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Evaluating Urban Flood Risk and Mitigation Strategies Using Hydrological and Hydraulic Modelling: A Case Study

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Abstract

This study aims to analyze the characteristics of the Tallo River runoff before and after infrastructure development; identify the main factors causing flood inundation in the affected area and develop flood mitigation strategies based on hydrological and hydraulic modeling. The methods used include data collection using 15 years of rainfall data (2010–2024), topographic maps (DEM), and land use information; hydrological analysis by calculating the design flood discharge using the Rational and Nakayasu methods; hydraulic modeling with HEC-RAS 2D flood inundation simulation to understand the pattern of inundation distribution due to increasing runoff discharge; evaluation of the impact of development by comparing the runoff discharge before and after development and identifying its contribution to flood risk and mitigation strategies by compiling technical recommendations such as raising the embankment, improving drainage, and increasing the elevation of the affected area. The results of the study indicate that flooding in the Tallo River is mainly caused by the river's inability to accommodate the runoff discharge and the backwater effect of the urban drainage system. The increase in discharge due to the construction of a shopping center was recorded as very small (0.84 m³/second) and was not significant to the occurrence of flooding. The proposed mitigation strategies include building a 2.5-meter high embankment, increasing drainage capacity, and regulating the elevation of the affected area. This study is expected to be a reference in flood risk management based on hydrology and hydraulics in urban areas.

Introduction

Floods are natural disasters that often occur during the rainy season. Floods are defined as a scientific event caused by overflowing water from rivers due to water volume exceeding the available river capacity (Kodatie, 2013) . Floods that have occurred recently are more likely to be caused by human activity. Many factors cause floods, including high rainfall intensity, river shallowing due to sedimentation, changes in land use, and the lack of smooth water flow due to large amounts of waste (Hadisusanto, 2011; Mfon et al., 2022; Blöschl, 2022; Lisetskii & Buryak, 2023). In many cases of urban flooding, the main factor causing flooding is due to changes in land function on river banks (Limantara, 2010) . According to PP No. 38 Article 10 Paragraph 2 of 2011, the river boundary line is at least 100 m (one hundred meters) from the right and left edges of the riverbed along the river channel. This means that land conversion is not allowed within the river boundary. However, in reality, land conversion still occurs on river

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banks, resulting in narrowing of the river body and causing flooding. In addition to land conversion, high human activities are closely related to changes in land use in the upper reaches of the river, which can affect the rate of sedimentation in the river. The high rate of sedimentation that occurs reduces the river's capacity, which is also a supporting factor for flooding. Floods can hamper human activities in various sectors (2011). Floods can also cause material, non-material, social, psychological and health losses experienced by flood-affected communities. Therefore, the large potential for damage and losses arising from flooding events requires a solution to overcome the flood problem (BR, 1990; Wang et al., 2022; Ma et al., 2022).

Tallo River Basin is one of the watersheds located in Makassar City. Tallo River has a watershed area of around 432.21 km2 ^{with} a main river length of 77.90 km stretching from Gowa Regency, Maros Regency to Makassar City. Administratively, Tallo River is under the auspices of the Jeneberang-Walanae River Basin Center (BBWS). The division of Tallo River Basin itself includes the upstream part in Gowa Regency and Maros Regency while the downstream part is in Makassar City. Tallo River Basin is one of the watersheds that regularly experiences flooding every year. Flooding in this watershed occurs in the downstream area, namely around Makassar City. The routine occurrence of this flooding requires the Government to be alert to immediately study and resolve this flood problem (Khafifah et al., 2023; Sene, 2008).

In previous studies, there were several things that caused the vulnerability of flooding in the Tallo River, including the overflow of the Tallo River which exceeded the reservoir capacity, relatively flat topography, and inappropriate land conversion. Based on data from the National Disaster Management Agency, in 2025 flooding in the Tallo River caused thousands of houses to be submerged in floodwater in Makassar City, especially in Tamalanrea District (Setyawan et al., 2013).

With a fairly high level of vulnerability, a study needs to be conducted on how much the Tallo River is capable of dealing with floods and what technical handling is appropriate. This study covers two aspects, namely the hydrological and hydraulic aspects of the river. To analyze the hydraulic aspects of the river, many researchers use HEC-RAS software. According to Gusta Gunawan in his research on "Bengkulu Water Flood Forecasting Model Using the HEC-RAS Application and Geographic Information System" defines HEC-RAS (Hydrologic Engineering Center - River Analysis System) as software designed for flood discharge forecasting on rivers with the lump model concept. In his research conducted in 2018, he studied the level of reliability of the HEC-RAS software in discharge forecasting and flood simulation. It was concluded that the level of reliability of the HEC-RAS application increases if the data on the geometric river used for the study is quite detailed and accurate. Thus, the HEC-RAS application can be used accurately enough in discharge analysis and flood simulation studies (Gunawan, 2018; Al-Hussein et al., 2022; Costabile et al., 2021).

Tallo River in Makassar City is one of the main rivers that experiences periodic flooding, especially during high rainfall. Increasing infrastructure development around the river basin (DAS), such as the rapid development of shopping centers, has the potential to affect runoff discharge and flood inundation. This phenomenon is exacerbated by a suboptimal urban drainage system, causing runoff water to not be effectively disposed of into the Tallo River. Therefore, research is needed to identify the main factors causing flooding and the impact of development on runoff discharge and mitigation solutions that can be applied.

