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CLIMATE-ADAPTIVE DRAINAGE DESIGN BASED ON RAINFALL INTENSITY–DURATION–FREQUENCY ANALYSIS AND RUNOFF SIMULATION

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Abstract
This study aims to develop a climate-adaptive drainage design framework through the integration of rainfall Intensity Duration Frequency (IDF) analysis and runoff simulation. Historical rainfall data from 2000–2026 were analyzed to evaluate rainfall variability, extreme rainfall characteristics, and hydrological responses under different land-use conditions. The results indicate an average annual rainfall of 3,249 mm/year with increasing variability in recent years, suggesting a growing influence of climate variability on extreme rainfall events. Frequency analysis using the Log-Pearson Type III distribution was employed to derive design rainfall and construct IDF curves. The analysis shows that rainfall intensity increases significantly with shorter storm durations and higher return periods. Runoff simulations further reveal that urbanized areas generate substantially higher peak discharges than permeable land covers due to greater surface imperviousness. These findings highlight the importance of integrating IDF-based hydraulic design, land-use management, and green infrastructure measures to improve drainage system resilience. The proposed approach provides a practical framework for enhancing urban drainage performance under changing climatic conditions.
Keywords: climate-adaptive drainage, IDF analysis, rainfall variability, runoff simulation, urban hydrology

INTRODUCTION

Global climate change has increased hydrometeorological variability which is characterized by an increase in the intensity and frequency of extreme rainfall events in different regions of the world (Tan et al., 2019). The change in rainfall pattern has a direct effect on the increase in surface runoff volume, which in many cases exceeds the design capacity of existing drainage infrastructure (Jing et al., 2022). This condition makes conventional drainage systems increasingly vulnerable to inundation and flooding, especially in urban areas with high levels of development.

In addition to the influence of climate change, changes in land cover due to urbanization have also altered the hydrological response of catchment areas and increased the potential for surface runoff (Ding et al., 2022). Increased runoff discharge not only triggers recurrent inundation, but also accelerates the erosion and sediment transport processes that can lead to siltation of drainage channels (Chen et al., 2022). The accumulation of sediment gradually decreases the hydraulic capacity of the channel, increasing the risk of system failure in draining peak discharges during extreme rainfall events (Straffelini et al., 2022).

In drainage planning practice, the determination of rainfall designs generally still refers to the historical Intensity-Duration-Frequency (IDF) curve

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which is based on the assumption of climate stationarity (Mccurdy & Travis, 2018). This approach has limitations in representing changes in rainfall characteristics that occur due to climate change, so it has the potential to produce designs that are less adaptive to future conditions (Bremer et al., 2022). Therefore, the integration of adaptive hydrometeorological analysis and rainfall runoff simulation is important to support a more representative and sustainable evaluation of drainage system capacity (Mao et al., 2021).

The main problem identified in Makassar is the inability of the existing drainage system to accommodate the increase in peak discharge which causes repeated inundation events. These conditions are allegedly influenced by the use of designed rainfall data that no longer reflects current hydrometeorological conditions and the limited evaluation of channel capacity based on integrated hydrological and hydraulic modeling (Luo & Shao, 2022). The gap between existing infrastructure capacity and actual hydrological load points to the need for a more adaptive approach to drainage planning to climate change.

