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Flood Mitigation Strategy Based on Hydrological and Hydraulic Modelling in the Urban Area

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Abstract

The urgency of this research lies in the need for a scientific-based solution in understanding the pattern of runoff and flood inundation to support effective mitigation planning. 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.

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; Javadinejad, 2022; Angelakis et al., 2023; Rijal et al., 2024). 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). In many cases of urban flooding, the main factor causing flooding is due to changes in land function on river banks (Limantara, 2010; Ma et al., 2022). 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 banks, resulting in narrowing of the river body and causing flooding. In

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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).

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). 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).

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

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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.

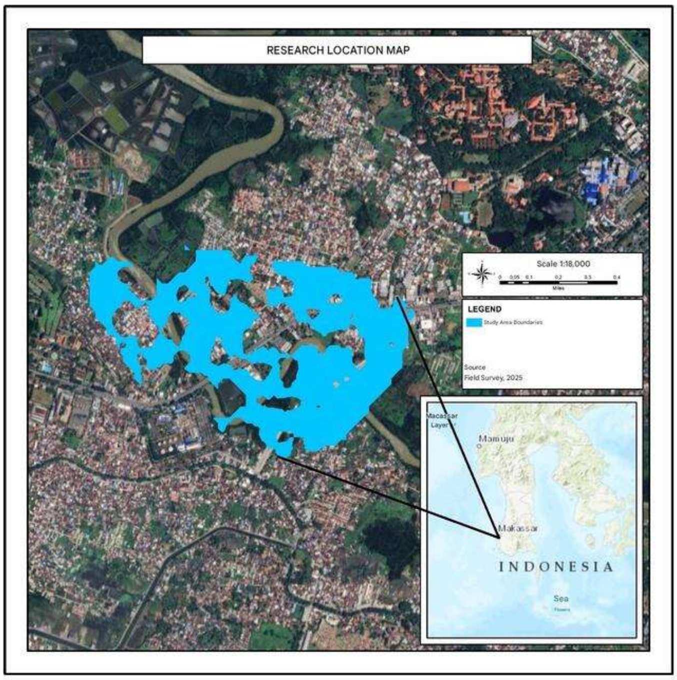

Figure 1Study Site Locations, Google Earth 2024

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., 2024) .

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 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

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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. This research is expected to provide significant contributions to water resources management and urban flood mitigation, especially in Makassar City.

Data Analysis

The research topic employs a quantitative descriptive design that incorporates hydrological and hydraulic modelling in interdiscovering the runoff and flood inundation trends in Tallo River Basin. The analysis starts with broad data collection which comprises of both primary and secondary sources. Direct field observations were made and primary data were recorded where the researchers were able to inspect the prevailing physical aspects of the river channels, the drainage systems around them and the zones that are prone to frequent floods. The setting of the context was secured through these observations since they captured space and structural information that is real-time and very necessary to ensure accuracy of modeling.

The secondary data, however, furnished the required historical and geographic data in the analysis. This consisted of a 15-year mean (2010-2024) of rainfall measurements recorded on the two major stations used, namely, Paotere and Sultan Hasanuddin Maritime. The other secondary information included high resolution digital elevation, model (DEM) maps of land-use classification, and spatial planning material in the city of Makassar. All these data were used to assist in the successive hydrology modeling and situation scenarios.

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Statistical analysis of rain fall was used as the start of the hydrological analysis. Some probability distribution techniques were employed in calculating design rainfall at various returns (2, 5, 10, 25, 50, and 100 years) using Normal, Log-Normal, Gumbel, and Log-Pearson III distributions. Out of this, the Gumbel distribution selected as the most suitable in terms of the tests done to suit the distributions, such as the chi-Square testing together with the Smirnov-Kolmogorov testing. Conducting design rainfalls, the paper has carried on with estimating their design flood discharges through two complementary techniques including the Rational technique and the Nakayasu hydrograph. The two-method modeling improved the reliability of discharge estimations because of its ability to accommodate small-scale urban runoff as well as the larger time-scale hydrological responses.

The Hydraulic modeling of the physical processes of flood run through HEC-RAS 2D Software. This model has simulated behavior of a flood flow and degree of inundation under unsteady flow conditions based on the topography of the DEM and the flood discharges inferred. The simulations gave a topographical insight of the flood spreading in the river channel and floodplains that were urbanized and validated the surface water values as well as the depths. Specifically, the model also emphasized backwater influences arising due to the inefficient drainage system capacity that led to frequent cases of flooding across the important urban corridors such as the Jalan Perintis Kemerdekaan. An essential part of the analysis assessment was a review of the hydrological aspects of development in the research region. This was achieved by comparing the discharges of the run off prior and after the building of a shopping center in the Trade and Service Zone. The analysis based on the Rational method showed an insignificant rise in peak discharge (0.84 m 3/s), which indicated that despite the impact development had on the runoff characteristics, its input to the floods of large size was rather low.

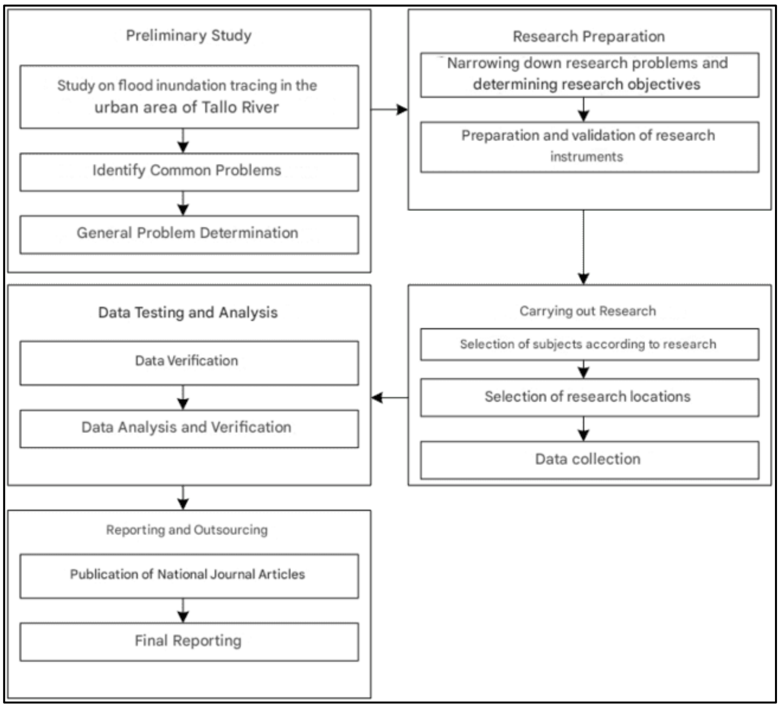

Figure 2Research Stages

Finally, the research presented the strategies of flood mitigation using the combination of the model-based scenarios and spatial planning. Simulated results formed the basis of the development of recommendations, which included technical possibilities of raising

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embankments of the rivers by up to 2.5 meters, improvement of urban drainage channels, and adjusting the height of the land surface in flood-prone territories. Spatially based intervention measures were also suggested, which entails better and improved land use regulation within the catchment, and that which encompasses optimal urban zoning, so as to assist long-term risk reduction of floods. A combination of these strategies would confirm that pairs engineering solutions against urban planning are vital in managing floods in fast growing urban river basins such as Tallo.