The formulation of the problems in this study are (1) What are the characteristics of the Tallo River runoff discharge before and after infrastructure development; (2) How big is the

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influence of development on increasing runoff discharge and flood inundation; (3) What solutions can be applied to mitigate flooding in the Tallo River.

Methods

Research Location and Time

This research was conducted in the Tamalanrea District, Makassar City. South Sulawesi Province, during a period of 4 (four) months in 2025. The observation location covers the administrative area of Tamalanrea Jaya Village, Tamalanrea District, which is located between 5° 8'49.64" South Latitude and 119°28'54.02" East Longitude to 5° 8'43.01" South Latitude and 119°28'24.59" East Longitude.

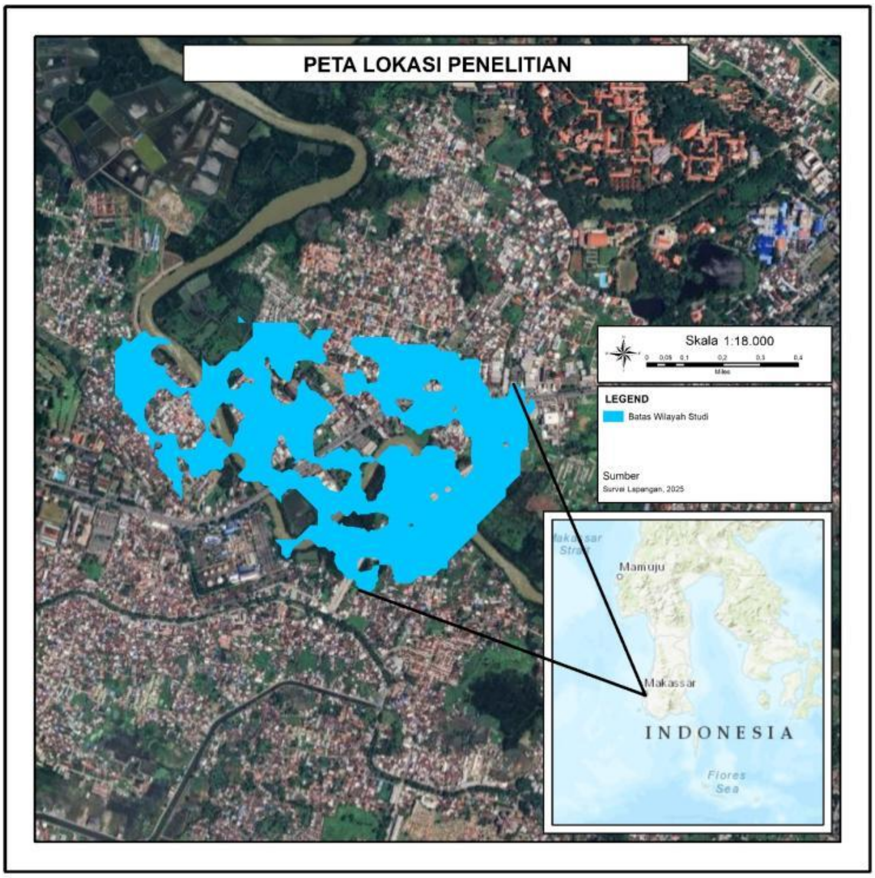

Figure 1Study Site Locations, Google Earth 2024

Tools and Materials

This study uses a hydrological and hydraulic approach with several Hydrological Analysis methods: Calculating the design flood discharge using the Rational and Nakayasu methods based on rainfall data from 2010–2024; Hydraulic Modeling: Flood inundation simulation using HEC-RAS 2D to understand the pattern of inundation distribution due to increased runoff discharge; Development Impact Evaluation: Comparing the discharge before and after the Development of Shopping Centers in the Trade and Service Area to determine its contribution to flooding; and Mitigation Strategy: Preparing recommendations, such as raising embankments and improving drainage systems to reduce flood risk (Marselina et al., 2022).

Hydrological analysis is the initial stage of a flood risk assessment process, where this study is very crucial in knowing the occurrence of floods at the study location. The results of the

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hydrological analysis are in the form of determining the design flood discharge, which discharge will be the reference in the hydraulic analysis to determine the flood recurrence period that is in accordance with the events in the field (Ramos & Besharat, 2021) .

Compared with previous studies that only focused on the analysis of runoff discharge without considering the impact of development on the hydrology of the area, this study offers a more comprehensive approach with several advantages: Integration of Hydrology and Hydraulic Analysis: Using a combination of Rational and Nakayasu methods for runoff discharge calculations and 2D HEC-RAS-based hydraulic modeling for flood inundation distribution simulation; Long-Term Data-Based Approach: Using 15 years of rainfall data (2010–2024) to improve the accuracy of the design flood discharge calculation; Identification of Backwater Effects: This study found that flooding on Jl. Perintis Kemerdekaan was not only caused by river overflow, but also by the backwater effect of the urban drainage system experiencing flow obstructions and Infrastructure-Based Recommendations: Not only providing an analysis of the causes of flooding, this study also offers concrete solutions, such as raising the embankment by 2.5 meters and increasing the elevation grading of the affected area (Hou et al., 2023; Rauf, 2025) .

