesi Province, is classified as steep-sloping, with a topographical condition of 15%, causing rainfall from the upstream area to rapidly flow downstream, increasing the risk of flooding in low-lying areas with high population density. The objectives of this study are: analyzing the flood-affected areas along the Karema River and developing effective and efficient evacuation routes to mitigate the impact, using quantitative descriptive and spatial analyses with HEC-RAS and ArcGIS software. The results indicate that the Simboro rainfall station represents the upstream watershed area of the Karema River. The Log Pearson Type III method was used to determine the design rainfall, yielding a 25-year return period rainfall of 258.443 mm. The PSA 007 method (Genta model) was applied to obtain the hourly net rainfall. A flood design analysis was performed deploying the Synthetic Unit Hydrograph (SUH) Nakayasu method, resulting in a peak flood discharge (Q25) of 593.443 m³/s. A flood hydraulic simulation of the Karema River was performed using the Hydrologic Engineering Center's River Analysis System (HEC-RAS) version 6.4.1 with unsteady 2D flow analysis. This simulation produced a flood-affected area of 2.432989 km², with an average flood velocity ranging from 52.08 m/s to 61.67 m/s and an average flood depth ranging from 4.4 m to 4.9 m in two sub-districts: Karema and Simboro. This area falls into the high-hazard class for the flood category. Therefore, a flood disaster evacuation/mitigation route was developed based on spatial analysis, resulting in two types of evacuation routes: primary collector roads with two evacuation paths and primary local roads with eight evacuation paths. Additionally, eight checkpoint locations were marked to indicate the flood arrival times.

Keywords-flood-prone areas; Karema Watershed; GIS; mitigation; evacuation routes; infrastructure

I. INTRODUCTION

Floods are among the most frequent and destructive natural disasters, posing serious threats to human lives, infrastructure, and socio-economic activities, particularly in low-lying and densely populated areas [1]. These disasters are often triggered by extreme rainfall events, exacerbated by topographical, hydrological, and land-use conditions [2]. In tropical regions, such as Indonesia, the intensity of rainfall combined with steep topography and inadequate drainage systems significantly increases flood risk. According to BNPB (2023), floods accounted for nearly 50% of all natural disasters in Indonesia over the past decade [3]. In the context of watersheds, flood vulnerability is greatly influenced by upstream-downstream interactions, where high runoff velocity from steep terrain intensifies the downstream inundation [4]. The Karema Watershed (DAS Karema), located in Mamuju Regency, West Sulawesi, exemplifies such conditions, with a slope gradient of approximately 15%, classified as steep-sloping. This topography accelerates the flow of rainfall from upland areas to lowlands, increasing the flood occurrences in downstream urban zones. The development in urban areas that are vulnerable to flooding often lacks sufficient hydrological planning, which increases the exposure of communities [5]. In the Karema and Simboro sub-districts along the lower Karema River, many settlements are located in areas heavily impacted by flooding, with hydrological and hydraulic modeling being vital for accurately assessing the flood risk and planning disaster mitigation strategies [6]. The HEC-RAS is widely utilized to simulate the flood behavior and evaluate inundation under various return periods [7]. Integrating HEC-RAS with Geographic Information Systems (GIS) enables a detailed visualization of flood-prone areas and supports the identification of critical infrastructure and safe evacuation routes [7]. Authors in [8] employed HEC-RAS 2D to model flooding in the Brahmaputra Basin, while authors in [9] used similar methods in urban areas of Pakistan. Authors in [10, 11] demonstrated the effectiveness of HEC-RAS in flood mapping and disaster preparedness in the Bengawan Solo River and the Citarum Basin, respectively. Despite the advances in flood modeling technologies, detailed two-dimensional unsteady flow simulations remain limited in eastern Indonesia, particularly in Sulawesi, due to scarce data, especially regarding local rainfall and streamflow records, and the absence of integration with evacuation planning. This study addresses this gap by conducting integrated hydrological, hydraulic, and spatial analyses of the Karema River using HEC-RAS 2D and GIS. Despite the limited discharge data, the research simulates flood hydrographs for various return periods by applying the Nakayasu SUH and PSA 007 (Genta) models [12]. Spatial analysis helps design effective evacuation routes based on flood depth, flow velocity, and accessibility [13]. This study aims to identify flood-affected zones and develop evacuation strategies, thereby contributing to local disaster risk reduction and the broader scientific understanding of flood vulnerability in steep, tropical watersheds.