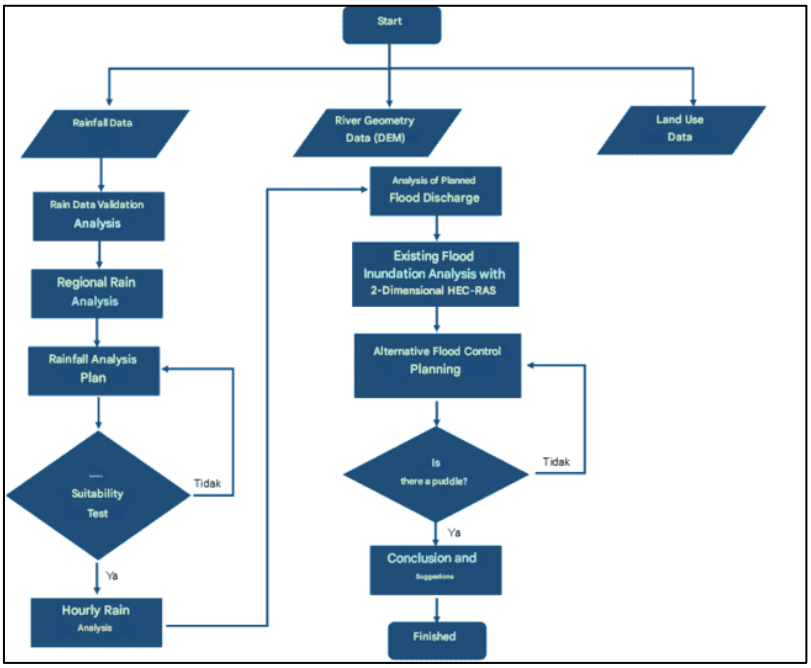

Figure 3Methods and Data Analysis

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

Results and Discussion

Hydrological Analysis

Rain Data

research location is in the downstream area of the Tallo River with location coordinates 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. The area of the Tallo River basin is 346.22 km ^{2} . Research location plan located at a distance of ± 14 km from the mouth of the Tallo River which is a lowland area close to the coast, so it is greatly influenced by the ebb and flow of sea water. In addition, the branching river network shows the complexity of the flow in the Tallo River estuary area . Based on data obtained from *the website of* the Meteorology and Geophysics Agency of the Republic of Indonesia, it is known that there are five (5) stations, but there are two (2) stations that have complete rainfall recording data, namely the nearest Rain station (with a distance of ≤ 15 km) from the project location, namely the Paotere

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Maritime Station and the Sultan Hassanudin Rain Station with the availability of rainfall data for 15 years in sequence (2010 - 2024). The details of the rainfall data will be displayed in Table 1as follows.

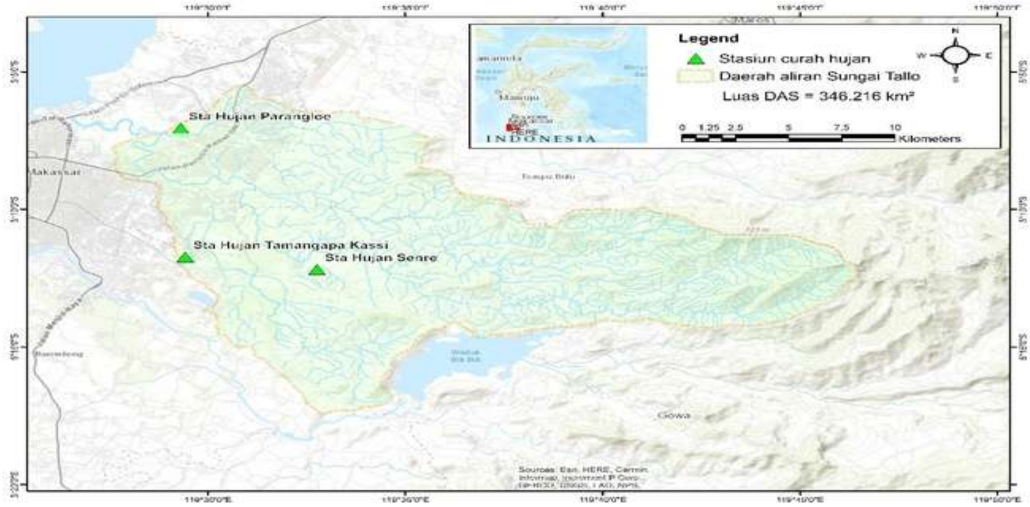

Figure 4Location of Rainfall Stations around the Study Location, Google Earth 2024

Table 1Rain Data Recapitulation

No.	Year	Rain Station [mm/day]	
		Paotere	**Sultan Hasanuddin**
1	2010	180	106
2	2011	122	129
3	2012	141	103
4	2013	120.8	110
5	2014	137.9	123.6
6	2015	160.3	136.1
7	2016	188.7	139.3
8	2017	156	162.5
9	2018	152.1	141.6
10	2019	107	197
11	2020	122.9	144.2
12	2021	218.8	243.3
13	2022	155.3	166.3
14	2023	200	166.8
15	2024	140	162.3

Rain Data Consistency Test

In this study, a rainfall data consistency test will be conducted as one of the standards in the hydrological calculation process using secondary data from rainfall data recording at a predetermined rainfall station. This rainfall data consistency test will be conducted based on several assumptions that may occur in the field, namely: a) There is an error in recording rainfall data by the operator; b) There is an indication of tool movement; c) There is damage to the tool during the rainfall data recording period The consistency test of rainfall data in this study will be carried out using the Rescaled Adjusted Partial Sums (RAPS) test. The final conclusion obtained if the data is valid is that it must be able to meet 80% of the requirements

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to pass the test. This RAPS test is a test to see the consistency of rainfall data per rainfall station. In this test, rainfall data will be tested at a rainfall station that is far from other stations or it can be said that this rainfall station stands alone or individually. In this study, there are five rainfall stations that will be tested. This method will carry out the value of the rainfall data consistency test by looking at the cumulative value of the deviation from the trend of the data owned (Jaramillo-González et al. 2023; Kim et al. 2020) . The equation of the RAPS test is as follows.

$$Sk^{**} = \frac{Sk*}{Dy}$$

Where the Dy equation is as follows

$$Dy = \sqrt{\sum_{i=1}^{N} \frac{Y_{i-}\bar{Y}}{N}}$$

Information:

Sk** : Rescaled Adjusted Partial Sums (RAPS) test result.
Sk* : Cumulative value of deviations from the average value.
Dy : Standard deviation of the Y data series.
Yi : The ith Y data value.
N : Number of data

Based on the equation above, this RAPS test will use a degree of freedom of 5% or can be said to be a degree of confidence of 95% with the limits of the Q and R values of the RAPS test. The Q and R limit values in this study are as follows.

