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Assessing Urban Flooding and Drainage System Performance in Urban Area: A Mononobe Equation and Manning Formula Approach

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ABSTRACT

Climate change causes erratic rainfall and often results in flooding of urban areas. Floods are hydrometeorological disasters that occur in various regions of Indonesia. Flood vulnerability in urban areas has increased over the past 30 years. Kauman Village is included in the Asri water catchment area, which has an Asri primary channel downstream of the urban area of Nganjuk District. However, from 2019 to 2022, the urban area of Nganjuk District, including Kauman Village, was affected by flooding. Urban floods inundated office areas, schools, housing, and public facilities such as the Nganjuk District General Hospital. The factor indicated as the cause of flooding is the clogging of the drainage channel with rubbish. Therefore, field research and mathematical calculations were conducted to evaluate the discharge capacity of drainage channels in the village. Based on the research, it was found that the existing drainage channel discharge in the research area could not accommodate the planned discharge for the 10-year return period. In addition, there are 33 channels that are unable to accommodate the planned discharge because the channel dimensions are too small, some channels are slightly damaged, sedimentation occurs, and they are blocked by rubbish. Drainage channels that do not function optimally affect urban flooding. Therefore, several efforts have been made to reduce the risk of flooding by changing the dimensions of drainage channels, normalizing drainage channels, and getting used to maintain drainage channels and not throwing rubbish in drainage channels.

Introduction

In some areas, climate change causes erratic rainfall, frequently occurring with high rainfall. High rainfall and changes in land use enable flooding to occur. In addition, drainage infrastructure and topographical characteristics affect the occurrence of flooding [1,2]. Owing to changes in land use, the effects of climate change, and the influence of urbanization, flood risk in metropolitan areas has increased over the past 30 years [3,4]. Flooding is a hydrometeorological disaster that occurs in many parts of Indonesia. Urban flooding occurs during heavy rain with an intensity of more than 100 mm/day in urban areas and causes damage to public facilities [5].

The occurrence of heavy rain in upstream rivers, which causes downstream river discharge to rise, damage to water bodies, such as broken embankments, and inundation due to drainage channels being unable to hold and drain rainwater properly are some of the causes of urban flood disasters in Indonesia [6]. Increased rainfall does not imply that the discharge and extent of flooding have increased. The size, terrain, and characteristics of the watershed are among the elements that affect flooding [7]. However, high rain intensity fills the drainage channel. Some drainage channels have minimal capacity, so rainwater sometimes does not enter the channels and causes inundation and flooding [8]. Floods in urban areas cause buildings and public facilities to submerge, hampering sustainable development [9]. Drainage canals contribute to sustainable development, particularly concerning climate change and urbanization [10].

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The Nganjuk Regency is one of the areas that often experiences floods in East Java during 2019 to 2022 [11]. According to information from the Central Bureau of Statistics for Nganjuk Regency in 2022, 29% more villages and wards in the region have experienced flooding in the previous two years [12]. Urban floods in 2021 inundated four villages in Nganjuk District, one of which was Kauman Village, up to 60 cm in height [13]. Kauman Village is in the urban area of the Nganjuk District, with an area of 3.23 km^2. Government offices, schools, and *Rumah Sakit Umum Daerah* (RSUD) are located in the village. However, in the last four years, Kauman Village has experienced urban flooding during the rainy season with high rainfall intensity. Rainwater inundated the hospital at a height of 10 cm, disrupting hospital service activities [14,15].

Nganjuk District has two primary drainage channels that collect rainwater from the secondary and tertiary channels before it flows into the river as the main water body. One of the primary drainage channels is the Asri drainage channel, which is included in the Asri water catchment area downstream of Kauman Village. However, urban flooding still frequently occurs in this area. One of the causes of flooding in this area is that tertiary drainage channels in residential areas and secondary channels in the Kauman sub-district are clogged with sediment and rubbish; thus, they are unable to accommodate and channel rainwater. Therefore, it is necessary to conduct field research to determine whether the discharge capacity of existing drainage channels in Kauman Village is in accordance with the planned discharge, which can then be used as a recommended strategy for preventing urban flood disasters.