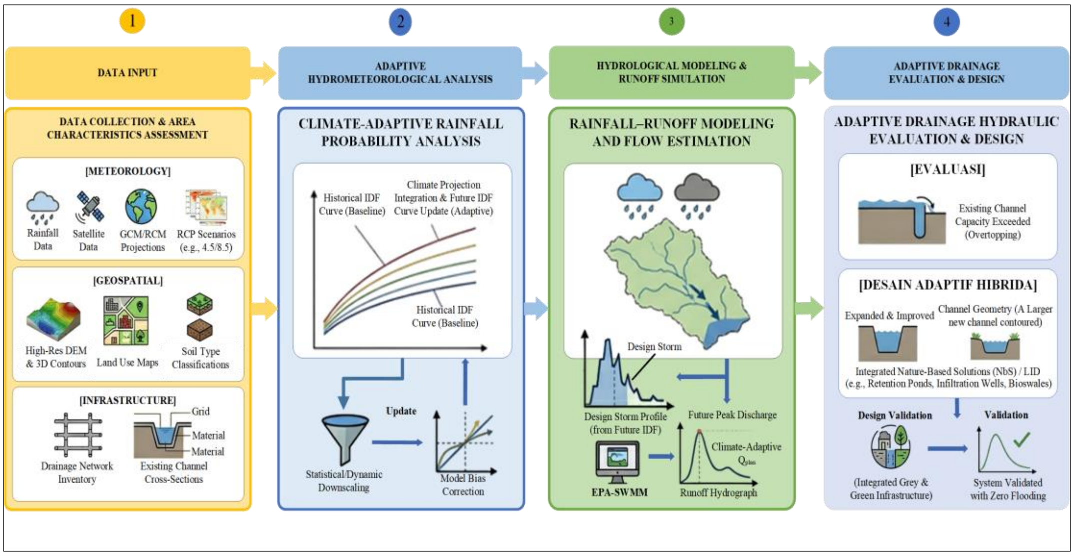

Figure 1. Climate Change-Based Adaptive Drainage Design Research Framework

This study aims to develop a climate-adaptive drainage design framework through the integration of adaptive IDF analysis, rainfall-runoff simulation, and hydraulic evaluation of drainage systems. Specifically, this study aims to: (i) update the IDF curve using historical data and climate projections; (ii) simulate peak runoff and discharge responses using adaptive design rainfall; (iii) evaluate the capacity of the existing drainage system against future hydrological conditions; and (iv) formulate recommendations for more resilient and sustainable drainage designs. The contribution of this research lies in the development of an integrated framework that links climate change analysis, hydrological modeling, and hydraulic evaluation as the basis for decision-making in adaptive drainage planning.

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METHODS

This study develops a spatial hydrological modeling framework to support the design of climate-adaptive drainage systems in the Makassar area. The research framework integrates observation of the physical condition of the channel, land use analysis, and surface runoff estimation as the basis for evaluating the performance of the existing drainage system (Huo et al., 2021). This approach was chosen because urban areas have a high level of vulnerability to various hydrometeorological risks influenced by climate change, so an adaptation strategy is needed that can improve resource management efficiency and infrastructure resilience in a sustainable manner (Gaborit, 2022). This study uses historical rainfall data for the period 2000–2026 obtained from climatology stations and verified using Global Precipitation Measurement (GPM) satellite data to improve the accuracy of rainfall characteristic analysis, Intensity–Duration–Frequency (IDF) curve, and surface runoff simulation (Zhang et al., 2022), while Digital Elevation ModSel (DEM) is used to support topographic analysis and delineation of catchment areas (Yan et al., 2020). In addition, this approach serves as the basis for the development of early monitoring systems in the face of long-term climate change uncertainty (Haasnoot et al., 2018).

The design rainfall analysis was carried out using the general frequency factor (Chow) method to obtain the amount of extreme rainfall in various repeat periods. The planned rainfall is calculated using the equation:

$$X_T = \bar{X} + K \cdot S \qquad (1)$$

where X_T is the rainfall plan (mm),$\bar{X}$ is the average annual maximum rainfall (mm), K is the frequency factor obtained from the selected probability distribution, and S is the standard deviation of rain data (mm).

The intensity of rainfall in design I is determined using the Mononobe method as follows:

$$I = \left(\frac{X_r}{24}\right) \times \left(\frac{24}{t_c}\right)^{2/3} \qquad (2)$$

where I is the intensity of rain (mm/h), $(X_r/24)$ is the maximum rainfall of 24 hours (mm), and T is the duration of rain (hours).

The time of concentration T is calculated using Kirpich's equation:

$$t_c = 0.0195 \times \left(\frac{L}{\sqrt{S_0}}\right)^{0.77} \qquad (3)$$

where T is the concentration time (minutes), L is the length of the farthest flow trajectory (m), and S is the slope of the land (m/m).

To illustrate the region's hydrological response to rainfall events, surface runoff depth was estimated using the Soil Conservation Service Curve Number (SCS-CN) method (Allali et al., 2022). This method considers the relationship between total rainfall and the maximum retention capacity of the catchment area (Qin et al., 2023). The depth of runoff is calculated using the equation:

$$Q_d = \frac{(P - 0.2S)^2}{P + 0.8S} \qquad (4)$$

for $P > 0.2S$, where as $Q = 0$ when $P\backslash 0.2S$.