Table 2Critical Q and critical R values of the RAPS test

n	Q/√n (90%)	Q/√n (95%)	Q/√n (99%)	R/√n (90%)	R/√n (95%)	R/√n (99%)
10	1,05	1,14	1,29	1,21	1,28	1,38
20	1,10	1,22	1,42	1,34	1,43	1,60
30	1,12	1,24	1,46	1,40	1,50	1,70
40	1,13	1,26	1,50	1,44	1,53	1,74
50	1,14	1,27	1,52	1,47	1,55	1,78
100	1,17	1,29	1,55	1,50	1,62	1,86
∞	1,22	1,36	1,63	1,62	1,75	2,00

In decision selection, the value of Q and R count ≤ Q $_{critical}$ and R $_{critical}$. The summary of the RAPS test results in this study is as follows.

Table 3Recapitulation of RAPS Test Results

No.	Rain Station	RAPS Test Score	RAPS Test Value Limits	Information
1.	Sultan Hassanudin Station	Q = 2.65 R = 2.53	Qcritical = 4.57 Critical = 5.25	Consistent
2.	Paotere Station	Q = 2.12 R = 2.08		Consistent

Rain Data Homogeneity Test

After ensuring that the data held at the rain station is consistent, the next stage in the data validation phase is to conduct a homogeneity test of the rain data. The purpose of this test is to see the homogeneity of the data in the rain data held. This homogeneity test will be divided

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into three tests, namely the t-test, the f-test and the persistence test. The complete explanation of each of these tests will be described in the following sub-chapters as follows.

T-Test

The t-test is part of the homogeneity test to see the stability of the average trend of rainfall data owned by a rainfall station within a certain period of time that has been determined for its use (Klau et al. 2024) . The equation of the t-test is as follows.

$$t = \frac{(\overline{X_1} - \overline{X_2})}{\sigma\left(\frac{1}{N_1}+\frac{1}{N_2}\right)^{0.5}}$$

$$\sigma = \left(\frac{n_1.S_1{}^2 + n_2.S_2{}^2}{n_1 + n_2 - 2}\right)^{0.5}$$

$$Dk = N1 + N2 - 2$$

Information:

t	: calculated t variable.	σ	: Standard deviation.
$\overline{X_1}$	: Average of the 1st sample.	$S_1{}^2$	: Standard deviation value of group-1.
$\overline{X_2}$	: Average of the 2nd sample.	$S_2{}^2$	: Standard deviation value of group-2.
N_1	: Number of samples of the 1st set.	dk	: Degrees of freedom.
N_2	: Number of samples of the 2nd set.		

In this t-test, the mechanism is to compare the calculated t value with the critical t value (tcr). After being compared, two possibilities will be obtained, namely: a) If the calculated t value > tcr or critical t, it means that the data shows a stable average (homogeneous); b) If the calculated t < tcr or critical t, it means that the data does not show a stable average (not homogeneous).

Based on the equation and mechanism above, this t-test will use a degree of freedom of 5% or a degree of confidence of 95% with a specified critical value limit (tcr) by referring to the t-test distribution table. The complete results of the t-test in this study will be described in Table 4below.

Table 4Summary of T-Test Results

No.	Rain Station	T count	T critical	Information
1.	Sultan Hassanudin Station	T count = -0.78	T critical = 2.16	Homogeneous
2.	Paotere Station	T count = -0.07		Homogeneous

F-Test

The f-test is part of the homogeneity test to see the stability of the rainfall data trend variant owned by a rainfall station within a certain period of time that has been determined for its use (Sheng et al. 2023) . The equation of the f-test is as follows.

$$F = \frac{N_1.S_1.(n_s - 1)}{N_2.S_2.(n_1 - 1)}$$

$$dk_1 = N_1 - 1$$

$$dk_2 = N_2 - 1$$

Information:

F	: Calculated F value	dk_2	: Group-2 degrees of freedom.
S_1	: Standard deviation value of group-1.	N_1	: Number of samples in group-1.
S_2	: Standard deviation value of group-2.	N_2	: Number of samples of group-2.
dk_1	: Group degrees of freedom-1.		

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In this f-test, the mechanism is to compare the calculated f value with the critical f value (fcr). After being compared, two possibilities will be obtained, namely: a) If the calculated f value > fcr or critical f, it means that the data shows that it has the same data variance; b) If the calculated f < fcr or critical f, it means that the data does not show the same data variance.

Based on the equation and mechanism above, this f-test will use a degree of freedom of 5% or a degree of confidence of 95% with a specified critical value limit (fcr) by referring to the f-test distribution table. The complete results of the f-test in this study will be described in Table 5below.

Table 5Summary of F-Test Results

No.	Rain Station	F count	F critical	Information
1.	Sultan Hassanudin Station	F count = 0.31	F critical = 6.84	Homogeneous
2.	Paotere Station	F hirung = 0.38		Homogeneous

Persistence Test

The persistence test is the final stage of homogeneity test which aims to determine the independence of rainfall data at the rainfall station used. The assumption that the data comes from a random sample must be tested, which is generally a requirement in probability distribution analysis. Persistence is the independence of each value in a time series. The persistence test equation will be shown in the equation below.

$$t = KS\left(\frac{m-2}{1-KS^2}\right)^{0.5}$$

Information:

t : Calculated t value
m : n-1
n : Number of data
KS : Correlation coefficient

In this persistence test, the comparison mechanism is the same as the t-test, namely comparing the calculated t value with the critical t value (tcr). After being compared, two possibilities will be obtained, namely: a) If the calculated t value> tcr or critical t, it means that the data shows data persistence or it can be said that the data is random; b) If the calculated t <tcr or critical t, it means that the data does not show data persistence or it can be said that the data is independent. The testing stage is generally called data screening, with the aim of checking and sorting data groups with the aim of obtaining sufficiently reliable Hydrological data for further Hydrological analysis. The recap of the persistence test results will be shown in Table 6 below this.

Table 6Recapitulation of Persistence Test Results

No.	Rain Station	T_{count}	$T_{critical}$	Information
1.	Sultan Hassanudin Station	T count = 2.69	T critical = 3.05	Homogeneous
2.	Paotere Station	T count = -0.25		Homogeneous

Source: Analysis Results, 2025

Regional Rain Analysis

Based on 15 years of rainfall data, a regional rainfall analysis calculation can be carried out which is intended to determine the estimated rainfall that occurs at the study location. This study will consider two calculation methods, namely the arithmetic mean and *inverse distance*

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weighted (IDW). These two methods are considered because the locations of the two rainfall stations are not evenly distributed in the study location (Ruezzene et al. 2021) . The recapitulation of the results of the regional rainfall analysis will be shown in Table 7and Figure 5as follows.