Materials and Methods

The maximum daily rainfall data input for at least the last ten years has been used in drainage system research for hydrological analysis [16,17]. Seven rain observation stations in the Nganjuk urban area and its surroundings (as shown in Figure 1) provided data for the last 15 years (2003–2022) regarding the highest daily rainfall for this research. Rainfall data were used as inputs for hydrological analysis to calculate the rainfall intensity for a 10-year return period, which was then used to calculate the planned flood discharge. In addition to hydraulic analysis to calculate the existing channel discharge, direct measurements were performed in the field to determine the type and size of each channel.

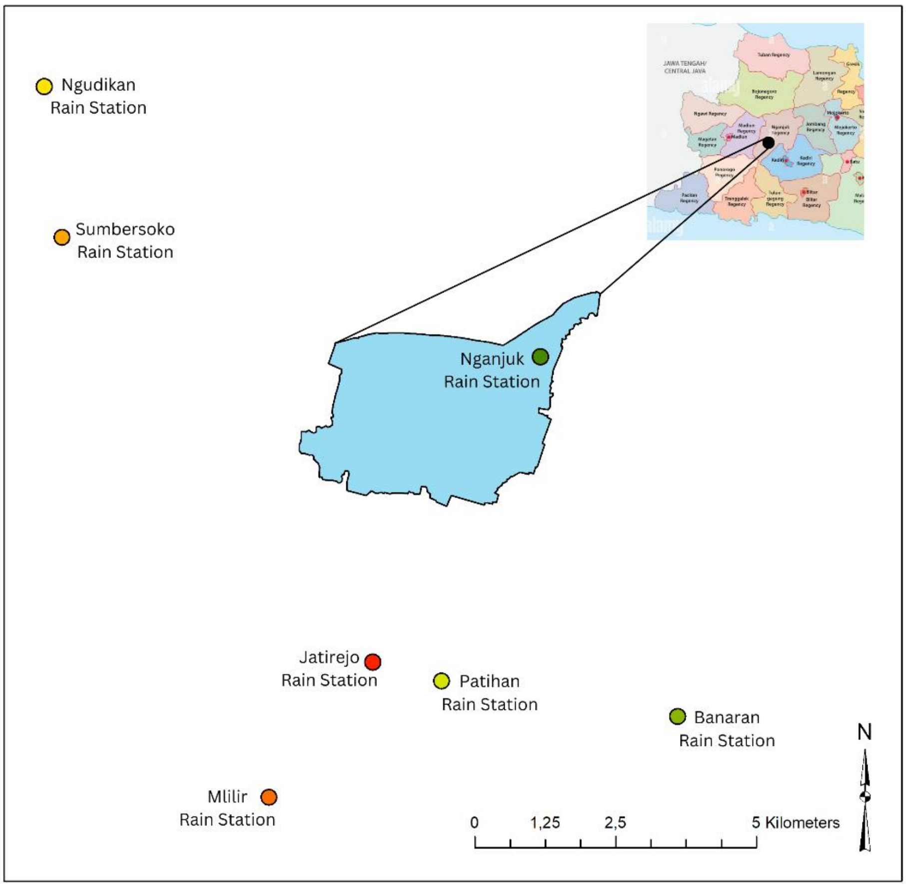

Figure 1. Location of rain observation stations.