II. RESEARCH METHOD

The study utilizes a systematic approach to analyze the flood-prone areas, commencing with historical flood surveys and the collection of rainfall and topographic data. The maximum daily rainfall is analyzed statistically using the Chi-Square and Smirnov-Kolmogorov tests to determine the most suitable probability distribution. The PSA 007 method (Genta model) is employed to derive hourly rainfall, and the Nakayasu SUH is used to estimate the design flood discharge. In the context of hydraulic modeling, DEMNAS data are integrated into HEC-RAS 6.4.1, a software platform that facilitates the execution of critical tasks, such as polygon mesh creation, boundary definition, roughness coefficient assignment, and hydrograph input within the 2D unsteady flow module. Subsequently, the simulation results are processed in ArcGIS 10.6 to generate flood extent maps, followed by model verification to ensure the accuracy of the simulation, as shown in the flowchart in Figure 1.

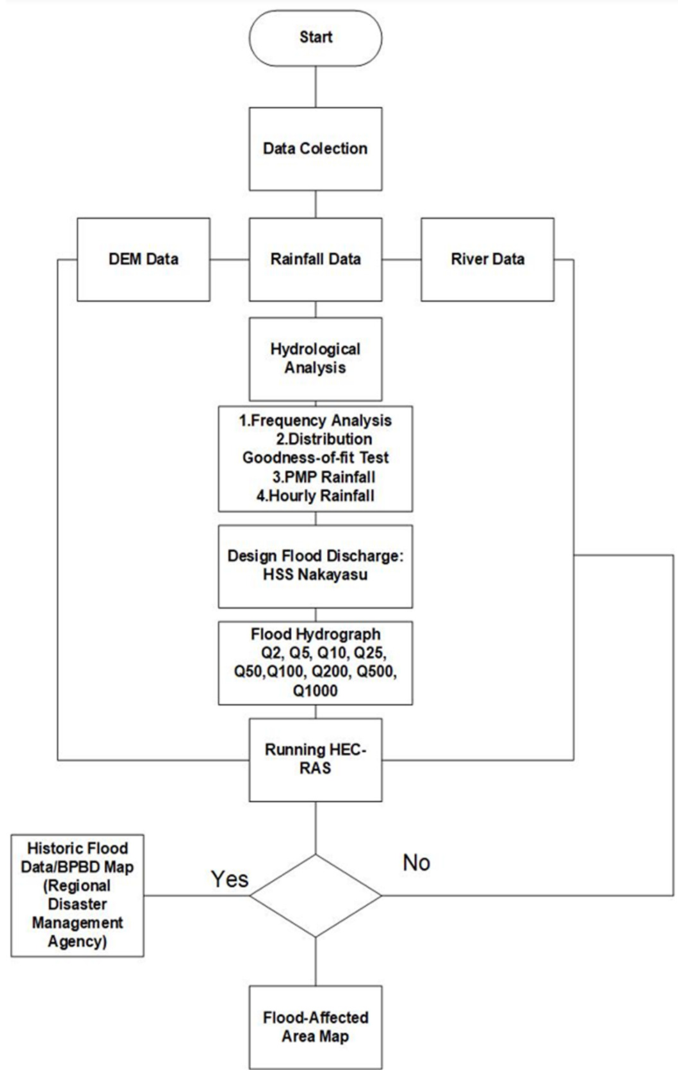

Fig. 1. Flowchart.

The study was conducted along the Karema River within the Karema Watershed (DAS Karema), located between 118°51'E–118°56'E longitude and 02°40'S–04°44'S latitude, as depicted in Figure 2. The research was conducted over a period of three months and included both primary and secondary data collection to support hydrological and hydraulic modeling. Primary data were obtained through field surveys, while the secondary data included river geometry from DEMNAS, watershed maps from Balai Wilayah Sungai V Kalukku-Karama, rainfall data (2014–2024) from the Simboro/Simkep station (BMKG), and tidal data for boundary analysis. A suite of digital tools was employed for the analysis, including Microsoft Excel for data processing, Global Mapper for spatial data management, HEC-RAS 5.0.7 for hydraulic modeling, and Google Earth Pro for satellite imagery and geospatial referencing.