Table 7. Recapitulation of Regional Rain Analysis Results Using the Average Calculation Method and Inverse Distance Weighted (IDW)

Year	**Area Rain Analysis [mm/day]**	
	Arithmetic Mean	***Inverse Distance Weighted***
2010	143.0	149.5
2011	125.5	124.9
2012	122.0	125.3
2013	115.4	116.3
2014	130.8	132.0
2015	148.2	150.3
2016	164.0	168.3
2017	159.3	158.7
2018	146.9	147.8
2019	152.0	144.1
2020	133.6	131.7
2021	231.1	228.9
2022	160.8	159.8
2023	183.4	186.3
2024	151.2	149.2

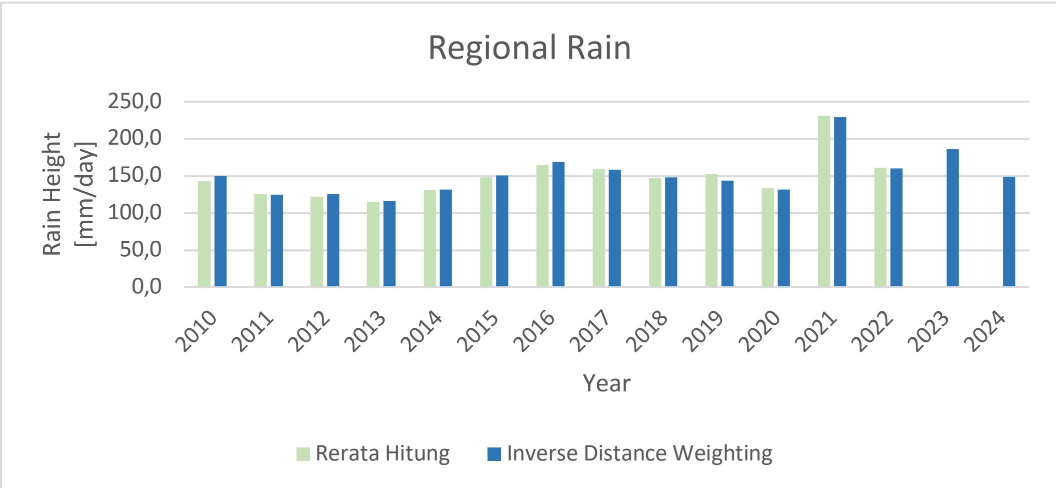

Figure 5Graph of Results of Regional Rain Analysis Using the Average Ca.lculation Method and Inverse Distance Weighted (IDW)

Based on these two results and taking into account the purpose of this study for mitigation efforts, *the inverse distance weighted* (IDW) method will be used as the result of regional rainfall analysis.

Design Rain Analysis

Design rainfall is the next stage in the Hydrology study after knowing the regional rainfall forecast that occurs at the study location. In the design rainfall analysis, there are several methods that can be used. In this study, there are four calculation methods that will be carried

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out and will be considered in choosing a method that is suitable for the conditions and objectives of the study. The four methods are the normal, log-normal, gumbel and log-pearson III methods (Shamkhi, Azeez, and Obeid 2022; Tan, Liew, and Ling 2021) . The equations for each method will be described as follows.

Normal Method

Y $=\bar{Y} - k.sd$

Information:
Y : Design rainfall value using normal method
$\bar{Y}$: Mean value of the variable
k : characteristics of normal probability distribution (Gauss reduction table)
sd : Standard deviation

Log-Normal Method

Y = Log($\bar{Y} - k.sd$)
Information:
Y : Logarithmic value of design rainfall log Normal
$\bar{Y}$: Logarithmic value of the mean of the variate
k : characteristics of the log normal probability distribution (Gauss reduction table)
sd : Standard deviation

Gumbel Method

X = $\bar{X} + \frac{S}{Sn}$(Y-Yn)
Information:
X : Gumbel design rain
S : Standard deviation
Sn : Standard deviation of the reduced variate
Yn : Average value of variate reduction
Y : The reduction value of the variate of a certain return period variable
$\bar{X}$: Average value of the variable

Pearson Log III Method

Y $=\bar{Y} - k.sd$
Information:
Y : Design rainfall value of Pearson III log
$\bar{Y}$: Logarithmic value of the mean of the variate
k : Characteristics of the Pearson III log distribution
sd : Standard deviation

Based on the equations in each method, the design rainfall will be obtained with several recurrence periods, namely 2, 5, 10, 25, 50 and 100 years. The overall analysis results will be shown in Table 8 as follows.

Table 8Recapitulation of Design Rainfall

Repeat Time [Year]	Normal [mm]	Normal Log [mm]	Gumball [mm]	Pearson III Log [mm]	Frechet [mm]
2	151.54	149.38	147.51	151.52	145.36
5	175.18	172.51	178.77	173.43	169.15
10	187.57	186.03	199.46	184.96	187.00

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25	197.70	197.87	225.60	196.74	212.28
50	209.24	212.28	245.00	203.52	233.22
100	217.12	222.72	264.25	209.77	256.04

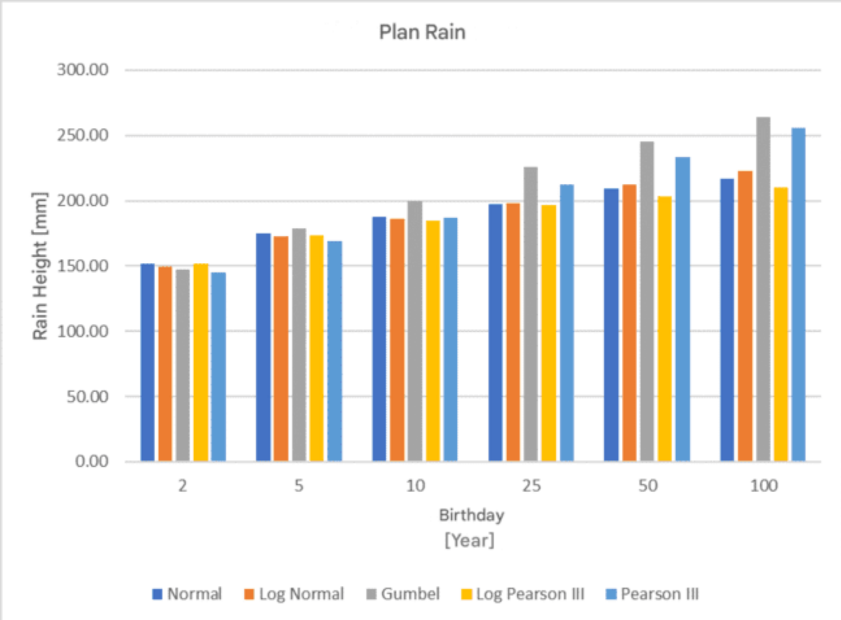

Figure 6Design Rain Recapitulation Graph

Figure 6 presents a comparative visualization of the design rainfall values calculated using five different statistical distribution methods: Normal, Log-Normal, Gumbel, Log-Pearson III, and Frechet. The graph plots design rainfall depths (in mm) against corresponding return periods (2, 5, 10, 25, 50, and 100 years), highlighting how each distribution method estimates rainfall intensity over increasing recurrence intervals. As expected, all methods show an upward trend, indicating that the magnitude of rainfall increases with longer return periods, which aligns with the hydrological principle that more extreme events are less frequent but more intense.