The maximum potential retention value is defined as:

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$$S = \frac{25400}{CN} - 254 \quad (5)$$

where Q is the depth of runoff (mm), P is the total rainfall (mm), S is the maximum potential retention (mm), and CN is the Curve Number representing the infiltration characteristics of the region.

Plan peak runoff discharge Q_P calculated using the Rational Method (Suzuki et al., 2022):

$$Q_P = 0.278 \cdot C_{gabungan} \cdot I \cdot A \quad (6)$$

$$C_{gabungan} = \frac{\sum_{i=1}^{n}(C_i \cdot A_i)}{\sum_{i=1}^{n} A_i} \quad (7)$$

where Q_P is peak discharge (m³/s), C is the combined flow coefficient, I is the intensity of the planned rain (mm/h), and A is the area of the water catchment area (ha).

The hydraulic capacity of the existing drainage channel is evaluated using the Manning equation (Yin et al., 2020):

$$Q_s = \frac{1}{n} \cdot A_s \cdot R^{2/3} \cdot S_0^{1/2} \quad (8)$$

where Q_s is the capacity of the channel (m³/s), n is Manning's coefficient of roughness, A is the wet cross-sectional area (m²), R are the hydraulic radius (m), and S is the energy slope of the channel.

The system performance evaluation is carried out by comparing the design runoff discharge Q_P to the capacity of the existing channel Q_s. The system is declared to be in critical condition if $Q_P > Q_s$. Based on the results of the evaluation, a hybrid adaptation scenario was developed that combines increasing the capacity of conventional drainage infrastructure with the implementation of nature-based retention facilities to reduce runoff volume and increase the resilience of the system to climate change.

RESULTS AND DISCUSSION

Characteristics of Annual Rainfall and Climate Variability

Annual rainfall analysis shows that the study area has wet climate characteristics with an average rainfall of 3,249 mm/year during the period 2000–2026. The data shows considerable fluctuations between years, with maximum rainfall reaching 5,250 mm/year in 2021 and a minimum of around 2,150 mm/year in 2026 Figure 2.

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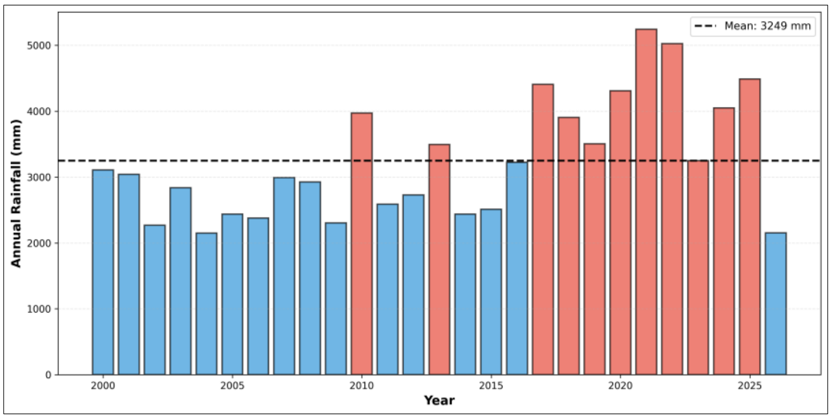

Figure 2. Annual Rainfall for the Period 2000–2026

Figure 2 shows the trend of increasing rainfall in the 2017–2025 period compared to the previous period. This condition indicates the influence of climate variability which has the potential to increase the incidence of extreme rainfall and the risk of surface runoff.

Table 1. Annual Rainfall Statistics

Parameter	Value
Period Dates	2000–2026
Average Rainfall	3.249 mm/year
Maximum Rainfall	5.250 mm/ year
Minimum Rainfall	2.150 mm/ year
Range of Variations	3.100 mm
Features	Fluctuating with an upward trend in the last decade

Table 1 summarizes the main statistics of annual rainfall which shows a range of variation of 3,100 mm with a pattern that tends to increase in the last decade. This increase is an important consideration in drainage planning because channel capacity needs to be adjusted to changes in rainfall characteristics in order to be able to effectively control runoff discharge.

Seasonal Distribution of Rainfall

Monthly rainfall analysis shows a clear monsoon pattern, with the rainy season lasting in November–March and the dry season in April–October. The highest rainfall occurred in January (16.6 mm/day), while the lowest value was recorded in August (1.7 mm/day).

