Integrated Hydrological Assessment and Urban Drainage Performance Analysis for Flood Disaster Mitigation

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ABSTRACT

Flooding in Sinjai City has disrupted urban activities and infrastructure, highlighting deficiencies in the existing drainage system. This study evaluates drainage characteristics and flood risk in North Sinjai using a descriptive-analytical approach based on hydrological data, rainfall patterns, land-use change, and topography. The results show that several drainage channels are undersized and not aligned with current runoff conditions, especially during extreme rainfall events. Additional contributing factors include low infiltration capacity, limited channel slope, sedimentation, and rapid land-use conversion. The study offers an integrative assessment of hydrological parameters to evaluate drainage performance in areas where advanced modeling is limited. Proposed measures include drainage rehabilitation, application of green infrastructure, such as retention ponds and permeable surfaces, and improved watershed management and zoning policies. These findings provide practical guidance for urban flood mitigation and support the development of resilient infrastructure in line with SDG 11 and SDG 13.

Keywords-urban drainage; hydrological analysis; flood risk; North Sinjai; Green infrastructure; SDG 11; SDG 13

I. INTRODUCTION

Urban flooding is a significant challenge in developing cities, particularly in Southeast Asia, where accelerated urban expansion intensifies hydrological vulnerability [1]. Rapid land conversion, inadequate infrastructure planning, and population growth have increased surface runoff and reduced infiltration capacity. In Indonesia, flood disasters frequently disrupt socio-economic systems, especially in areas lacking integrated mitigation planning [2]. Land-use changes significantly alter watershed hydrology and increase peak discharge during extreme rainfall events [3]. In addition, flood impacts extend beyond physical damage, affecting economic stability, infrastructure resilience, and community well-being [4]. These conditions highlight the need for comprehensive hydrological assessments, integrated with evaluations of urban drainage performance, to support effective and sustainable flood mitigation strategies.

Hydrological processes in urban catchments are increasingly complex due to anthropogenic activities and climate variability. Structural interventions and hydraulic modifications can influence downstream flood behavior and sediment transport [5]. While contemporary urban design integrates computational approaches to enhance flood resilience [6], adaptation strategies often remain fragmented, as observed in cities such as Jakarta and Bogor [7, 8]. Urban growth also alters microclimatic conditions and can intensify extreme rainfall patterns [9]. These dynamics underscore the importance of integrating hydrological analysis with drainage system performance to better understand and manage urban flood risks.

Developments in flood modeling have introduced various analytical tools ranging from empirical to physically based and hybrid approaches [10]. Model performance under climate change scenarios emphasizes the importance of calibration and validation [11], while soft computing methods improve predictive accuracy under uncertainty [12]. Urbanization and climate change influence flood volumes, requiring integrated drainage adaptation and planning [13]. In addition, interactions between land use, water systems, and socio-economic factors further complicate flood risk management [14]. Consequently, integrated assessment frameworks must consider both hydrological drivers and urban infrastructure capacity [15-21].

Advances in geospatial technologies, remote sensing, and GIS have significantly improved flood hazard mapping and spatial analysis [22, 26, 27]. However, policy integration remains challenging due to fragmented governance and institutional barriers [23, 24]. In developing countries, balancing flood protection with sustainable development is a key issue [25]. Although previous studies have addressed hydrological modeling [10-12], geospatial mapping [26-30], and adaptation strategies [6-8], the integration of watershed-scale hydrological assessment with detailed drainage performance evaluation remains limited. This gap reduces the practical applicability of research findings for infrastructure planning and flood mitigation in rapidly urbanizing regions.

Therefore, this study aims to develop an integrated framework that combines hydrological assessment and urban drainage performance analysis to support flood mitigation. The research contributes by integrating DEM-based hydrological modeling with drainage capacity evaluation, assessing system adequacy under peak discharge conditions, and providing spatially explicit recommendations. In addition, this study introduces quantitative indicators, including the Drainage Adequacy Ratio (DAR), Hydraulic Deficit Index (HDI), and Weighted Flood Risk Index (WFRI), to enhance analytical rigor and reproducibility. The novelty lies in combining multi-scale modeling approaches, specifically HEC-HMS and the Rational Method, within a structured framework that bridges hydrological analysis with practical infrastructure management. This integrated approach supports evidence-based decision-making and advances sustainable urban flood resilience.