Among the methods illustrated, the Gumbel distribution yields consistently higher rainfall values across most return periods, particularly for the 10-year, 25-year, and 50-year events. This characteristic makes it more conservative and thus suitable for flood risk analysis and infrastructure planning, where underestimation could lead to system failure. The Normal and Log-Normal methods tend to estimate slightly lower rainfall values, especially at higher return intervals, while the Frechet method exhibits the lowest rainfall depths for shorter return periods, though it converges closer to the others at the 100-year mark. The purpose of this figure is to visually support the decision-making process in selecting the most appropriate design rainfall method. By juxtaposing all five methods on a single graph, the figure makes it easier to identify deviations, trends, and the behavior of each distribution across various return periods. Ultimately, the graphical trend reinforces the study's choice of the Gumbel method for design rainfall, as it balances statistical rigor with practical safety considerations for flood modeling and urban infrastructure design.

Distribution Suitability Test

This rainfall data distribution suitability test is intended to see the design rainfall results from several methods to be able to describe a statistical distribution. This test is carried out to avoid statistical errors in decision making. The distribution suitability test will be carried out in two tests, namely the Chi-Square test and the Smirnov-Kolmogorov test. These two tests will see

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the largest deviations that occur in a distribution and are adjusted whether the deviations that occur are still within the permissible statistical limits or not (Enow 2022; Lanzante 2021). The recapitulation of the results of the distribution suitability test is as follows.

Table 9Summary of Distribution Suitability Test Results

Rainfall Design (mm)					
Repeat Time	**Normal**	**Normal Log**	**Gumball**	**Pearson III Log**	**Frechet**
2 years	151.5	149.4	147.5	151.5	145.4
5 years	175.2	172.5	178.8	173.4	169.1
10 years	187.6	186.0	199.5	185.0	187.0
25 years	197.7	197.9	225.6	196.7	212.3
50 years	209.2	212.3	245.0	203.5	233.2
100 years	217.1	222.7	264.3	209.8	256.0
Smirnov-Kolmogorov Checking					
Dmax	0.14	0.12	0.11	0.20	0.10
Degrees of Freedom	5%	5%	5%	5%	5%
Dcritical	0.34	0.34	0.34	0.34	0.34
Hypothesis	**OK**	**OK**	**OK**	**OK**	**OK**
Chi Square Checking					
Chi - Square calculation	0.67	3.33	3.33	2.00	2.00
Degrees of Freedom	5%	5%	5%	5%	5%
Chi Square critical	7.38	7.38	7.38	7.38	7.38

Based on the results in Table 9, it can be concluded that all methods passed the distribution suitability test, so the Gumbel Method will be used as design rainfall in this study.

Tallo River Design Flood Discharge

Based on the results of the design rainfall analysis, a design flood discharge analysis will be carried out using the Nakayasu method on the Tallo River. The outlet boundary of the Tallo Watershed is on the Tallo River section near the Shopping Center Development in the Trade and Services Area. The recapitulation of the design flood discharge with the Nakayasu HSS is as follows.

Table 10Recapitulation of the Design Flood of the Nakayasu HSS Tallo River

t	Q2thn	Q5thn	Q10thn	Q20thn	Q25thn	Q50thn	Q100thn	Q1000thn
O'clock	**m3/s**							
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.00	74.30	90.69	102.97	117.07	120.12	134.05	149.02	208.43
2.00	63.56	77.58	88.09	100.15	102.76	114.68	127.48	178.31
3.00	46.53	56.80	64.49	73.33	75.23	83.96	93.33	130.55
4.00	35.52	43.35	49.23	55.97	57.42	64.09	71.24	99.64
5.00	29.51	36.02	40.90	46.50	47.71	53.25	59.19	82.79
6.00	25.05	30.57	34.71	39.47	40.49	45.19	50.24	70.27
7.00	14.52	17.73	20.13	22.88	23.48	26.20	29.13	40.74
8.00	8.29	10.12	11.49	13.07	13.41	14.96	16.63	23.27
9.00	5.07	6.19	7.03	7.99	8.20	9.15	10.17	14.23
10.00	3.29	4.01	4.56	5.18	5.32	5.93	6.59	9.22
11.00	2.13	2.60	2.95	3.36	3.45	3.85	4.27	5.98
12.00	1.38	1.69	1.91	2.18	2.23	2.49	2.77	3.88

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13.00	0.90	1.09	1.24	1.41	1.45	1.62	1.80	2.51
14.00	0.58	0.71	0.80	0.92	0.94	1.05	1.16	1.63
15.00	0.38	0.46	0.52	0.59	0.61	0.68	0.76	1.06
16.00	0.24	0.30	0.34	0.38	0.39	0.44	0.49	0.68
17.00	0.16	0.19	0.22	0.25	0.26	0.29	0.32	0.44
18.00	0.10	0.13	0.14	0.16	0.17	0.19	0.21	0.29
19.00	0.07	0.08	0.09	0.11	0.11	0.12	0.13	0.19
20.00	0.04	0.05	0.06	0.07	0.07	0.08	0.09	0.12
21.00	0.03	0.03	0.04	0.04	0.05	0.05	0.06	0.08
22.00	0.02	0.02	0.03	0.03	0.03	0.03	0.04	0.05
23.00	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.03
24.00	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02
25.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
26.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
27.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
28.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
29.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
31.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
32.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
33.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
34.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
35.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
36.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
37.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
38.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
39.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
40.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
41.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Furthermore, in order to calibrate the flood event on February 12, 2025, a hydraulic analysis will be carried out using the results of the design flood discharge at a certain return period so that it can be known at what return period the flood will occur on February 12, 2025.

Hydraulic Analysis of Tallo River

The Tallo River hydraulic analysis is intended to see the flood water level that occurred by referring to the flood inundation map that occurred on February 12, 2025. On the inundation map, there are indications of an overflow of the Tallo River caused by the inadequate capacity of the River and the presence of backwater at the urban drainage outlet, causing flooding on Jl. Perintis Kemerdekaan.

General

Hydraulic analysis was conducted using the unsteady flow model approach using HEC-RAS v 6.4.1 software issued by the US Army Corps of Engineers. This modeling was simulated using 2D simulation using DEM data to describe the geometry of the earth's surface shape obtained from the United States Geological Survey (USGS). In this simulation, it is expected to be able to model how the flow conditions in the river channel and the flow on the overflowing riverbank.