Hydrological Analysis

Hydrological analysis is a calculation of planned discharge with the following steps: regional rainfall calculations use the algebraic average method, the Thiessen Polygon method, and the Isohyet method; the calculation of planned rainfall for a 10-year return period uses frequency analysis with the Normal distribution, Log Normal distribution, Log Pearson III distribution, and Gumbel distribution; the probability distribution test uses the Chi Square test method and the Smirnov Kolmogorov test method; the calculation of rain intensity using the Mononobe Equation; and the calculation of planned discharge uses the Rational method with the following formula:

$$Q = 0.00278\, C\, I\, A \tag{1}$$

Explanation:

Q : design flood discharge (m^3/second)

C : surface flow coefficient

I : rain intensity (mm/hour)

A : drainage area (Ha)

Hydraulic Analysis

The discharge of the present drainage channel and anticipated flood discharge were calculated using hydraulic analysis based on the Indonesian National Standard [18]. The existing channel discharge is calculated using the following equation:

$$Q = \frac{1}{n} . R^{\frac{2}{3}} . S^{\frac{1}{2}} . A \tag{2}$$

Explanation:

Q : existing channel discharge (m^3/second)

n : wall hardness coefficient depending on the type of channel material or Manning coefficient

R : hydraulic radius (m)

S : channel slope

A : wet cross-sectional area of the channel (m^2)

The magnitudes of the existing drainage channel discharge and planned discharge were compared using a Paired Sample T-Test (t-test) using SPSS software. If the discharge capacity of the existing drainage channel is smaller than the planned discharge capacity, the channel will not be able to accommodate and channel rainwater to the water body, resulting in puddles or flooding. The results of the analysis were used to formulate appropriate flood mitigation measures for the research area.

Results and Discussion

Kauman Village is one of the villages in the urban area of Nganjuk Regency. Several government offices near the main hospital in the Nganjuk Regency are located in Kauman Village. The former irrigation canals dominate Indonesia's drainage systems. Drainage channels often serve as irrigation channels and rainfall collection systems in both rural and urban areas. Even household channels for waste disposal and sanitation function as rainwater drainage channels [19–21]. In addition, problems with the drainage system in Indonesia are always the same every year, namely, the blockage of rainwater flow due to sediment and garbage in the canals, causing inundation and even flooding [20,22,23]. Urban drainage channels in Indonesia are classified as rectangular or trapezoidal channel sections with concrete or riverstone constructions [22–24]. The urban drainage networks in Indonesia include primary, secondary, and tertiary networks with natural patterns. The natural network is a mechanism for rainwater flow from tertiary and secondary channels to be collected directly into natural channels, namely, rivers. Because Indonesia uses natural networks, open channels predominate the country's drainage system, along with a few closed channels [19,21].

Similar to other parts of Indonesia, Kauman Village has primary, secondary, and tertiary drainage networks. The network includes 52 tertiary drainage channels along the road, one secondary channel, and one primary channel. The primary feature of an open, square-cross-section tertiary drainage channel is its concrete structure. However, there is also a trapezoidal tertiary channel with a stone masonry. This tertiary channel collects rainwater and household wastewater and then flows to the secondary channel. The secondary drainage channel in Kauman Village is referred to as Dr. Soetomo and has a trapezoidal cross-section of stone masonry and open construction. Water from the secondary channel is channeled into the primary Asri channel. The urban drainage system of the Nganjuk Subdistrict has two primary channels, one of which is the Asri Channel, whose drainage area covers Kauman Village. The cross-sectional shape of Asri's primary canal is a square with a stone masonry construction. The types of drainage channels in Kauman Village are listed in Table 1.

Table 1. The types of drainage channels in Kauman Village.