The novelty of the proposal from the aspect of approach and method is the Utilization of 2D HEC-RAS with Unsteady Flow Simulation (Patil & Kambekar 2022; Sadiqzai et al., 2024) . Unlike previous studies that used an empirical approach or simple simulation, this study uses numerical modeling that is more accurate in describing the dynamics of flood flow; evaluates the impact of development on Runoff Discharge; Quantitative analysis is carried out to assess how much influence the development of shopping centers has on increasing runoff discharge and flood inundation risk and simulates mitigation strategies based on a combination of engineering and spatial planning: Not only providing technical solutions such as embankments, this study also considers spatial aspects and elevation grading as long-term mitigation efforts (Kamiana, 2011).

Research Implementation

Stages Achieved: a) Collection of hydrological data for the last 15 years; b) Initial analysis of Tallo River runoff discharge using the Rational and Nakayasu methods; c) Identification of the main factors causing flood inundation around the study area; d) Stages to be carried out: 1) Hydraulic modeling using HEC-RAS 2D to obtain a more accurate inundation pattern; 2) Simulation of various flood mitigation scenarios, including raising embankments and improving drainage systems; 3) Validation of model results with field data to improve the accuracy of flood predictions; a) Planned Stages: b) Development of a sensor-based and IoT runoff discharge monitoring system for early detection of floods; c) Study of the impact of land use changes on long-term flood risk; d) Implementation and evaluation of proposed flood mitigation solutions through collaboration with local governments and relevant stakeholders.

Data Analysis

This study employs a quantitative approach combining hydrological and hydraulic analyses to examine the runoff behavior and flood inundation patterns of the Tallo River. The analysis is grounded in both primary and secondary data sources. Primary data were obtained through field observations, which involved assessing the existing river morphology, the state of the drainage infrastructure, and identifying the locations affected by recurring floods. Secondary data include 15 years of rainfall records (2010–2024) sourced from the Paotere and Sultan Hasanuddin Meteorological Stations. In addition, Digital Elevation Model (DEM) maps were utilized to represent the topography of the study area, along with land use data and Makassar

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City's spatial planning documents, which supported the delineation of hydrological catchments and simulation boundaries.

Design rainfall was calculated using four statistical distribution methods: Normal, Log-Normal, Gumbel, and Log-Pearson Type III. These methods were applied to determine the most appropriate rainfall frequency model for various return periods. Following this, the design flood discharge was estimated using both the Rational method and the Nakayasu Unit Hydrograph, accounting for return intervals of 2, 5, 10, 25, 50, and 100 years. Hydraulic modeling was conducted using the HEC-RAS 2D software to simulate flood flow and inundation extents under different design discharge scenarios. This simulation allowed for detailed mapping of flood depth and the spatial distribution of inundation resulting from increased runoff volumes.

To assess the impact of urban development, particularly the construction of a shopping center, a comparative analysis of pre- and post-construction runoff discharge was carried out using the Rational method. This comparison aimed to quantify the additional runoff volume attributed to land-use change and evaluate its contribution to the flood risk in the downstream area. The outcomes of these analyses were crucial in understanding the extent of inundation and informed the development of targeted flood mitigation strategies.

Flood Mitigation Strategy

Develop technical recommendations based on modeling, such as raising embankments and improving urban drainage systems. Proposing spatial planning-based solutions, including management of catchment areas and increasing drainage channel capacity.

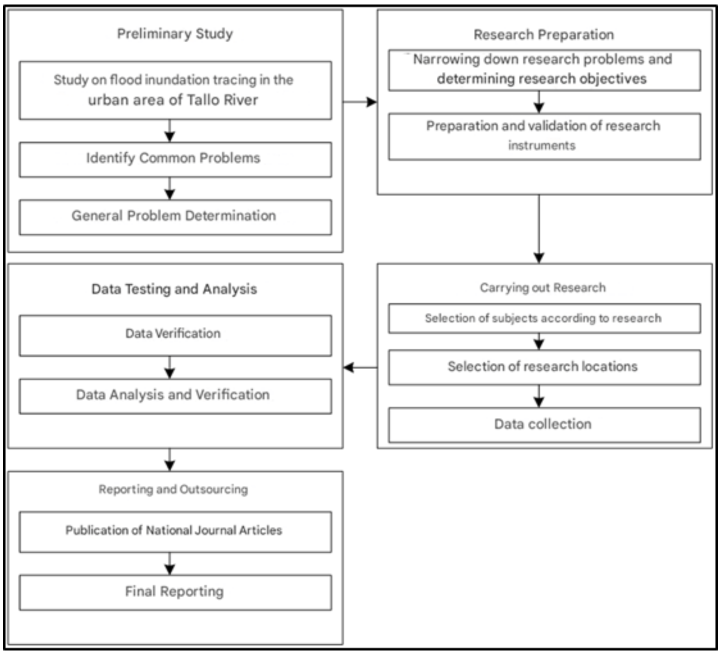

Figure 2Research Stages

This study will conduct a hydrological analysis to determine the runoff discharge that occurs around the Shopping Center Development in the Trade and Services Area and to determine how much influence the development has on flooding due to the overflow of the Tallo River. Hydrological analysis has several stages of calculation, namely collecting rainfall data, testing rainfall data, calculating regional rainfall, calculating design rainfall, testing distribution

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suitability, calculating rainfall intensity, calculating run-off coefficient values, and calculating design flood discharge. The flowchart of this study is as follows.