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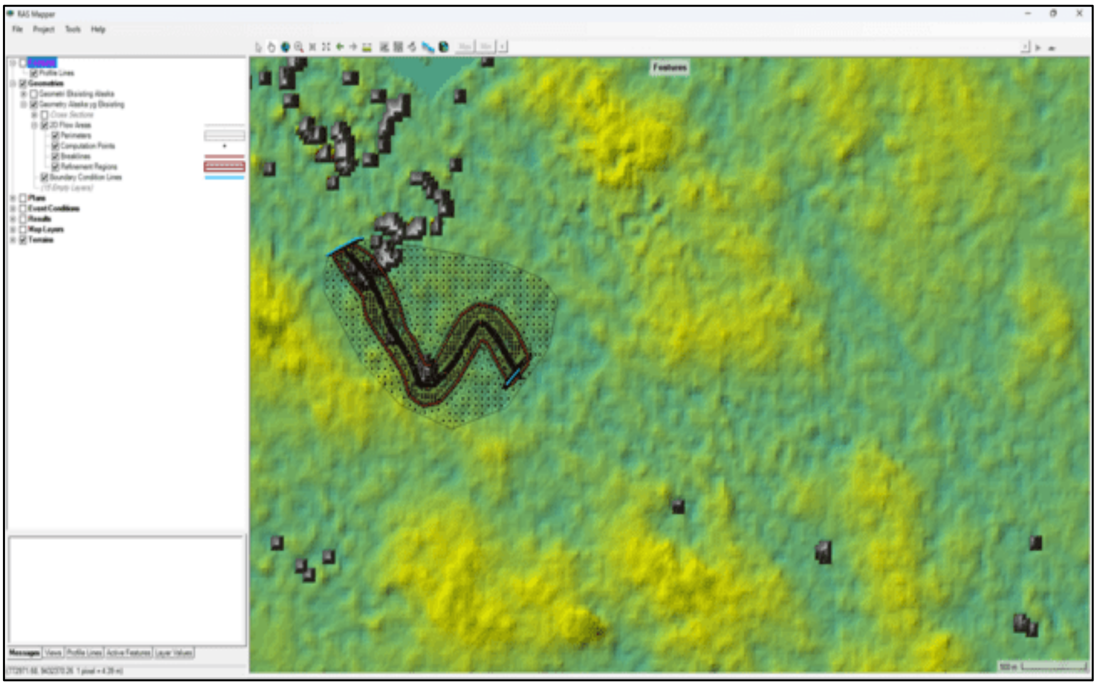

Figure 7Image of Earth Surface Shape from DEM Data from USGS.

Geometry Data

In this simulation, a 2.1 km long river segment is depicted in a 2D geometric situation with the river channel and its perimetry area as shown in the image below:

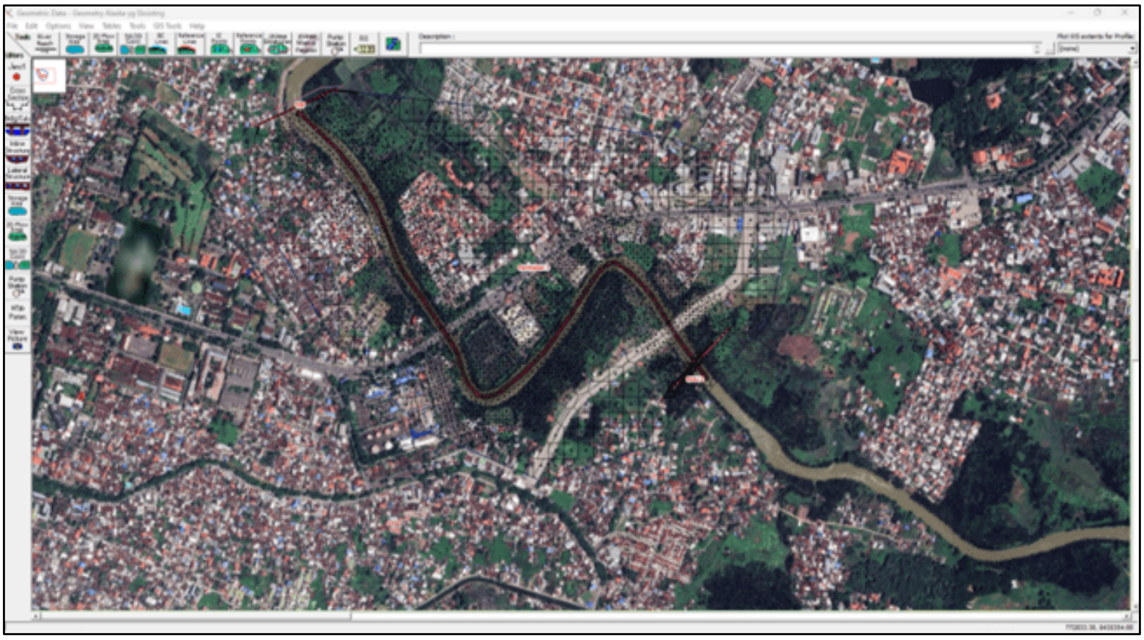

Figure 8. 2D geometry situation

Modeling Parameters

Parameters Used for Hecras Analysis

Q25 year discharge : 120.12 m3/sec

Channel Slope : 0.00016

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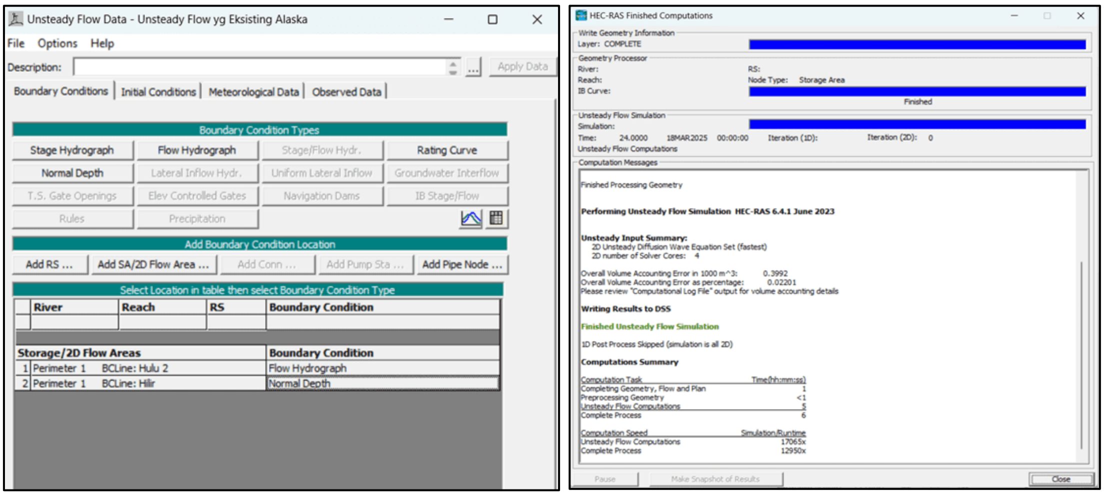