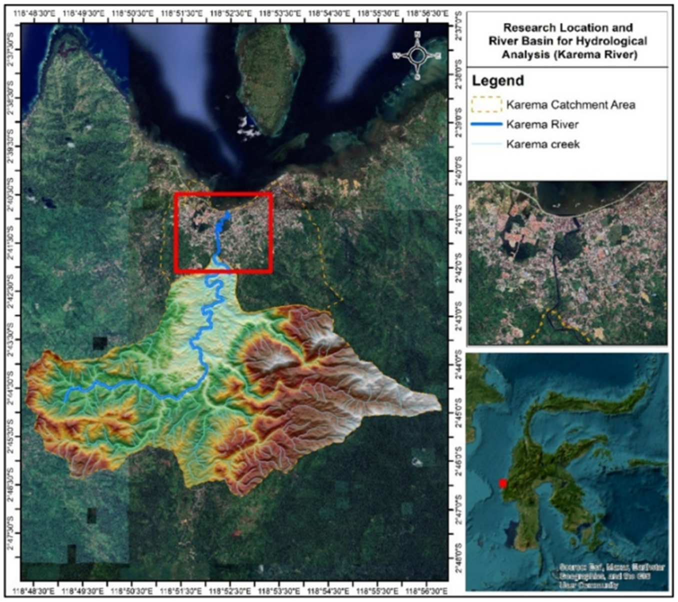

Fig. 2. Research location in Karema watershed.

III. RESULTS AND DISCUSSION

A. Physical Conditions of The Research Area

Administratively, the Karema Watershed is located in Mamuju District, extending over an area of 21.45 km² and comprising six sub-districts, as portrayed in Table I. The topography of the area is characterized by a combination of flat and hilly terrain, i.e. 40% of the area is classified as flat to gently undulating coastal terrain with slopes ranging from 0% to 5%, while the remaining 60% is considered hilly land with slopes ranging from 5% to over 40%. From a geological perspective, the watershed contains a variety of geological features, including volcanic rock formations, such as the Adang Volcanic Rocks, as well as marine sedimentary formations, such as the Mamuju Formation and Quaternary Alluvium. Additionally, the region is characterized by the presence of tectonic features, including faults and folds. The primary land use is mixed dryland agriculture and forest areas, as stated in the 2014–2034 West Sulawesi Spatial Plan. The land is composed of secondary mangrove forests (15.530 ha), dryland farming (6,309.3 ha), mixed agriculture (6,474.75 ha), and smaller portions of residential areas, shrubland, and open land. The topography of the region is characterized by the presence of two distinct soil types: loose alluvial soils in the coastal areas and more erosion-prone podzolic soils in the hills. From a hydrogeological perspective, the watershed is characterized by the presence of both intergranular and fissure flow aquifers. Productive aquifers with shallow water tables are found in coastal zones, while deeper and moderately productive layers dominate inland areas. The fissure flow aquifers, found within weathered bedrock, exhibit spring discharges that can reach up to 30 lt/sec. Demographically, Mamuju District had a population of 65,402 in 2023, with population densities ranging from 78.78 people/km² to 549.67 people/km², thereby directly influencing the flood risk exposure, particularly in densely populated areas. Tidal data from BMKG between April and June of 2025 demonstrate significant variations, with highs exceeding 1.2 m and lows measuring below -0.8 m. These variations are critical for the development of models that predict the flood risks in downstream estuarine zones affected by tidal backflow.