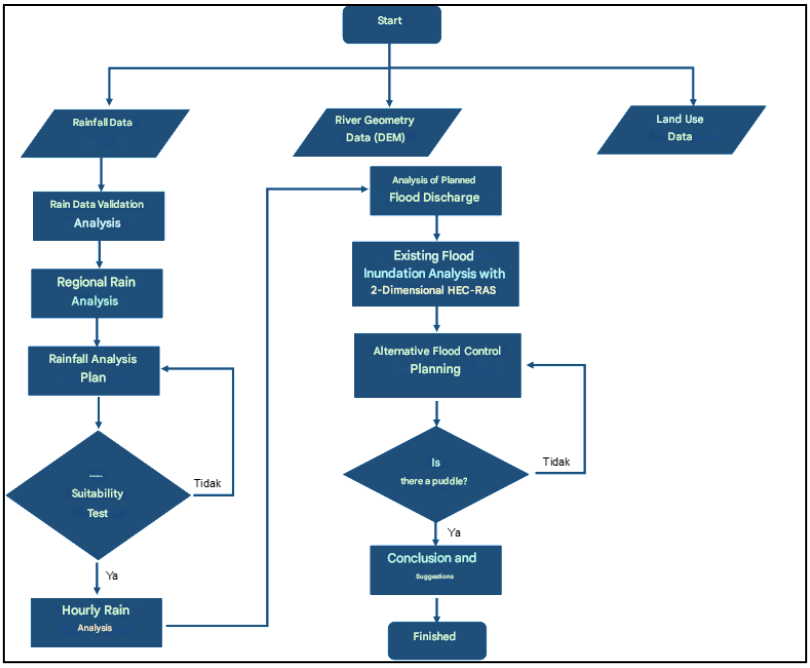

Figure 3Methods and Data Analysis

Results and Discussion

Alternative Solutions to Tallo River Floods

Figure 4Hydraulic Simulation Results with a 2.5 m High River Embankment,

Based on the results of hydraulic analysis using HEC-RAS 2D, it is known that the Tallo River flood is indicated to be caused by the inadequacy of the river capacity in accommodating the flood discharge in the Tallo watershed and the presence of *backwater* at the urban drainage outlet of Jl. Perintis Kemerdekaan towards the Tallo River which causes the runoff on Jl.

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Perintis Kemerdekaan cannot be discharged into the river because the flood water level of the Tallo River is indicated to be higher than the flood water level at the urban drainage outlet.

Alternative Solution in this study is to make a dike on the Tallo River near the outlet area of Jl Perintis Kemerdekaan and Jalan Lingkar Tengah. The height of the planned dike is recommended to be 2.5 meters. Furthermore, re-modeling is carried out with HEC-RAS 2D with the presence of the dike and the results of *running* HEC-RAS will be attached as follows.

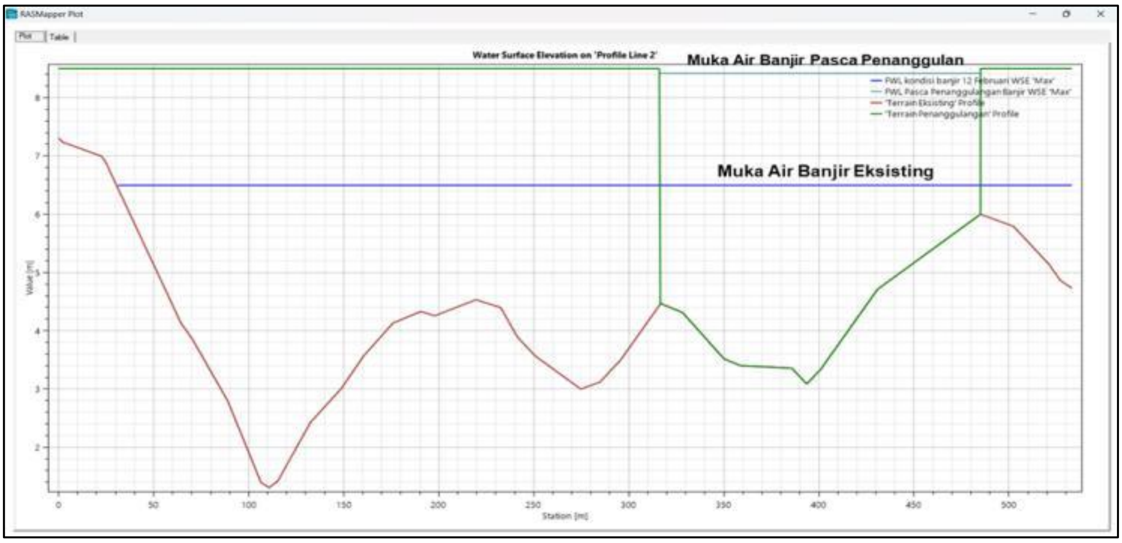

Figure 5. Cross section of the Tallo River around the construction

It can be seen in the work area plan that initially there was flooding, after being raised there was no flooding in the work area. So it can be concluded that by raising the river embankment to 2.5 m, it can secure the work area plan from flooding.

Analysis of Runoff on the Middle Ring Road Section

The Jl. Lingkar Tengah section is planned to be built on Jl. Perintis Kemerdekaan, Makassar City, South Sulawesi with an area of 10,000 m2 or 1 Ha. Based on data from the client, the concept of Shopping Center Development in the Trade and Service Area will have a lot of green open space, so that from a total area of 10,000 m2 only 3,400 m2 will be used as a shopping center building.