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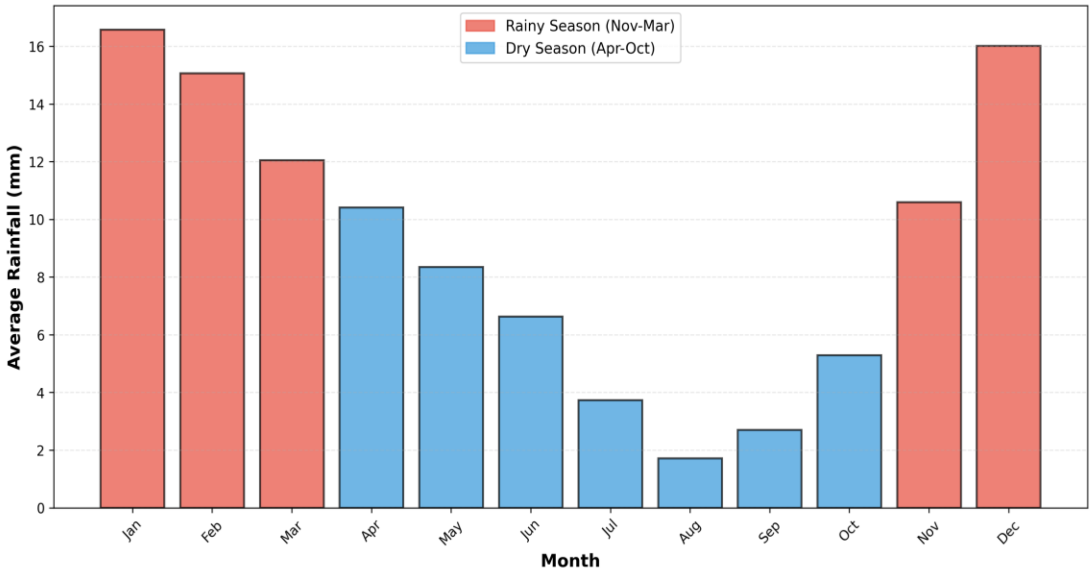

Figure 3. Monthly Rainfall Distribution

To give an overview of rainfall patterns throughout the year, the average value of monthly rainfall is presented in Table 2.

Table 2. Average Monthly Rainfall

Months	Rainfall (mm/day)	Category
January	16.6	Rainy season
February	15.0	Rainy season
March	12.1	Rainy season
April	10.4	Transition
May	8.3	Scarlet Witch
June	6.6	Scarlet Witch
July	3.7	Scarlet Witch
August	1.7	Scarlet Witch
September	2.7	Scarlet Witch
October	5.3	Transition
November	10.6	Rainy season
December	16.0	Rainy season

The distribution shows that the highest potential runoff occurs in the December–February period when the intensity of rainfall reaches maximum conditions. Therefore, the capacity of drainage channels needs to be planned based on peak rainy season conditions to reduce the risk of inundation and overflow of surface flows.

Annual Maximum Rainfall Analysis

An annual maximum rainfall evaluation is performed to identify the characteristics of extreme events that are the basis for frequency analysis. The histogram in Figure 4 shows a relatively concentrated annual maximum rainfall distribution in the range of 70–100 mm.

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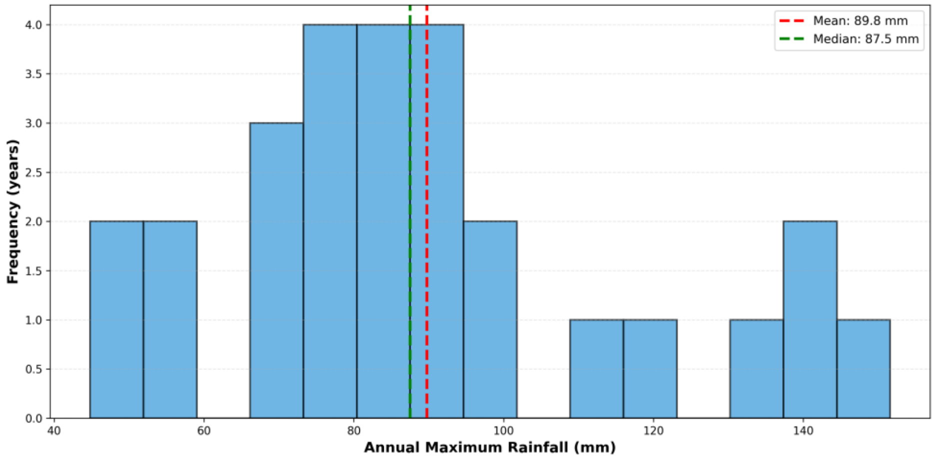