II. MATERIALS AND RESEARCH METHOD

A. Study Area

The research was conducted in North Sinjai District, Sinjai City, South Sulawesi, Indonesia, a region that has experienced frequent urban flooding, particularly during high-intensity rainfall events. The study area encompasses urbanized zones, agricultural lands, and undulating topography. The spatial extent was delineated based on hydrological catchment boundaries and administrative limits, enabling accurate mapping of drainage networks and runoff patterns.

B. Data Collection

This study used both primary and secondary data. Primary data were collected through field surveys conducted from March to May 2025 at 12 selected sites representing upstream, midstream, and downstream drainage zones in Sinjai Regency, selected based on preliminary GIS analysis of flood-prone areas, land-use variation, and drainage density. Measurements included channel dimensions, slope gradients, and soil infiltration rates, measured with a double-ring infiltrometer, with repeated tests to ensure consistency. Secondary data were obtained from sources such as the Meteorology, Climatology, and Geophysics Agency (BMKG), local government agencies, and remote sensing platforms, including rainfall data (2015–2024), spatial data from PUPR, and LULC and DEM data from the United States Geological Survey (USGS).

To ensure a clear and systematic analysis, a structured workflow was employed, comprising rainfall analysis, runoff estimation using the Rational Method, drainage capacity calculation using Manning's equation, and GIS-based flood risk mapping. Supporting datasets included long-term rainfall records, DEM data, LULC maps, and drainage network data, ensuring a logical and reproducible process from data input to flood risk identification.

C. Methodological Approach

The study employed a descriptive-analytical framework integrating spatial, statistical, and hydrological analyses. The methodology is structured in four main stages:

1) Hydrological Analysis

Hydrological parameters, such as rainfall intensity, frequency, and duration, were analyzed using frequency analysis methods (Gumbel and Log-Pearson Type III distributions) to determine design storms for 2-, 5-, and 10-year return periods. The Rational Method was applied to estimate peak runoff (Q) using:

$$Q = C * I * A \quad (1)$$

where Q is the peak discharge (m³/s), C is the runoff coefficient based on land use, I is the rainfall intensity (mm/hr), and A is the catchment area (ha).

To strengthen the analytical rigor of this study, a measurable performance indicator was introduced: the DAR. This index quantitatively assesses the capacity of drainage systems relative to the design discharge. The DAR is defined as:

$$\mathrm{DAR} = \frac{Q_{capacity}}{Q_{design}} \quad (2)$$

where $Q_{capacity}$ represents the existing drainage capacity (m³/s) and Q_{design} represents the peak runoff discharge (m³/s). A DAR value greater than or equal to 1 indicates that the drainage system is adequate, whereas a value less than 1 indicates insufficient capacity and a higher risk of flooding. In addition, the HDI is calculated to quantify the magnitude of insufficiency, expressed as:

$$\mathrm{HDI} = Q_{design} - Q_{capacity} \quad (3)$$

Positive HDI values indicate a deficit in drainage capacity, while negative values indicate surplus capacity. These indicators provide a more robust and interpretable basis for evaluating drainage system performance and identifying priority areas for intervention.

2) *Drainage Capacity Evaluation*

The hydraulic capacity of the drainage channels was calculated using Manning's equation, which is widely applied for open channel flow analysis. The equation is expressed as:

$$Q = \frac{1}{n}\sqrt[3]{(AR)^2}\sqrt{S} \quad (4)$$

where $Q$is the discharge (m³/s), $n$is the Manning roughness coefficient, A is the cross-sectional flow area (m²), R is the hydraulic radius (m) defined as the ratio of the flow area to the wetted perimeter ($R = A/P$), and $S$is the channel slope (m/m). The values of $A$and Pwere obtained from field measurements of channel geometry, while the slope $S$was determined from topographic survey data. The Manning roughness coefficient, *n,* was selected based on standard references according to channel conditions (e.g., concrete-lined or natural channels). This approach ensures an accurate estimation of drainage capacity for comparison with peak runoff discharge.

3) *Infiltration and Land Use Evaluation*

Infiltration tests were conducted in representative areas to assess soil infiltration capacity. The results were integrated with land use classification (residential, agricultural, commercial) to evaluate imperviousness and surface runoff potential. Satellite imagery and GIS analysis (using QGIS and ArcGIS) were used to quantify changes in land cover over the past five years.