Figure 9Running Un Steady Flow Process, Source: 2025 Analysis Results

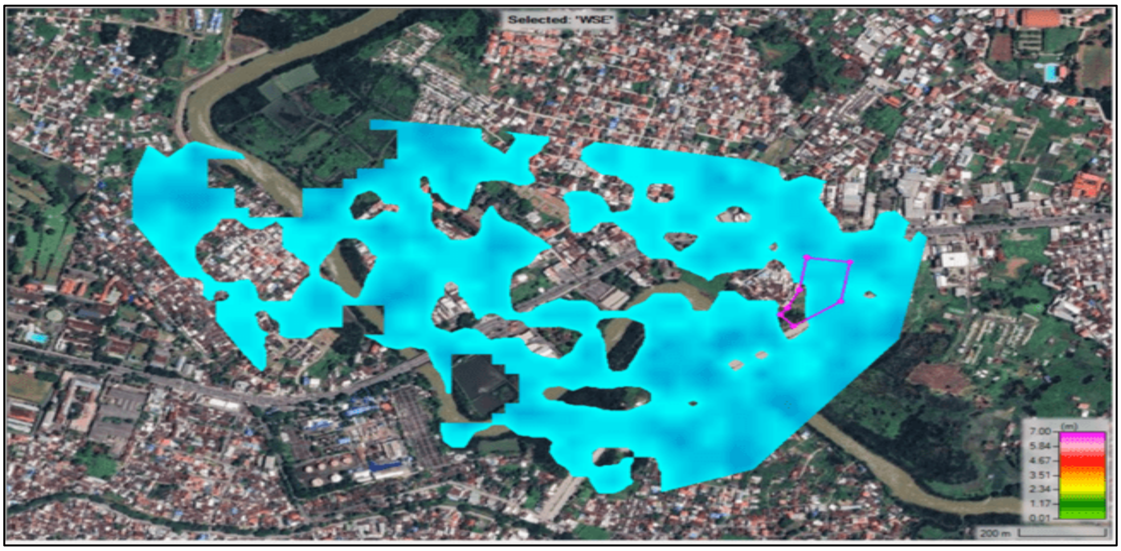

Figure 10Flood Inundation Around the Study Location, Source: 2025 Analysis Results

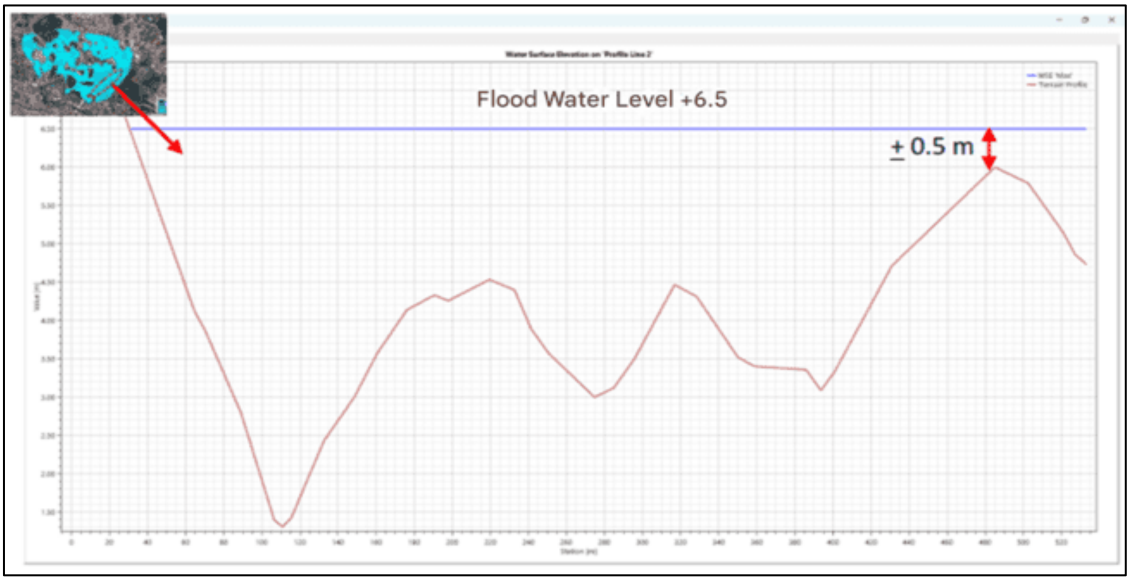

Figure 11Cross Section Around the River and Study Location

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After conducting a hydraulic simulation trial with several repetition periods, it was found that the simulation that corresponds to the flood event on February 12, 2025 is with the design flood discharge Q25 with a discharge of 120.12 m3 / sec. It can be seen in the cross-section of the image above that the water level is 0.5 m from the river embankment and inundates the Jalan Perintis Kemerdekaan area, which is in accordance with the flood inundation map data.

Hydrological Modeling, Urbanization Impact, and Mitigation Measures in a Rapidly Changing Watershed

The results of the present study exemplify the imperativeness of involving intense hydrological modeling in grasping the complexity of the flood behavior in urbanizing watersheds. Rainfall distribution models selections and validation lie in the deep roots of this modelling process. In this research, Gumbel distribution was finally chosen as the best statistical model that could be used in determining design rainfall. This was not a random decision. This was done on the basis of comparative distributions fitting and statistical tests which included the Chi-Square test and Smirnov-Kolmogorov tests which affirmed the ability of the Gumbel distribution to fit the resultant rainfall pattern with minimal variation. This choice was in line with the recommendations of previous works, including in tropical and monsoon climates with high rainfall variability, carried out by Kripalani & Kulkarni (1997), who concluded that the Gumbel method is preferable in modeling extreme precipitation occurrences. The findings of Nandargi and Dhar (2012) similarly demonstrated that Gumbel distribution is best to use in estimation of design rainfall in infrastructure planning at a flood-prone Indian river basins. Application of this study increases the certainty of future flood discharge estimation, and future infrastructure design are concrete and based on actual assessment of downpour maxima.

Going further with the design rainfall estimates, the study integrated the Rational method and Nakaysu unit hydrograph method in modeling flood discharge. Both techniques have their own strengths and by using the two, a cross-validation of findings was possible. Rational method is simple and applicable to urban catchments and thus is frequently applied in the initial flood study. Nevertheless, it does not have the capacity of recording temporal variation in flow. In correcting this, Nakayasu method was used, which is more specific in time distribution of run off considering the response time of a catchment. A combination of the two methods can be justified with the help of research conducted by Salvadore et al. (2015), according to which hybrid modeling approaches provide a more reliable flood projection, particularly in semi-urban basins, where a combination of land cover and infiltration properties is observed. Wurbs (2006) also discovered that when methods are combined, one can assign both the spatial and temporal uncertainty and it will be easy to determine the peak discharge values that can be used both to provide the emergency response and the long term infrastructure design. This study increases the credibility of the estimates by comparing their results to the observed events and demonstrates that the selected modeling framework is appropriate in modeling real-world conditions.