Figure 4. Annual Maximum Rainfall Histogram

The average annual maximum rainfall value is 89.8 mm, while the median is 87.5 mm. The proximity of the two parameters shows that the data distribution does not experience too large a deviation from the middle value. However, there are several extreme rainfall events with a value of more than 130 mm that have the potential to significantly increase runoff discharge.

Table 3. Annual Maximum Rainfall Statistics

Parameter	Value
Average	89,8 mm
Median	87,5 mm
Minimum	45 mm
Maximum	152 mm
Dominant Distribution	70–100 mm

The presence of extreme rainfall in the tail part of the distribution indicates the need to use a probabilistic approach in determining the planned rainfall. Average usage alone is not sufficient to represent the hydrological risks that can occur over the service life of the drainage infrastructure.

Frequency Analysis and Determination of Rain Plan

Frequency analysis is used to obtain the amount of planned rainfall based on a specific repetition period. The results of the probability distribution comparison show that the Type III Log-Pearson approach provides a more consistent representation of the observed data pattern than the Gumbel distribution.

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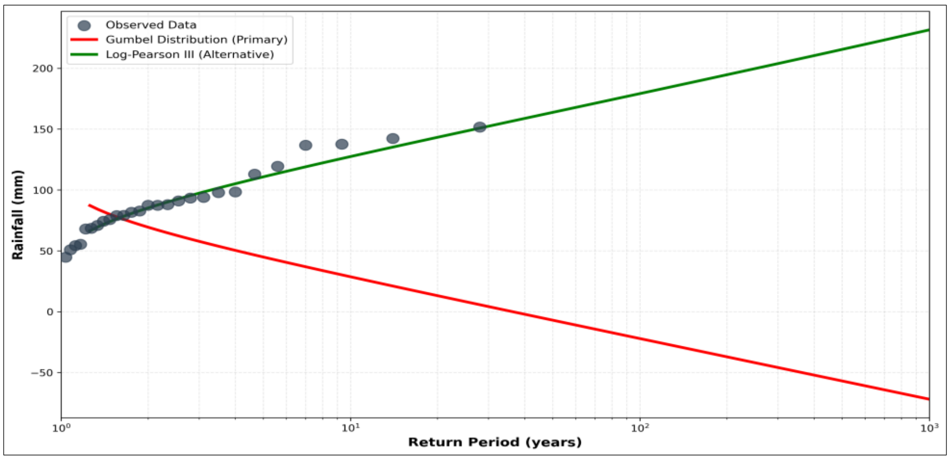

Figure 5. Rainfall Frequency Analysis

The Log-Pearson III curve shows a tendency to increase rainfall as the re-period increases. The phenomenon is in accordance with the principle of hydrological probability that events with fewer chances will result in greater rainfall. Therefore, the Log-Pearson III distribution is used as the basis for the formulation of the Intensity–Duration–Frequency (IDF) curve.

Table 4. Rainfall Plan Based on Re-Period

Re-Period (Years)	Rainfall Plan (mm)
2	90
5	113
10	137
25	152
50	175

The increase in the planned rainfall value in a larger re-enactment period suggests that urban drainage systems should be designed based on a level of risk appropriate to the function of the area. Densely populated urban areas require a higher level of protection than agricultural areas or open spaces.

Frequency Duration Intensity Curve (IDF)

The IDF curve is a key component of drainage planning because it relates the relationship between rainfall intensity, event duration, and re-period. The results of the analysis showed that the intensity of the rain increased significantly at a shorter duration.