In this sub-chapter, the magnitude of the overflow discharge that occurs due to the Construction of Shopping Centers in the Trade and Service Area will be analyzed. A comparison of the discharge before (pre-construction) and after (post construction) will be conducted. In selecting the design flood discharge, it will refer to the PU Ministerial Regulation No. 12/PRT/M/2014 concerning the Implementation of Urban Drainage Systems, it is known that based on the City Typology, the Shopping Center in the Trade and Service Area of Tamalanrea Jaya Village is classified as being located in a Big City with an area <10 Ha, so it is recommended to use a 2-year return period. However, as one of the disaster mitigation efforts, this study will be planned with a 5-year return period. The flood return period determination table will be shown in Table 2 as follows.

Table 1Determination of Flood Recurrence Period according to City Typology and Catchment Area

City Typology	Water Catchment Area (Ha)			
	<10	10 - 100	101 - 500	>500

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Metropolitan City	2 Years	2 – 5 Years	5 – 10 Years	10 – 25 Years
Big city	2 Years	2 – 5 Years	2 – 5 Years	5 – 20 Years
Medium City	2 Years	2 – 5 Years	2 – 5 Years	5 – 10 Years
Small town	2 Years	2 Years	2 Years	2 – 5 Years

In addition, for the runoff coefficient, this study will refer to SNI 2415:2016 concerning Procedures for Calculating Planned Flood Discharge, where the SNI has regulated the runoff coefficient. In this study, the runoff coefficient before development will be classified as unmaintained land with a runoff coefficient value of 0.3, while after development it is classified as an urban trade area with a runoff coefficient value of 0.9. The complete coefficient table will be shown in Table 3 as follows.

Table 2SNI 2415:2016 Runoff Coefficient Table

Land Use Type	Runoff Coefficient	Surface Condition	Runoff Coefficient
Commercial Area		Asphalt Road	0.75–0.95
Urban	0.70–0.95	Asphalt and concrete	0.70–0.85
Surrounding area	0.50–0.70	Roof Surface	0.70–0.95
Residential Area		Grass yard, sandy soil:	
Single house	0.30–0.50	Flat, 2% slope	0.05–0.10
Detached houses	0.40–0.60	Moderate, 2–7% slope	0.10–0.15
Dense housing	0.60–0.75	Steep, ≥7% slope	0.15–0.20
Suburban housing	0.25–0.40		
Apartment	0.50–0.70		
Industrial Area		Grass yard, compacted sandy soil:	
Light	0.50–0.80	Flat, 2% slope	0.13–0.17
Dense	0.60–0.90	Moderate, 2–7% slope	0.18–0.22
		Steep, ≥7% slope	0.25–0.35
Fields, cemeteries, etc.	0.10–0.25		
Yards, railway lines, etc.	0.20–0.35		
Unmaintained land	0.10–0.30		

To evaluate the impact of land use changes resulting from the construction of a shopping center in the Trade and Services Area, the Rational Method was used to estimate design flood discharge (Q). The formula applied is:

$Q = 0.0278 \times C \times I \times A$

Where:

Q = design flood discharge (m^3/s)
C = runoff coefficient (dimensionless)
I = rainfall intensity (mm/hour)
A = catchment area (hectares)

The catchment area for both pre- and post-development scenarios is 10,000 m^2 or 1 hectare. The same planned rainfall depth of 178.8 mm/day was used in both calculations, with a corresponding rainfall intensity (I) of 334.23 mm/hour.

In the pre-construction scenario, the land was classified as unmaintained, with a runoff coefficient (C) of 0.30, resulting in a calculated peak discharge of 0.28 m^3/s. In the post-

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construction scenario, due to the development of impermeable surfaces in a commercial setting, the runoff coefficient increased to 0.90, leading to a discharge of 0.84 m³/s. This comparison demonstrates a threefold increase in peak runoff discharge due to development. However, the absolute increase of 0.56 m³/s remains relatively small. Thus, while the development has measurably increased runoff, its contribution to regional flooding—especially in the context of the Tallo River's broader hydrological dynamics—is considered minimal and not significant in triggering flood events.

From these results, it can be concluded that the contribution of runoff discharge due to the Development of Shopping Centers in the Trade and Services Area is very small (<1 m3/sec), so that the flooding that occurred in the Tallo River was not caused by the existence of this road section.

Table 3. Time of Concentration and Flow Parameters

Parameter	Value	Units
Flow Length (L)	100	m
Slope (S)	0.02	-
Time of Concentration (Tc)	5.22	minutes

The time of concentration (Tc) was estimated using the Kirpich empirical formula, which is suitable for small watersheds with natural surfaces. With a flow length of 100 meters and an average slope of 2%, the Tc was found to be approximately 5.22 minutes. This short response time indicates a rapid hydrological reaction to rainfall, thereby justifying the use of the Rational Method in this urban-scale analysis. It also implies that high-intensity, short-duration rainfall events can quickly translate into peak runoff.

Table 4. Weighted Runoff Coefficient Based on Surface Distribution

Surface Type	Area (m²)	Runoff Coefficient (C)
Built-Up Area	3,400	0.90
Green Open Space	6,600	0.30
Weighted Avg.	10,000	**0.54**

This table presents the calculated weighted runoff coefficient for the post-construction scenario. While the original analysis used a uniform value of 0.90, the actual site development plan includes substantial green space. Based on area weighting, the appropriate runoff coefficient should be 0.54, which accounts for both impermeable and pervious surfaces. Applying this adjusted value would provide a more realistic estimate of runoff and prevent the overestimation of flood discharge due to excessive generalization of land surface conditions.