4) *Flood Risk Mapping*

The WFRI was developed to integrate multiple contributing factors into a single composite indicator, and it is calculated using:

$$\mathrm{WFRI} = \sum_{i=1}^{n} (w_i \times X_i) \quad (5)$$

where $w_i$represents the weight assigned to each variable and X_i represents the standardized value of the corresponding variable. In this study, the selected variables include rainfall intensity, runoff discharge (Qdesign), drainage adequacy (DAR), land use, and slope. All variables were normalized to a 0–1 scale before analysis to ensure comparability.

The weighting scheme was determined through a combination of literature-based justification and expert judgment, taking into account the relative influence of each factor on flood occurrence. Rainfall intensity and runoff discharge were assigned higher weights due to their dominant role in flood generation, followed by drainage adequacy, while land use and slope were assigned moderate weights. The final WFRI values were classified into flood risk categories (low, moderate, high) using equal interval classification in a GIS environment. This approach allows for a comprehensive and spatially explicit assessment of flood risk. Table I shows the variables and weights for the WFRI.

TABLE I. VARIABLES AND WEIGHTS FOR WFRI

No	Variable	Symbol	Weight (wi)	Justification
1	Rainfall intensity	X1	0.30	Primary driver of flood events
2	Runoff discharge	X2	0.25	Represents peak flow magnitude
3	Drainage adequacy	X3 (DAR)	0.20	Reflects system capacity
4	Land use	X4	0.15	Influences infiltration/runoff
5	Slope	X5	0.10	Affects flow velocity and accumulation

5) *Data Processing Tools*

In this study, the Hydrologic Engineering Center–Hydrologic Modeling System (HEC-HMS) and the Rational Method were integrated to capture hydrological responses at different spatial scales. HEC-HMS was used for watershed-scale analysis to simulate rainfall–runoff processes and estimate hydrographs based on basin characteristics and temporal rainfall distribution, thereby being suitable for complex, time-dependent systems. In contrast, the Rational Method was applied to smaller urban catchments to estimate peak discharge using rainfall intensity, runoff coefficients, and catchment area, assuming uniform rainfall. This integration enables a comprehensive multi-scale analysis, where HEC-HMS provides macro-scale hydrological context and the Rational Method offers micro-scale evaluation relevant to urban drainage systems. Due to limited observed discharge data, direct model calibration and validation were constrained; however, reliability was supported by parameter selection informed by established literature and consistency checks against regional hydrological characteristics. Model outputs were also compared with reported flood events and known flood-prone locations to assess plausibility. Although this approach provides reasonable confidence in the results, the absence of direct calibration introduces uncertainty, and future studies are proposed to incorporate observed discharge data for more rigorous validation.

III. RESULTS AND DISCUSSION

A. *Biophysical Characteristics of North Sinjai Regency*

Understanding the biophysical characteristics of North Sinjai Regency is essential for evaluating flood risk and drainage system performance, as these characteristics, including administrative divisions, topography, and soil types, provide the basis for hydrological behavior and urban planning decisions. North Sinjai is one of the districts within Sinjai Regency, South Sulawesi, Indonesia, bordered by neighboring districts such as West Sinjai, East Sinjai, and Sinjai Utara, and includes urban and peri-urban areas such as Balangnipa, Bongki, and Lamatti Rilau, which are particularly relevant for flood management due to their population density and infrastructure concentration. The administrative layout plays a key role in resource allocation, emergency response coordination, and implementation of mitigation infrastructure, where overlapping responsibilities in boundary areas can lead to drainage misalignment and maintenance gaps. Therefore, understanding these administrative boundaries is important for developing integrated watershed management strategies across regions. Figure 1 depicts the administrative map of Sinjai Regency, South Sulawesi province.

The contour map of Sinjai Regency shows a varied topography, with elevations ranging from near sea level in coastal areas to over 1,000 m in the highlands. In comparison, North Sinjai is predominantly lowland with elevations between 5 and 200 m above sea level. Urban settlements are mostly located on gentle slopes (<5%), making them prone to water stagnation due to limited runoff. These low-gradient areas are particularly vulnerable to drainage inefficiency during high-intensity rainfall events. In contrast, the southern and southeastern regions have steeper slopes, which generate rapid runoff and increase downstream pressure on lowland drainage systems. This topographic variation requires different flood mitigation approaches, including retention and slow-release strategies in upstream areas and improved drainage capacity in downstream zones. Figure 2 illustrates the contour map of Sinjai Regency.