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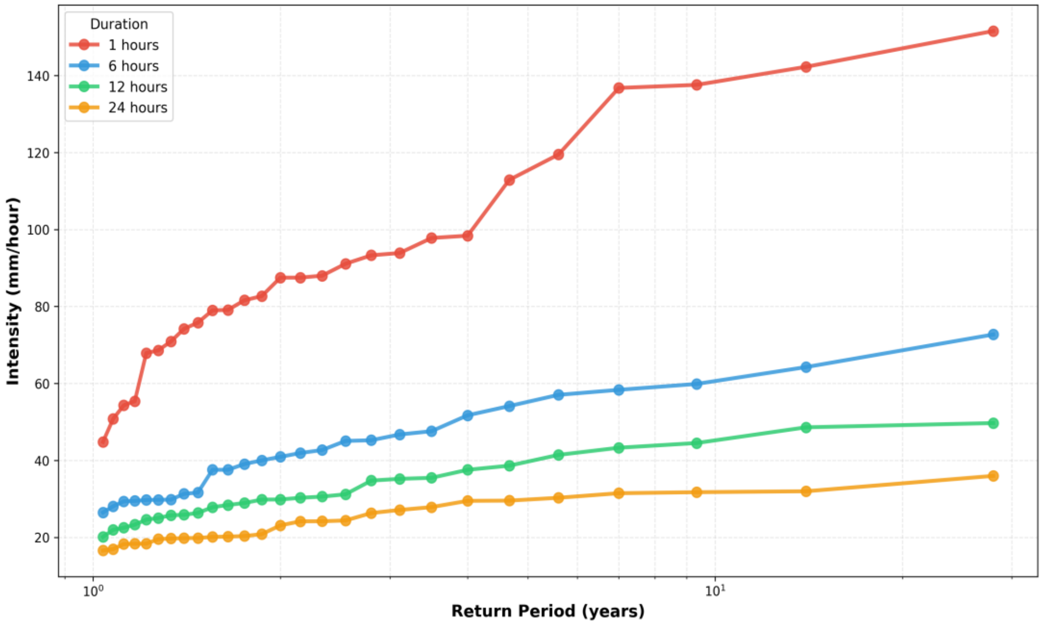

Figure 6. Frequency Duration Intensity Curve (IDF)

In the 25-year anniversary period, the intensity of rain reached around 151 mm/h for a duration of 1 hour, while at a duration of 24 hours it was only around 36 mm/hour. This pattern shows that short rainfall events have the potential to produce greater peak discharges than long-duration rains.

Table 5. Rain intensity plan based on re-period

Re-Period (Years)	1 hour	6 hour	12 hour	24 hour
2	79	38	28	20
5	91	45	31	25
10	98	52	38	29
25	151	73	50	36

This trend suggests that urban drainage channels are particularly sensitive to the occurrence of short-duration and high-intensity rainfall. Therefore, the use of IDF data is an important element in determining the dimensions of channels that are able to function optimally in changing climatic conditions.

Surface Runoff Discharge Simulation

Runoff discharge is calculated using a runoff coefficient approach that represents different types of land use. The simulation was carried out on a catchment area of 10 km² with three main scenarios, namely urban areas (C = 0.7), suburban areas (C = 0.5), and agricultural areas (C = 0.3).

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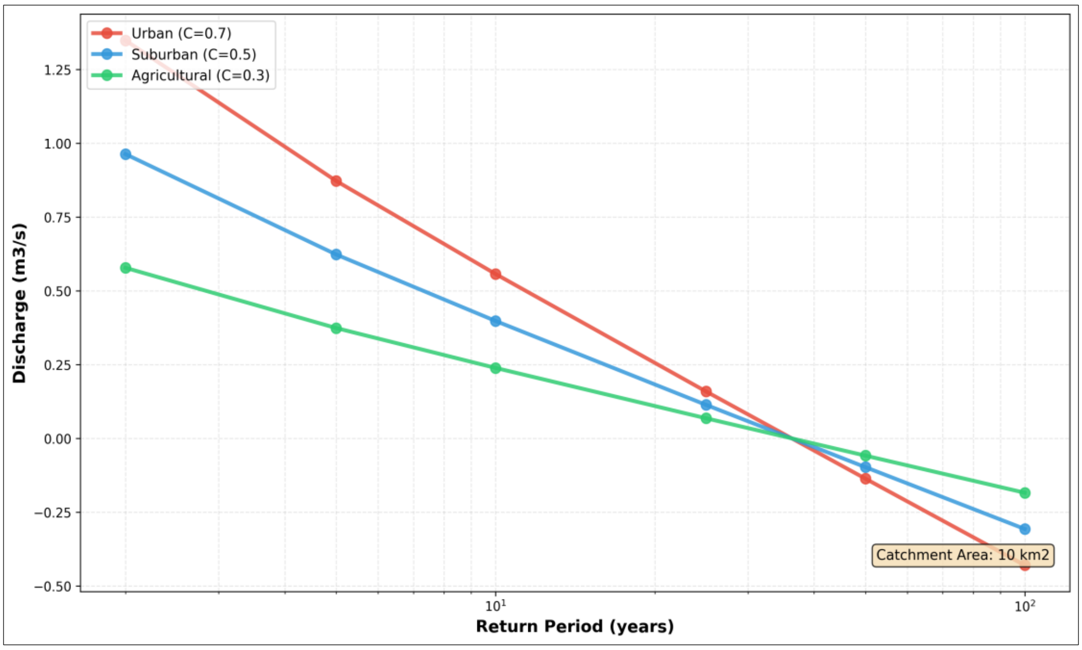