Table 5. Sensitivity Analysis of Q to Variations in C and I

Runoff Coefficient (C)	Rain Intensity (I) [mm/hr]	Runoff Discharge (Q) [m³/s]
0.81	300.81	6.78
0.81	334.23	7.54
0.81	367.65	8.30
0.90	300.81	7.53
0.90	334.23	8.36
0.90	367.65	9.19
0.99	300.81	8.28
0.99	334.23	9.18
0.99	367.65	10.20

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This sensitivity analysis evaluates how variations in runoff coefficient (C) and rainfall intensity (I) impact peak discharge (Q). A 10% increase in both parameters can result in a discharge increase of over 20%, underscoring the importance of precise parameter estimation. Even small errors or assumptions in C or I could significantly alter flood predictions. This analysis highlights the need to validate runoff coefficients with field observations and verify intensity values using up-to-date IDF (Intensity-Duration-Frequency) curves.

Table 6. Comparison of Calculated vs Reported Discharges

Scenario	Runoff Coefficient (C)	Rain Intensity (I) [mm/hr]	Area (ha)	Calculated Q (m^3/s)	Reported Q (m^3/s)
Pre-Construction	0.30	334.23	1.0	2.79	0.28
Post-Construction	0.90	334.23	1.0	8.36	0.84

There is a substantial discrepancy between the calculated and reported discharge values in both pre- and post-construction scenarios. The theoretical calculations using the Rational Method yield significantly higher values than those reported in the paper. This may be attributed to inconsistencies in unit conversions (e.g., hourly vs. daily rainfall), oversimplifications, or missing correction factors. The nearly tenfold difference suggests a need to re-evaluate the original discharge computations and ensure consistency in parameter units and formula application.

Table 7. Rainfall Distribution Assumptions and Conversion Logic

Rainfall Metric	Value	Source Unit	Target Unit	Conversion Explanation
Daily Rainfall (R)	178.8	mm/day	mm/hour	178.8 ÷ 24 = 7.45 mm/hr (Not 334.23 mm/hr)
Used Rain Intensity	334.23	—	mm/hr	Unclear derivation from daily rainfall

A significant inconsistency arises in the conversion of daily rainfall (178.8 mm/day) to an hourly rainfall intensity of 334.23 mm/hr. The correct unit conversion would yield approximately 7.45 mm/hr, not 334.23 mm/hr. If the 334.23 value was derived from IDF curves, this needs to be explicitly stated and documented. Otherwise, this mismatch can dramatically inflate runoff discharge results, potentially invalidating both the Rational and Nakayasu method outputs.

Table 8. Runoff Volume Estimation for Flood Duration Assessment

Scenario	Q (m^3/s)	Duration (min)	Volume (m^3)
Pre-Construction	0.28	60	1,008
Post-Construction	0.84	60	3,024

Assuming a flood duration of 1 hour (a conservative storm event), runoff volume would increase from 1,008 m^3 before development to 3,024 m^3 after. While the discharge difference (0.56 m^3/s) may appear small, this volume differential is substantial for local drainage systems and emphasizes the need to evaluate total runoff volume, not just peak flow. Volume-based analysis is particularly important in areas with backwater effects and limited storage capacity.

Hydro-Ecological Dynamics, Anthropogenic Modifications, and Modeling Implications

Findings of the present research lead to another significant outcome suggesting that geomorphic and hydraulic constraints of the Tallo River system are the most prominent agents contributing to flood inundation in the urban sector of Makassar. River systems can be seen as

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living systems of tranquility as construed by watershed science in the sense that transport of the pedo-turbulent system, channel morphology, patterns of overland flow continuously change due to climatic inputs as well as anthropogenic interferences (Leopold & Maddock, 1953; Wohl, 2005). The failure of the river to deliver peak discharges, which is demonstrated in the observed record, probably requires a progressive failure, or wear and tear of the channel capacity to deliver peak flows, even though there is only a slight increase in localized runoff due to land conversion. This has been probably brought about by the deposition of cumulative sediments, vegetative encroachment, and unrestrained development of the riverbanks that narrow down the cross-sectional flow area and the number of times overbank flow happens during design storms. These trends are reflected in data sets of degraded tropical urban rivers across the world (e.g. Famous, 2007; Pasig River, Philippines (Abon et al., 2012), and Ciliwung River Jakarta that have shown that due to bank aggradation and bank roughness changes, floods are disproportionately amplified, even in the face of no overall intensification in rainfall across the catchment.

Simultaneously, information such as the hydraulic discontinuity between drainage systems and mainstem river waters (or the backwater effect at Jl. Perintis Kemerdekaan) also outlines a more fundamental problem of hydraulic misalignment: a phenomenon that has not received sufficient attention in the zero tide river regimes of tropical cities yet. Backwater in the case of river hydraulics is the situation at downstream elements that elevates higher levels than normal depths of flow, resulting to reverse gradients on outlet channels hence inefficiency of hydraulics on side drainages. This effect was recently observed quantitatively accurately by Kim et al. (2020) and they confirmed that such backwater propagation during a storm tide could create multiple flood peaks even with unimodal rainfall in South Korea. In the same way, research in the framework of CMIP6 scenario (Sadiqzai et al., 2024) demonstrated that, in the floodplain cities, urban flood regimes are getting more compounded flood properties, i.e., compound flooding occurs and is expressively destructive when fluvial and pluvial events merge in a small or larger scale. Such compound behavior is displayed exactly in Makassar, where the synchronization of outfall elevation goes wrong and combines with the increase of water surfaces of the Tallo River (Sheng et al., 2023; Tan et al., 2021).