The soil map of Sinjai Regency shows that North Sinjai is mainly dominated by alluvial and clay loam soils with low to moderate infiltration capacity. The presence of grumusol and regosol soils, which have fine textures and high water retention, increases the risk of waterlogging, especially under urban compaction. In contrast, andosol soils with higher infiltration capacity are found in elevated and forested areas but are less common in North Sinjai. Ongoing land use changes from green areas to urban development further reduce infiltration and increase flood risk. Therefore, incorporating soil characteristics into drainage planning, including the use of green infrastructure such as permeable pavements and bioretention systems, is essential. Overall, the combination of lowland topography and sensitive soil conditions makes North Sinjai highly prone to flooding. Figure 3 displays the soil type map of Sinjai Regency.

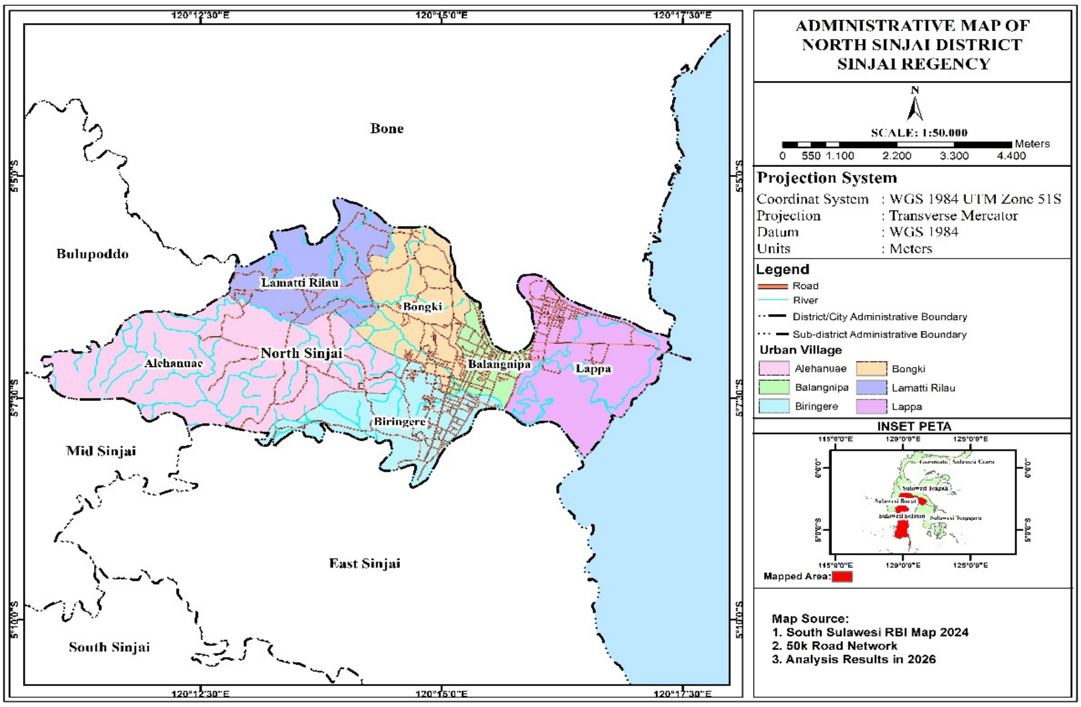

Fig. 1. Administrative map of Sinjai Regency.