Figure 7. Surface Runoff Discharge Simulation

The simulation results show that urban areas produce the highest runoff discharge compared to other types of land use. In the 2-year replay period, the discharge reached about 1.35 m^3/sec, while the agricultural area was only about 0.58 m^3/sec. The difference is due to the increased surface area of the waterproof, which reduces infiltration and speeds up the surface flow process.

Table 6. Runoff Discharge by Type of Land Use

Re-Period (years)	Urban (m^3/s)	Suburban (m^3/s)	Agriculture (m^3/s)
2	1.35	0.97	0.58
5	0.87	0.62	0.37
10	0.56	0.40	0.24
25	0.16	0.11	0.07

The relationship between rainfall intensity and land use suggests that land-use change has an equally important contribution to climate change in increasing the risk of urban flooding. Therefore, a drainage design that focuses only on increasing the dimensions of the channel without paying attention to the management of the catchment area will have limited effectiveness.

Adaptive and Sustainable Drainage System Development Strategy

Based on the results of the analysis of rainfall, frequency distribution, Frequency Duration Intensity (IDF) curve, and runoff simulations, a drainage design approach that is adaptive to climate change and increased hydrological risk is needed. The application of adaptive re-period-based design is one of the main strategies, where the primary channel is designed using a plan rain with a higher re-period compared to secondary and tertiary channels. This approach allows drainage systems to have adequate capacity to accommodate increased rainfall intensity while maintaining development and operational cost efficiency.

In addition to increasing the capacity of the drainage network, the development of green infrastructure such as retention ponds, infiltration wells, bioretention, and infiltrative green open spaces needs to be integrated in the runoff management system. The simulation results show that areas with high levels of waterproofing produce greater runoff discharge, so land use control, the use of porous pavement, and the increase in vegetation area are important steps to reduce peak discharge. A combination of IDF-based hydraulic design, ecosystem-based runoff management, and regular updates of hydrometeorological data can improve the resilience of drainage systems to extreme rainfall events and support the development of more sustainable urban infrastructure.

CONCLUSION

This study shows that the rainfall characteristics in the study area have a fluctuating pattern with an increasing tendency in recent years. The analysis of annual rainfall for the period 2000–2026 yielded an average of 3,249 mm/year, while the monthly rainfall distribution showed the highest rainfall concentration in the December–February period. These conditions indicate the potential for increased surface runoff and the risk of inundation during the rainy season, so it needs to be a major consideration in drainage system planning.

The results of the frequency analysis showed that the Type III Log-Pearson distribution was able to represent the characteristics of extreme rainfall well and was used as the basis for the preparation of the Intensity-Duration–Frequency (IDF) curve. The IDF curve shows that rainfall intensity increases at shorter durations and larger repetition periods, which has direct implications for the increase in peak discharge in drainage systems. Runoff simulations show that areas with high levels of watertightness produce greater runoff discharge than areas with more permeable surfaces, so land-use changes are important factors that affect drainage performance.

Based on these results, climate-adaptive drainage design needs to integrate IDF analysis, runoff simulation, and land use management to increase the capacity and resilience of the system to extreme rainfall events. The implementation of green infrastructure, watertight surface control, and regular updates of hydrometeorological data can support the development of drainage systems that are more effective, sustainable, and responsive to the dynamics of climate change.

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