No	Channel	Construction type	Channel shape	Photo
1	Asri primary channel	Stone pair	Rectangle	
2	Dr. Soetomo secondary channel	Stone pair	Trapezoid	
3	Tertiary canal/road canal	Concrete	Rectangle	

No	Channel	Construction type	Channel shape	Photo
		Stone pair	Trapezoid	

Hydrological analysis of the planned rainfall calculation that meets the statistical requirements is the result of a log-normal distribution calculation; that is, rainfall in the return period of 2 to 50 years in the urban area of Nganjuk District is in the range of 20–50 mm/day and is included in the moderate rainfall category according to probabilistic estimates of 24-hour rainfall from the Meteorology, Climatology, and Geophysics Agency (BMKG). The flow of rainwater in the urban areas downstream of the Asri drainage channel in Kauman Village has a planned discharge of 9,506 m^3/second. Meanwhile, the existing Asri primary channel discharge is 5,217 m^3/second, so the Asri primary channel in the research area is unable to accommodate the planned discharge for the 10-year return period. Based on the field observations and mathematical analysis, the reasons for the existing drainage channel discharge not being able to accommodate the planned discharge were that the channel dimensions were too small, some channels were slightly damaged, sedimentation occurred, and they were clogged with rubbish. Mathematical calculations also indicated that the Asri primary channel downstream has the possibility of inundation for 59,056 min. The drainage network evaluation scheme for the Asri water catchment area in Kauman Village is shown in Figure 2.

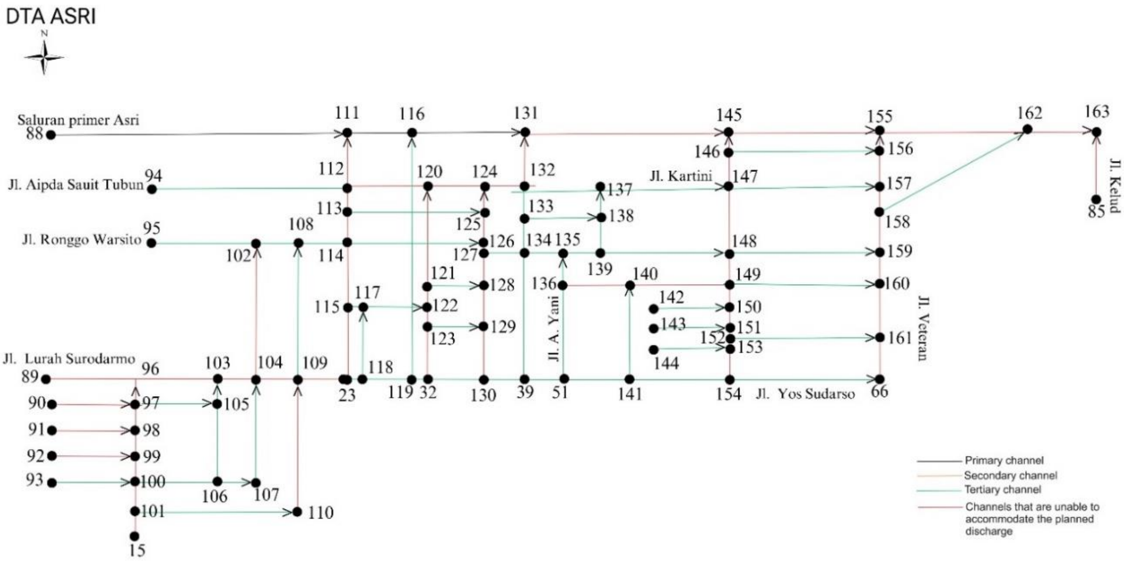

Figure 2. Evaluation scheme for the Asri water catchment area drainage network.

The scheme in Figure 1 shows that in the research area, 33 channels are unable to accommodate the planned discharge. The shortest inundation occurred in channels 132 to 131 over 4,348 min. Meanwhile, the longest inundation occurred in the 96 to 23 south channel for 72,228 min, which was caused by the dimensions of the channel being too small to accommodate the planned discharge. The Asri catchment area flooded for an average of 31,866 min. Most of the Asri primary channels are in good condition; however, there are several points where the plants have damaged the channel walls, resulting in the channel dimensions being too small to accommodate the planned discharge, as shown in Figure 3.

(a) west side (b) east side

Figure 3. Condition of the Asri primary channel.