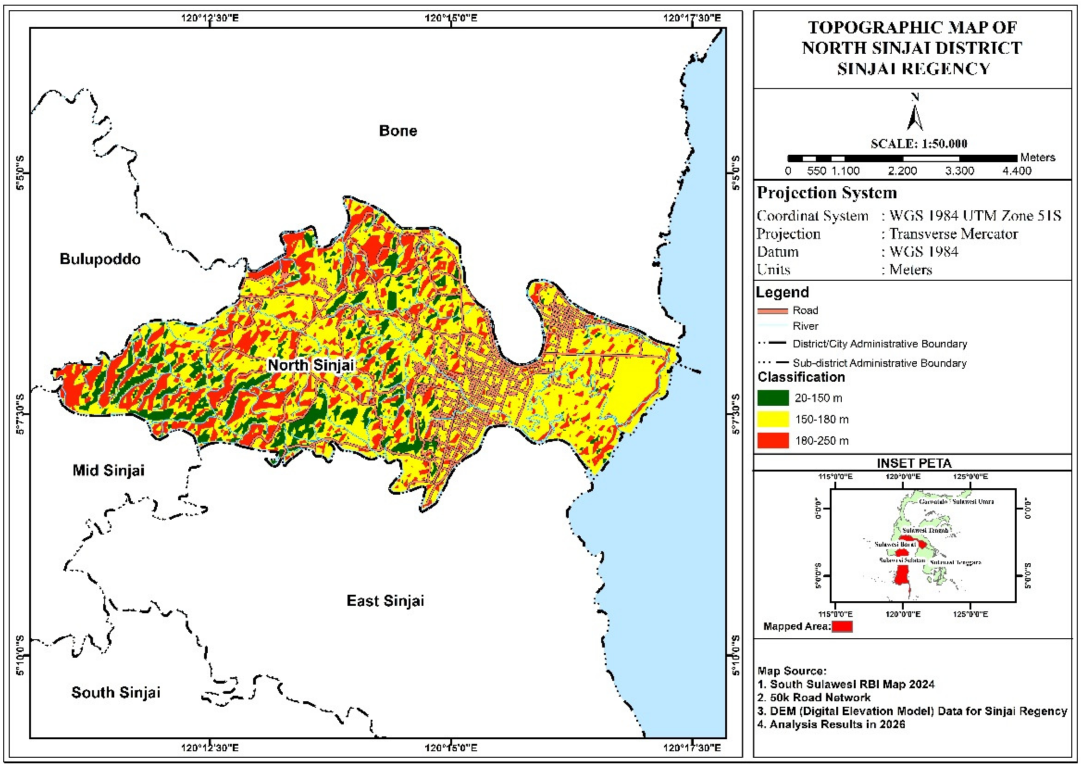

Fig. 2. Contour map of Sinjai Regency.

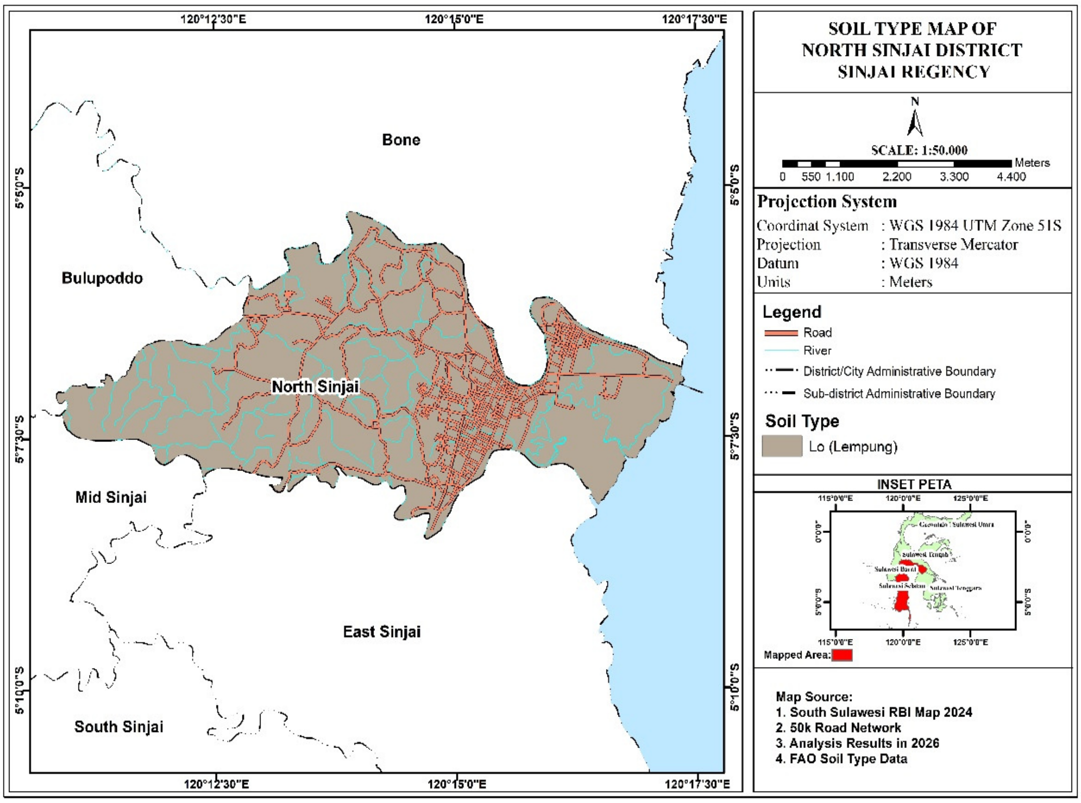

Fig. 3. Soil type map of Sinjai Regency.