Hydraulic modeling process based on HEC-RAS 2D was able to introduce a spatial clarity to the results of flood simulation and result in an improved analysis of the inundation risks. Compared to conventional one-dimensional modeling, two-dimensional hydraulic modeling has very important benefits. Where the 1D models consider the flow in the river channels, the 2D models redouble the flow analysis to the floodplain, including flow on land with modeling of distribution of flow overland and spreading of flood waters across the landscape. The spatial resolution would be especially useful in low-lying urban regions in Makassar, where a small change in elevation would make a difference to the direction of flow and extent of flood. According to the study by Adesina et al. (2025), 2D modeling using DEM facilitates a more

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precise delineation of floodplains and allows planning the zoning and infrastructure based on evidence. Xing et al. (2023) further emphasized that when it comes to employing high-resolution elevation data to flood maps, it helps increase precision in the flood maps, crucial to detect vulnerable assets like roads, residential premises, and public utility. This paper demonstrated that HEC-RAS 2D simulations can give credible visualization of water depth and pattern of its distribution, which is why it is always advisable to utilize the spatially explicit in future flooding risk studies.

Among the insights that are extremely important to be provided by the hydraulic simulation was the identification of backwater effects within the Jalan Perintis Kemerdekaan drainage corridor. A serious consequence of this backflow through which the river water flows into the drainage system rather than getting the urban runoff is the possible flood risk. The research observed that when high-discharge events occur, the level of Tallo River serves above the city drainage system outlets, and thereby urban floods occur due to the compressed discharge and lack of drainage of stormwater. This can be traced in another two riverine cities, Hamburg and Brisbane, where, due to the effects of the backwaters, inundation occurs locally and unpredictably (Cook, 2023). Backflow conditions suggest that it is not possible to deal exclusively with the flood management in Makassar by focusing on the upstream runoff regulation as we should also consider the hydraulic boundary conditions and outflow structure operation potential. LaHaye et al. (2023) stressed that the combinations of drainage and river management in low-gradient basins should be made to guarantee that surplus rainfalls would not be caught inside the urban areas. Findings in this context acknowledge the fact that the management of risk-of-backflow is not only an engineering affair, but also a major factor that determines flood vulnerability in urban areas with high population densities.

Although the research established that the direct hydrological contribution of the shopping center development was not very huge (0.84 m 3/s), the finding ought to be perused carefully. When many such developments go in a basin then these increments of runoff can add up, even though each one alone is tiny. Kaur (2022) demonstrated that there is a tendency in city densification that creates nonlinearity in runoff, because surface sealing, drainage lag time shortening, and soil compaction have cumulative effects. Even small scale developments add up to overwhelm the drainage systems and particularly where the drainage systems were not designed to serve the current intensities of land use. Other changes identified by Shuster et al. (2005) include the fact that growth of impervious surfaces increases the surface flow by decreasing infiltration, which causes faster and steeper flood peaks in the hydrologic cycle. Thus the cumulative effect of conversion of land into other use should be factored by planners or hydrologists into zoning decisions or revision of flood hazard maps. This point of view is evidenced by the results of this study that demonstrate that the small runoff growth on the development could turn out to be a substantial one when the drainage performance is stinted.

The recommended flood control plans in this work (embankment constructions, drainage development and grading of elevation) coincide with the best practices in urban flood prevention. Other like-minded approaches have been successful in other cities. As an illustration, Mukta et al. (2022) described the Cikapundung Watershed, where embanking of rivers and the expansion of drainage canals significantly decreased the number of floods. Similarly, Leducq & Scarwell (2018) reported that Hanoi city urban spaces gained much through the processes of raising critical infrastructure and regrading terrain in places that are safety threats. The way the spatial interventions (elevation control, land-use zoning, etc.) are implemented also responds to the guidance provided by Zhang et al. (2022) who emphasized that engineering solutions will not be able to ameliorate without combined spatial planning.

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This paper contributes to the body of evidence because it shows how scenario modeling can play roles in prioritizing which interventions would provide the most significant payoff and resilience.

This work also points at the necessity of the data on elevation and hydraulic with increased accuracy in future planning. Though the DEM data of the USGS incorporated in the present study was reliable and gave occupant of modeling, it lacks the efficacy to ingest the micro-topographic elements like little berms and roadside curbs and small channels. In the case of feasibility-level or engineering design work, a better bathymetric data of the channel due to a bathymetric survey more accurate -using Single Beam Echo Sounders would be much more benefit in the visualization of the channel geometry. Hamidifar et al. (2024) highlighted the fact that flood modeling at the level of engineering should promote the accurate estimates of cross-sectional profiles and sediment distributions, which can only be traced via field surveys. Kalore & Babu (2023) also noted that using approximate terrain data in hydraulic design can lead to under- or over-design of structures, increasing the risk of failure. Therefore, future studies should prioritize detailed surveys as part of the transition from planning to implementation.

The field evidence presented in this study shows that construction continues within areas that should function as riparian buffers. According to Indonesia’s PP No. 38/2011, the boundary of the river should be maintained at least 100 meters from the main riverbank to preserve natural floodplain function. However, urban expansion often occurs within this restricted area, reducing the river’s capacity to absorb peak flows and increasing flood damage potential. This regulatory gap is not unique to Makassar. Similar problems have been observed in Jakarta, where informal settlements along rivers have caused major drainage constraints (Prana et al., 2024), and in international contexts such as Vietnam and Bangladesh. The findings of this study suggest that technical solutions must be coupled with enforcement of land-use regulations to be effective. Without proper zoning, even the best-designed flood infrastructure can fail to protect communities.

Conclusion

This study has shown, through detailed hydrological and hydraulic modeling, that flood risk in the Tallo River Basin is shaped by a complex interaction of rainfall intensity, catchment response, and the limitations of urban drainage infrastructure. Using long-term rainfall records and tested statistical methods, we established that the 2025 flood event corresponds to a 25-year return period, and the resulting discharge estimates were consistent with field observations. By combining the Rational and Nakayasu methods, we captured both the peak magnitude and the temporal distribution of flood flows, providing a solid foundation for hydraulic simulation.

The 2D HEC-RAS model proved especially valuable in visualizing flood extent and flow dynamics across the landscape. One of the most important findings was the role of backwater effects from the Tallo River into the urban drainage outlets, particularly around Jalan Perintis Kemerdekaan. These effects—often overlooked—significantly contributed to the observed inundation, even though the additional runoff from new development was relatively minor. This highlights the importance of understanding flood risk not just in terms of rainfall and runoff, but also in terms of how and where the water moves through both natural and built systems. The proposed mitigation strategies—including raising river embankments, improving drainage channels, and adjusting land elevations—were not generalized solutions. They were based directly on the behavior of the system under modeled scenarios, and they are feasible within the context of Makassar’s urban layout. However, the technical solutions alone are not

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enough. Continued encroachment on riparian zones, combined with limited enforcement of existing spatial planning regulations, will continue to undermine flood resilience if not addressed. What is needed is a coordinated approach that combines hydrological understanding with regulatory enforcement and long-term spatial planning.

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. RA 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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