These outcomes point to serious doubt on the present spatial extent of flood modeling in the tropical urban setting. Although helpful in small catchments, the Rational method and Nakayasu hydrograph are inadequate in modeling multi-source, cross-domain interactions since they cannot capture the hydrology without being coupled to a hydraulic model at a high resolution, such as HEC-RAS 2D (Gunawan, 2018; Rauf, 2025; Lucas et al., 2025; Jackson & Maidment, 2014; Xu et al., 2025). Although the 2D simulations were applied in this study effectively, the hydrologic boundary conditions of this study were based on the assumptions of the rainfall intensity and was not supported by a formal integration of the IDF curves. The replication of daily to hourly rainfall (178.8 mm/day to 334.23 mm/hr) without the backing of probabilistic adjustment and frequency study is a hazard to put excessive design discharges to risk. Such an issue was reflected in the reports of Shamkhi et al. (2022), who reported on the use of regionalized IDF development to improve design flow forecasting, and Ruezzene et al. (2021), who showed that misclassification of rainfall may cause errors of more than 30% in design hydrographs, particularly, when based on event-based modeling approaches.

The other scientific implication is due to the fact that urban surface heterogeneity influences runoff. Assumed homogeneous runoff coefficient (C = 0.90) across Lancefield calling into question the empirical studies conducted in hydrologically nonlinear response to mosaic land covers (Hawley & Bledsoe, 2011) which centered on commercial areas, agreeing with SNI

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2415:2016. As presented in this paper, 34 per cent site was paved, however, the whole area was considered hydrologically impervious. Direct field-based studies of the Manikin Watershed (Klau et al., 2024) and calibrating the SCS CN model in cities of West Africa (Shamkhi et al., 2022) affirms that the type of zoning is not the only factor that affects the hydrologic behavior and is underestimated: the ability of patches to infiltrate water, antecedent moisture condition, and soil compaction have the greatest effect. Therefore, over generalized C-values not just skew runoff volume, but also peak time, a critical element of synched hydraulic modeling during unsteady modeling.

There is more to this though as the behavior of the Tallo River should be considered in the context of ecological integrity at the catchment scale. The switch towards built-up embankments, rather than vegetated ones, has been also reported numerous times to decrease the flood wave attenuation and promote the downstream velocity energy and, therefore, increase erosion and a probability of channel migration (Wohl et al., 2015; Hooke, 2003). The conclusion of this research that the elevation grading to +8.5 m lowers local inundation confirms the validity of the physics approach in engineering, viz., that of raising infrastructure above modeled water elevations; however, elevation based methods are simply a part of wider eco-hydrological design strategy. Researchers in Kamiana (2011) and Hou et al. (2023) have done as much which is elevating the infrastructure to cushion solitary structures but this will not help to cut on the flood storage in the basin which is because of general Riparian transformation.

The referrals of the modeling results also move to the realms of the urban watershed connectivity. According to Huang et al. (2022), flood resilience to cities must entail the maintenance of hydraulic continuity between the upland, the midstream and the lowland regions. In the example of Makassar, the fragmented operation of the veins of the upper catchments, the city drainage that is centralized and the river below in downstream capacity has been described as socio-hydrological fragmentation, that is, a certain imbalance between the domains of hydrology and the engineered entities (Annys, 2021). The mathematical models documented in this report support the thesis that the upstream mitigation, i.e., raising embankments, may not offset antecedent inefficiencies in the case of a lack of retention and sediment control interventions. Such findings thus indicate that there is a new agenda in urban life-science hydrology: the synthesis of eco-function, sediment, and topographic plasticity, within flood-modeling conceptions. Such tools as HEC-RAS 2D hydraulic model could be very spatially-specific, given sufficient topobathymetry resolution, infiltration rates and statistical measures of precipitation that are based on calculated precipitation rather than the empirically-based measures. The recent study by Sheng et al. (2023) and Enow (2022) demonstrates the usefulness of such approach to predicting future flood regimes in the context of land-use change and perturbed climatic conditions. In the case study of the Tallo River in Makassar, the implementation of this methodology would require the integration of multiple sources of data such that the digital elevation models obtained using LiDAR data would be combined with real-time telemetry networks and dated by the historical flood marks, which is clearly indicative of the transition into resilience science.