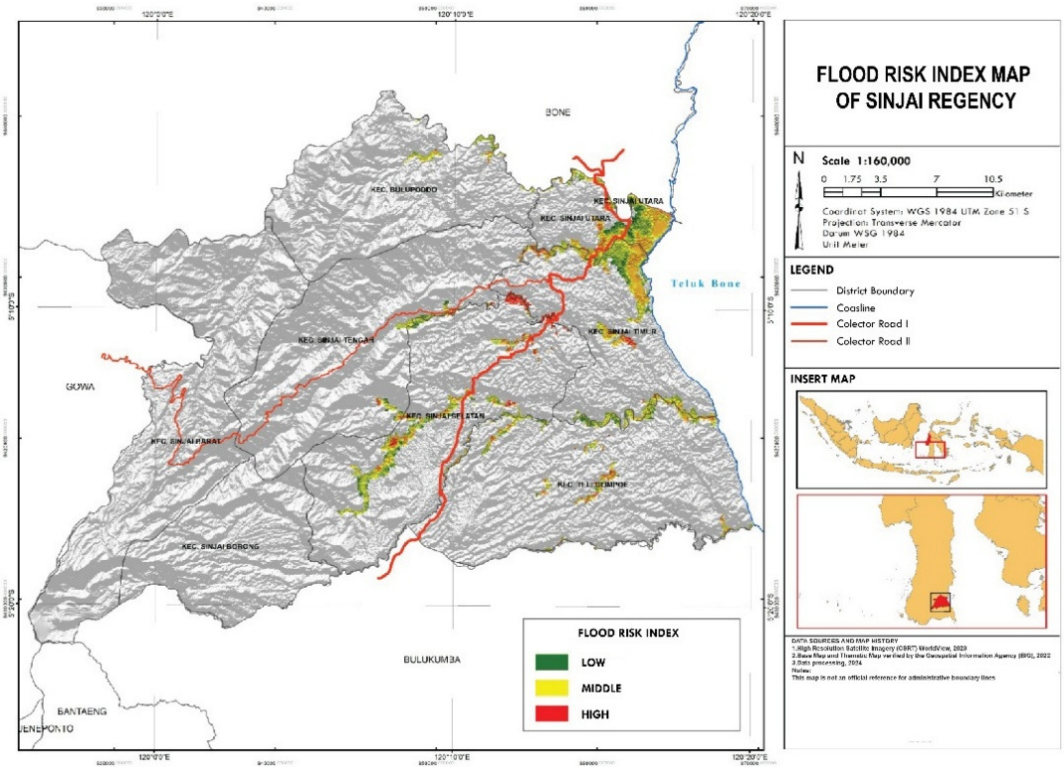

Fig. 4. Flood risk mapping and vulnerable zones of Sinjai Regency.

B. Hydrological Characteristics of North Sinjai Regency

The hydrological characteristics of North Sinjai Regency are influenced by rainfall patterns, river systems, and drainage conditions, with annual rainfall ranging from 2,500 to 3,500 mm and peak rainfall intensity exceeding 100 mm/day, according to data from the BMKG. These conditions, combined with increasing extreme rainfall events, significantly raise flood risk, especially in low-lying urban areas. The Tangka River functions as the main drainage system, but many secondary channels are constrained by sedimentation, limited capacity, and poor maintenance. Low infiltration capacity in urbanized areas, high runoff coefficients (>0.70), rapid land-use change, and reduced natural storage further intensify runoff and shorten response time to flooding. Additionally, weakened interaction between surface and groundwater, along with the loss of natural water bodies, increases vulnerability. Overall, the combination of high rainfall, low infiltration, land-use change, and inadequate drainage infrastructure makes North Sinjai highly prone to flooding, underscoring the need for integrated solutions, including drainage improvements, nature-based infrastructure, and stronger land-use regulation, to enhance urban resilience.