TABLE I. AREA SIZE BY SUB-DISTRICTS IN THE URBAN REGION OF MAMUJU DISTRICT

Village	Area/total area (km²)	Percentage of sub-districts
Binanga	48.36	19.64
Mamunuyu	40.37	16.40
Tadui	28.75	11.68
Karampuang	6.14	2.49
Rimuku	33.90	13.77
Karema	41.20	16.73
Batuppannu	23.40	9.36
Mamuju	246.22	100.00

B. Hydrological Analysis of Rainfall Data of Karema Watershed

The study area of the Karema River within the Karema watershed (DAS Karema) is presented, with rainfall data sourced from a monitoring station situated within the watershed. The ten-year historical data (2015–2024) presented in Table II were important for hydrological modeling, including design rainfall calculation, flood frequency analysis, and peak discharge estimation, as illustrated in Figure 3. In the absence of observed hydrographic data, the Nakayasu SUH method was used to support flood modeling due to its simplicity and reliable performance in data-limited contexts. The methodology relies on several parameters, including time to peak (T_p), centroid timing (T_g), hydrograph duration (*TB*), catchment area (*CA*), and main river length (*L*). The resulting time-discharge relationship for the Karema watershed is displayed in Figure 4.

TABLE II. ANNUAL MAXIMUM DAILY RAINFALL (MM) SIMBORO STATION

No.	Tahun	Stasiun Simboro
1	2015	59
2	2016	50
3	2017	63
4	2018	167
5	2019	90.8
6	2020	65
7	2021	71
8	2022	201
9	2023	99
10	2024	201

The Nakayasu SUH method was deployed to design flood analysis, a procedure based on the hourly net rainfall data and the correction ordinates of the Nakayasu hydrograph in Figure 4. This approach transforms rainfall into runoff, thus enabling the estimation of the peak discharge for various return periods, particularly in ungauged catchments, such as the Karema Watershed, where direct flow measurements are not available. The method is characterized by its ability to provide a reliable hydrological model, hence facilitating the accurate prediction of floods. The resulting peak discharge values for various return periods were: the second-order flow (Q2) was 210.02 m³/s, the fifth-order flow (Q5) was 335.457 m³/s, the tenth-order flow (Q10) was 435.37 m³/s, the twenty-fifth-order flow (Q25) was 593.443 m³/s, the fifty-order flow (Q50) was 727.358 m³/s, the hundredth-order flow (Q100) was 886.308 m³/s, the two-hundredth-order flow (Q200) was 1,069.155 m³/s, the five-hundredth-order flow (Q500) was 1,245.795 m³/s, and the one-thousandth-order flow (Q1000) was 1,615.164 m³/s. These values are critical for hydraulic modeling and floodplain mapping, forming the foundation for flood hazard assessment and mitigation planning. As shown in Figure 5, the time-discharge graph based on the Nakayasu SUH demonstrates the peak timing, rising and falling limbs, and total duration of the flood event. These characteristics are crucial for comprehending the watershed response and for the subsequent development of simulations.

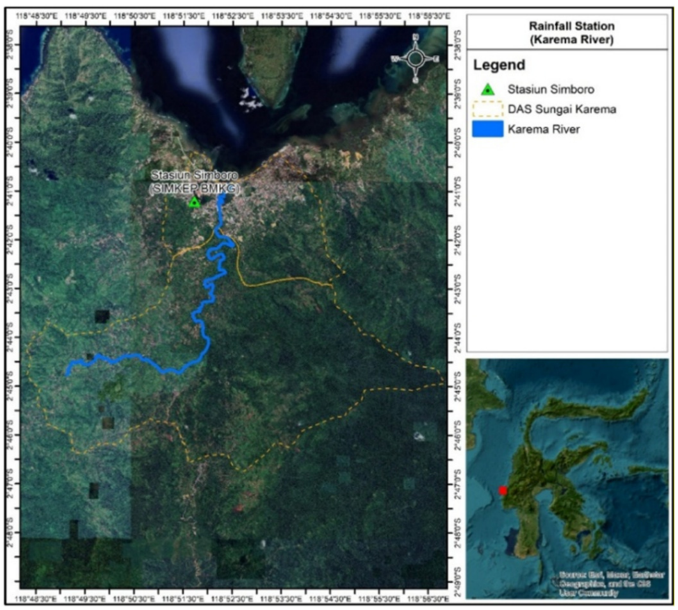

Fig. 3. Karema river basin and rainfall station locations.