According to several studies [25–28], the use of sustainable drainage systems can help reduce the likelihood of flooding. Low-impact development (LID) techniques including Rain Gardens (RG), Bio-Retention Cells (BRC), Green Roofs (GR), Infiltration Trenches (IT), Permeable Pavements (PP), and Vegetative Swales (VS) can be used to implement sustainable drainage systems. Rain characteristics can affect the effectiveness of the drainage systems. Effectiveness depends on the type of canal structure, rainfall, geometrical design of the canal, and the hydraulic properties of the canal drainage material. The use of sustainable pavement and green roofs on drainage channels can reduce the discharge and volume of rainwater runoff, allowing rainwater to drain more efficiently [29,30].

Several efforts that can be made to reduce the risk of flooding in the Kauman Village area as an Asri water catchment area are divided into technical and non-technical mitigation. Technical mitigation efforts that can be implemented include changing the dimensions of primary, secondary, and tertiary drainage channels that are too small; normalizing primary, secondary, and tertiary drainage channels to restore the function of drainage channels as recipients and channel rainwater through cleaning sediment and rubbish; and using biopores in schools, offices, markets, and parks/green open spaces to help reduce the flow of water held by drainage channels. Therefore, when it rains, the water absorbs more quickly into the ground and does not cause puddles, and coordinates with the Environmental Service to maintain roadside green vegetation adjacent to the drainage channels.

Meanwhile, non-technical flood mitigation is carried out through coordination with the Environmental Service to carry out flood risk reduction activities such as optimizing landfills so that people do not throw rubbish in drainage channels; regular outreach to the public and students about the importance of maintaining drainage channels for flood mitigation; optimizing Nganjuk Regency Regional Disaster Management Agency social media accounts for information on flood disaster status; and coordinating with relevant agencies to formulate regulations and policies regarding urban flooding, preparedness, and urban flood mitigation.

Conclusion

The results of the mathematical calculations indicate that the urban area of Nganjuk District in the return period of 2 to 50 years is in the moderate-rain category. Kauman Village is in the Asri water catchment area and has an Asri primary channel downstream with an existing channel discharge of 5,217 m^3/second. However, the planned discharge in the Asri primary channel is 9,506 m^3/second, so the existing drainage channel does not match the planned discharge, and the area has the possibility of inundation for 59,056 min. The causes of inundation and flooding in the research area in 2019 to 2022 were that the channel dimensions were too small, some channels were slightly damaged, sedimentation occurred, and they were blocked by rubbish. Several efforts have been made to reduce the risk of flooding by changing the dimensions of drainage channels, normalizing drainage channels, using biopores, and coordinating with the Environmental Service to maintain roadside greening vegetation. Meanwhile, non-technical efforts include coordination with the Environmental Service to carry out flood risk reduction activities, regular outreach to the public, students about the importance of maintaining drainage channels for flood mitigation, optimizing the Nganjuk Regency Regional Disaster Management Agency's social media accounts for information on flood disaster status, and coordinating with related agencies. To prepare regulations and policies regarding urban flooding, preparedness, and urban flood mitigation.

The research carried out has limitations and shortcomings; therefore, several suggestions that can be made in future research include increasing the amount of household wastewater entering the channel because the existing drainage channel is a multipurpose channel. However, this research only calculated the amount of planned discharge and existing channel discharge; therefore, the results of calculating the impact of flooding were significant. In addition, the evaluation uses only a comparison of the planned discharge and the existing channel discharge; therefore, there are several other factors that might influence the analysis results. Therefore, it is recommended to conduct an analysis of the river that functions as the main urban water body in Nganjuk District, namely, the Dungdet River, which is in the research area.

Author Contributions

SLR: Conceptualization, Methodology, Investigation, Writing – Original Draft; **SS**: Supervision, Validation, Writing - Review & Editing; **MM**: Supervision, Validation, Writing - Review & Editing.

Conflicts of interest

There are no conflicts to declare.

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