C. Flood Risk Mapping and Vulnerable Zones

A comparative analysis of design discharge (Q design) and existing drainage capacity (Q capacity) was conducted to quantitatively evaluate drainage performance in each critical segment. The design discharge was calculated using the Rational Method, while drainage capacity was estimated using Manning’s equation based on field-measured channel characteristics. The results, presented in Tables II and III, classify segments as inadequate when Q design exceeds Q capacity, indicating flood-prone conditions, and as safe when capacity is sufficient. Flood risk mapping further identified high-risk zones concentrated in Bongki, Balangnipa, and Lamatti Rilau, based on a composite index of runoff volume, drainage inadequacy, topographic conditions, and land use. The results were validated using flood occurrence data from the Regional Disaster Management Agency (BPBD), which showed a high spatial agreement of 85.3% between the mapped high-risk zones and observed flood events. Figure 4 portrays the flood-risk map and vulnerable zones in Sinjai Regency. Overall, the findings indicate that flood vulnerability is concentrated in low-lying, densely developed areas with high runoff coefficients and limited drainage capacity, consistent with patterns reported in previous studies linking urban flood risk to land use change and insufficient hydrological resilience.

The integrative approach in this study, combining rainfall intensity, land use, slope, and drainage data, confirms that multiple interacting factors drive flood vulnerability and aligns with previous GIS-based Weighted Overlay Analysis studies in South Sulawesi, which identify elevation and land use as key determinants. However, this study improves upon earlier work by incorporating localized hydrological validation, producing more specific and actionable risk assessments at the neighborhood scale. Consistent with studies in the Makassar area, the findings highlight that informal settlements along riverbanks—such as those near the Tangka River—are particularly vulnerable due to inadequate infrastructure and poor drainage integration. Unlike studies relying mainly on spatial modeling or historical flood frequency, this research integrates real-time drainage performance evaluation, offering stronger predictive capability under urban development and climate variability. Nevertheless, uncertainties remain, particularly in rainfall frequency analysis, and assumptions about the runoff coefficient, as limitations in data quality, spatial variability, and model simplifications may affect accuracy. Therefore, the results should be interpreted with caution, while future studies are proposed to include higher-resolution rainfall data, model calibration, and sensitivity analysis to improve reliability.

TABLE II. COMPARISON OF DESIGN DISCHARGE AND DRAINAGE CAPACITY

No	Drainage segment	Area (ha)	Q design (m^3/s)	Q capacity (m^3/s)	Capacity Status
1	Segment A	12.5	3.20	2.10	Inadequate
2	Segment B	8.3	1.85	2.40	Adequate
3	Segment C	15.2	4.10	3.00	Inadequate
4	Segment D	6.7	1.20	1.50	Adequate

TABLE III. COMPARATIVE ANALYSIS OF QDESIGN, QCAPACITY, AND HYDRAULIC PERFORMANCE INDICES

No	Segment	Q design	Q capacity	DAR	HDI	Status
1	A	3.20	2.10	0.66	1.10	Deficit
2	B	1.85	2.40	1.30	-0.55	Adequate

IV. CONCLUSION

This study provides a comprehensive evaluation of the drainage network and flood risk in North Sinjai Regency by integrating hydrological data, land use analysis, topographic assessment, and drainage performance metrics. The results indicate that several drainage channels are undersized and misaligned with current runoff conditions, particularly during high-intensity rainfall events, and that factors such as rapid land-use change, low soil infiltration, and inadequate channel slopes further increase flood vulnerability. Flood risk mapping identifies highly vulnerable urban zones where runoff exceeds the capacity of existing infrastructure. By combining spatial analysis with drainage performance evaluation, this study offers more targeted and practical insights compared to conventional approaches. The findings highlight that effective flood mitigation requires not only drainage improvement but also integrated watershed management and green infrastructure. Therefore, the present study proposes rehabilitating critical drainage segments, enforcing sustainable land use regulations, and implementing nature-based solutions to enhance infiltration and reduce runoff, supporting more adaptive and resilient flood management strategies in North Sinjai.

DECLARATION OF COMPETING INTERESTS

The authors declare that there are no competing interests.

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DATA AVAILABILITY

The data supporting the findings of this study are available from the author upon reasonable request.

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