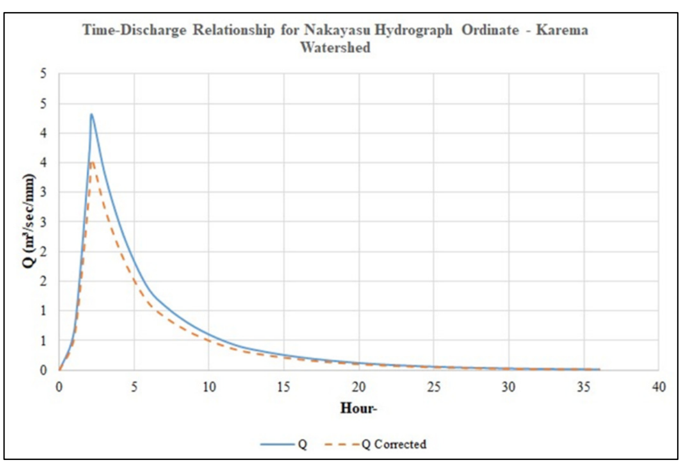

Fig. 4. Time-discharge relationship graph for the Nakayasu Hydrograph ordinate of the Karema watershed.

C. Analysis of Flood Affected Areas on the Karema River

The HEC-RAS modeling results for the study area, based on the input hydrograph data, are presented in Tables III-V, providing a quantitative overview of the flood inundation characteristics in various affected regions along the Karema River. The model was calibrated using the Q25 hydrograph, which represents a 25-year return period. This return period corresponds to a lower annual probability of occurrence (1/25 or 4%) compared to shorter return periods, such as 5 years (20%) or 10 years (10%). The selection of a higher return period is more appropriate for medium-term disaster mitigation planning and infrastructure design, as it considers more extreme flood scenarios.

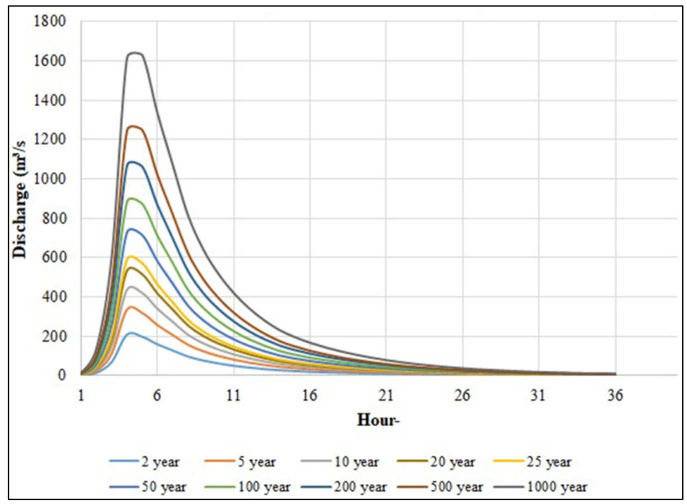

Fig. 5. Relationship between time and discharge based on the Nakayasu SUH for the Karema watershed.

TABLE III. FLOOD DEPTH

No	Ward	Flood depth (meters)			Location of puddles
		Max.	Minimum	Average	
1	Karema	12.64	0.001	4.90	River borders, residential areas
2	Simboro	12.70	0.001	4.40	River borders, residential areas

TABLE IV. FLOOD CURRENT SPEED

No	Ward	Current speed (m/s)			Location of puddles
		Max.	Minimum	Average	
1	Karema	6,821	0.00005	52.08	River borders, residential areas
2	Simboro	2,152	0.000051089	61.67	River borders, residential areas

TABLE V. FLOOD CLASS OF RESEARCH AREA BASED ON MODELING

No	Ward	Average depth	Flood classes based on water depth			Location of puddles
			Low <0.76 m	Medium 0.76 m - 1.5 m	High > 1.5 m	
1	Karema	4.9				River borders, residential areas
2	Simboro	4.4				River borders, residential areas

The HEC-RAS modeling results provide a comprehensive analysis of the flood depth, flow velocity, and flood classification across the Karema and Simboro wards. The maximum recorded flood depths were 12.64 m in Karema and 12.70 m in Simboro, with average depths of 4.90 m and 4.40 m, respectively. These substantial depths indicate the potential for severe inundation, particularly in the vicinity of riverbanks and within residential zones. Table IV further accentuates the severity by presenting the current speeds, which reveal alarmingly high values, particularly in Simboro, where the maximum speed recorded was 40,131 m/s. This is likely a data anomaly or an input error, as such velocity is physically implausible for riverine flooding. However, the average speeds continue to be high, suggesting the possibility of strong flood currents that could pose a threat to structures and human safety.