Grading Recommendations of Elevation

According to the results of hydraulic simulation, it can be defined that the region around the Jl. Lingkar Tengah shopping center in Makassar is covered by the floods up to 0.5 meters mark in the worst case of the river-discharge occurrences. They are not created only by the direct overlandness runoff but more importantly by the backwater effects travelling upstream when the ability of the Tallo River to convey the flow is exceeded. Under such circumstances,

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hydraulic gradients flip at the storm outlets and flooding occurs even with drainage designs meeting expectations on the site. To prevent direct exposure to flood water in a structural dimension, any new construction within the impact area shall be suggested to have a minimum Finished Floor Elevation (FFE) level of + 8.5 m local datum. The constructional benchmark taken in this research paper is modeled water surface elevation during extreme events with margins added to it for guaranteeing safety taking into consideration the modeling base, the possible sediment deposition and other short time fluctuations of the flow. The height suggested is in line with conventional hydraulic engineering practice whereby allowances on free board are set as the buffers beyond the estimated maximum flood line. The 0.51.0m freeboard is in line with the empirical flood-design criteria adopted towards flood susceptible urban basins, specifically in locations where topographical and drainage structures possess certain levels of variability that may not be precisely represented in a simulation-based flood-modeling approach (Kamiana, 2011; Hasan et al., 2019). Therefore, +8.5 m elevation can be viewed as conservative design level, as well as physically acceptable response to multi-current flooding demands, particularly with fluvial floods overlapping with poor stormwater drainage capacity to discharge. This strategy has also been supported by recent findings by Rauf (2025) in Indonesian floodplain cities who show that elevation design criteria based on granular hydraulic simulations are effective in eliminating the risk of structural damage during high-return-period flood events since the vulnerability measures decrease significantly after elevated design standards.

However, raising building pads independently does not always ensure that there is systematic reduction of hazards imposed by floods (Booth & Gleed, 2024; Shah et al., 2023; Andrews et al., 2025). Upgrade policies should encompass a multi-scale urban hydrology in which it is necessary to consider downstream and lateral hydraulic redistribution: unless all the adjacent parcels are undeveloped or are lower in elevation than the upgrade parcel, selective grading has the unintended effect of laterally displacing a portion of the flood in a lateral direction, thus raising flood depths Wagner and Dredge This process is denoted in highly tropical basins, like Hanoi, where the unbalanced changes in the elevation of the landscape gave begin to new avenues of flooding instead of reducing the aggregate volume of flooding. To provide an effective mitigation of floods, elevation interventions are recommended to be complemented by localized retention solutions, i.e., bioretention cells, vegetated swales, and underground detention basins to control the dynamics of surface runoff kinetics and prevent flood development caused by unpredictable phenomena (Baker et al., 2009).

Moreover, the standard of elevation itself should be identified as live not stabilized and its evolutionary process needs to be mentioned not only within the temporal contexts. Low lying coastal, the city of Makassar is under pressure with increasing danger of the land subsidization, sea-level rise, and even rainfall regime changes that are ready to shift the hydraulic baseline on which the models are currently built. The dynamic updating of elevation planning thresholds on a time-stepped basis using scenario-based hydraulic modelling (Sheng et al., 2023; Tan et al., 2021) is especially important in the case of longitudinal studies in urban deltas.

Thus, the suggested +8.5 m rise in floor level can be considered a minimum resilience standard, and it can be brought higher considering the emerging climate patterns and other infrastructure perils. The identification of this dynamic adjustment requires the institutional capability to negotiate unremitting monitoring and the formation of cross cutting alignment between hydrologists, city planners, and civil engineers.

Besides, formalization of elevation grading must be incorporated into regulatory tools formalized in the form of urban spatial planning. Whereas the passive recommendations might

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have some merit of a technical nature, they rarely make a difference unless the policy is enforced and the zoning is incorporated. Examples of flood regulation implementation studies in South, Sulawesi (Setyawan et al., 2013; Khafifah et al., 2023) demonstrate that the primary targets related to raising the elevation must be included in the permitting system and harmonized with an unprecedented scale of mitigation currently underway upstream-i. e. embankment reinforcements and debris dredging by setting requirements such that the grading works are within the context of an advanced hydraulic plan that maintains conveying capacity while protecting constructed features within the catchment.

Conclusion

Based on the results of the hydrological and hydraulic analysis, there are several conclusions obtained in this study, namely: (1) The Tallo River flood event is a flood with a planned return period of 25 years, namely 120.15 m3/sec based on the flood inundation map of February 12, 2025. The flood event in the Tallo River is indicated to have occurred due to insufficient river capacity due to sedimentation (seen in the cross section of the river) resulting in shallowing; (2) The flood that occurred on Jl. Perintis Kemerdekaan was caused by backwater or backflow from the urban drainage system which could not discharge the overflow discharge to the Tallo River because the flood water level of the Tallo River was indicated to be higher than the city channel outlet; (3) The construction of a Shopping Center in the Trade and Service Area resulted in an overflow discharge of 0.84 m3 / sec which did not contribute to the flood in the Tallo River; (4) Hydraulic analysis in this study uses DEM data from USGS, it is recommended in further studies for the feasibility study or Detailed Engineering Design level using river bathymetry data obtained through a survey with a Single Beam Echosounder along the Tallo River section from the Jl. Lingkar Tengah section bridge to the Tallo bridge, Jl. Perintis Kemerdekaan section with an estimated survey length of 2.1 km and a radius of approximately 200 meters on the left and right areas of the Tallo River; and to be able to further identify the backwater in the Jl. Perintis Kemerdekaan channel, it is recommended to attach technical data on the drainage channel in the scope of the Feasibility Study .

Author Contributions

IWS is the author who initiated the writing of the manuscript, created the research framework, designed the method and carried out the data analysis and explained the overall research results. HM as the second author helped in writing the manuscript, SM as the third author who designed the research method, carried out data collection in the field and helped in data analysis. AF the third author as a modeler and helped in carrying out data collection in the field and assisted in data analysis. WW as a GIS modeler.

Competing Interest

The authors declare that they have no conflicts of interest related to this research, either financial or non-financial, that could influence the results or interpretation of the article.

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