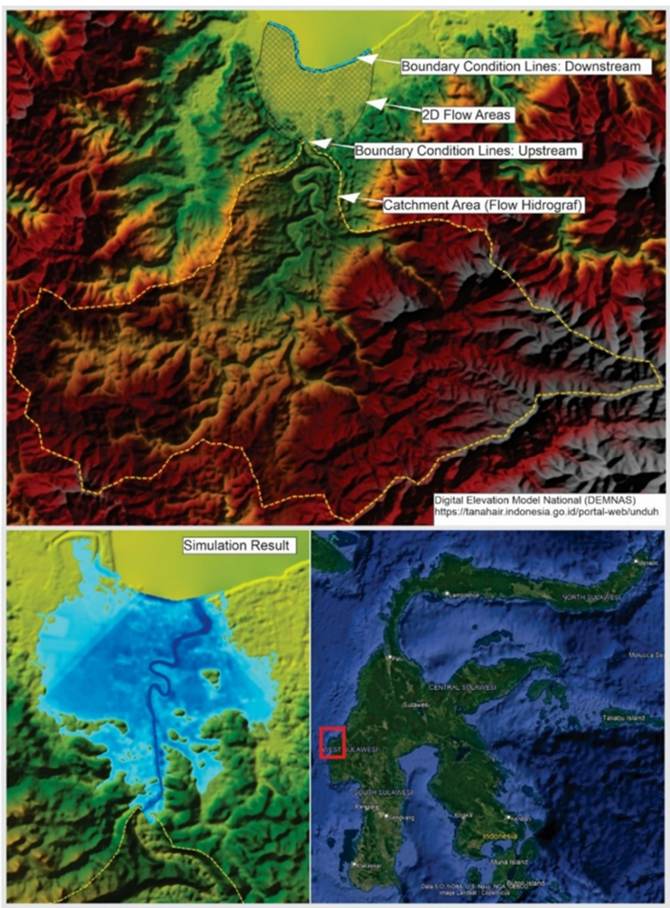

Fig. 6. Hydraulic Analysis with CFD - HEC-RAS 2D unsteady flow data.

A classification system for flood-prone areas based on the average water depth has determined that both Karema and Simboro fall within the "high" flood class category, with average water depths far exceeding 1.5 m. These findings underscore the vulnerability of these wards to extreme flooding, reinforcing the necessity of comprehensive mitigation strategies. In light of the modeled conditions, a strategic approach should be adopted, with a focus on enhancing infrastructure, optimizing drainage systems, and establishing early warning systems. The modeling results serve as a vital reference for planning evacuation routes and allocating resources for disaster preparedness in the affected areas. The hydraulic analysis uses two-dimensional unsteady flow simulations with Computational Fluid Dynamics (CFD) in the HEC-RAS environment. Figure 6 presents the outcomes of the 2D unsteady flow modeling, which captures the dynamic behavior of the water movement across the terrain based on input flood hydrographs, terrain data (DEM), and Manning's roughness coefficients.

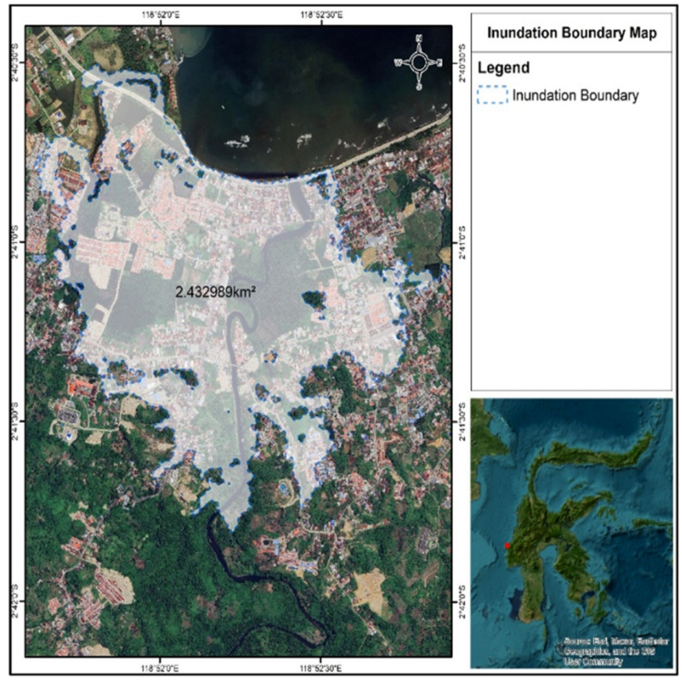

Fig. 7. Flood inundation map.

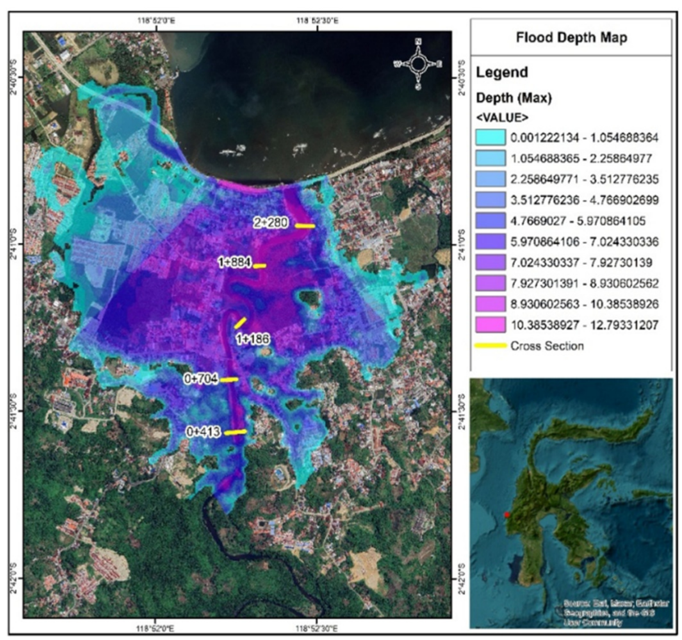

Fig. 8. Flood depth map.

This analysis facilitates a more precise depiction of the propagation of floodwaters over time and space within the Karema River Basin. Subsequent to the CFD simulation, Figure 7 presents the flood inundation map, which provides a visual representation of the spatial extent of the areas affected by the modeled flood event. This map is essential for identifying critical zones with the highest risk of being submerged. Figure 8 illustrates the flood depth map, which displays the variation in water depth across the flooded area. As demonstrated by the extant research, these visual outputs provide essential information for flood risk assessment and emergency response planning. They aid decision-makers in designing effective mitigation strategies and infrastructure interventions.

IV. CONCLUSIONS

The hydraulic flood simulation of the Karema River using Computational Fluid Dynamics (CFD) through the Hydrologic Engineering Center's River Analysis System (HEC-RAS) 6.4.1 software, with a 2D unsteady flow analysis, produced significant results for the flood risk assessment in the region. The simulation revealed that the average flood flow velocity ranged between 52.08 m/s and 61.67 m/s, indicating a fast water movement that could pose a significant threat to infrastructure and human safety. Furthermore, the average flood depth exhibited a range from 4.4 m to 4.9 m, indicating levels of severe inundation. The total inundated area in the downstream part of the Karema River was approximately 2.432989 km², affecting two main urban wards: Karema (0.820 km²) and Simboro (1.610 km²). It is evident that the flood hazard classification for both wards is characterized as high-hazard, underscoring the pressing necessity for comprehensive flood mitigation strategies and the implementation of resilient infrastructure to safeguard the vulnerable population and built environment.

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