Urban Drainage Channel Redesign Based on Design Flood Analysis: A Case Study of Gunung Anyar Kidul, Surabaya

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Abstract

Rapid urban development has significantly increased impervious surfaces, resulting in higher surface runoff and frequent urban flooding. Gunung Anyar Kidul, one of the rapidly developing residential areas in Surabaya, has experienced recurring inundation due to inadequate drainage capacity. This study aims to evaluate the hydraulic performance of the existing secondary drainage channel and propose an optimal channel redesign based on the design flood discharge. Hydrological analysis was conducted using the Gumbel distribution to estimate the five-year return period rainfall, while the Rational Method was employed to calculate the design discharge following the Indonesian Standard (SNI 2415:2016). Hydraulic capacity was evaluated using Manning's equation. The results indicate that the five-year design rainfall reached 169.288 mm/day, producing a rainfall intensity of 177.087 mm/h and a design discharge of 7.583 m^3/s. The existing channel capacity was only 2.793 m^3/s, indicating that the drainage system is hydraulically insufficient. A redesigned trapezoidal channel with a bottom width of 1.80 m and a flow depth of 1.50 m increased the channel capacity to 7.83 m^3/s, satisfying both the design discharge and the freeboard requirement specified in SNI 03-3424-1994. The findings demonstrate that channel enlargement combined with routine maintenance can substantially improve drainage performance and reduce urban flood risk in Gunung Anyar Kidul.

Keywords: *Gumbel Distribution, Hydraulic Capacity, Manning Equation, Open Channel, Urban Drainage, Rational Method*

1. Introduction

Urban drainage systems are essential components of urban infrastructure, functioning to collect, convey, and discharge stormwater efficiently in order to minimize flooding and maintain public safety [1]. However, rapid urbanization has significantly altered the natural hydrological cycle by increasing impervious surfaces and reducing infiltration capacity [2]. The expansion of residential, commercial, and transportation infrastructure has resulted in greater surface runoff and higher peak discharges during rainfall events, thereby placing increasing pressure on existing drainage networks. As a consequence, many urban areas are experiencing more frequent flooding and waterlogging, particularly where drainage systems were designed under previous land-use conditions.

Surabaya, one of Indonesia's largest metropolitan cities, has experienced rapid urban growth over the past decade. In particular, the Gunung Anyar Kidul area in eastern Surabaya has undergone substantial residential development, accompanied by increasing population density and land-use conversion. These changes have increased stormwater runoff while the capacity of the existing drainage infrastructure has remained relatively unchanged. Consequently, localized flooding continues to occur during moderate to heavy rainfall events, indicating that the existing drainage system may no longer be capable of accommodating the generated runoff. Field observations revealed several factors contributing to the reduced performance of the drainage channel, including sediment accumulation, uncontrolled vegetation growth, structural deterioration, and solid waste deposition, all of which reduce the effective flow area and hydraulic capacity [3].

To address recurring flood events, the Surabaya municipal government has implemented various flood mitigation programs, including river normalization, sediment dredging, vegetation removal, and improvements to the primary drainage channels located near the Surabaya–Sidoarjo boundary. These measures have improved the conveyance capacity of the primary drainage network; however, inundation problems persist within the secondary drainage system of Gunung Anyar Kidul. This condition suggests that flood mitigation efforts should also focus on evaluating and improving the performance of secondary drainage channels, which play a critical role in collecting and conveying runoff from residential catchments before discharging it into the primary drainage system.

Previous studies have demonstrated that periodic evaluation of drainage channel performance is necessary to ensure that hydraulic capacity remains consistent with changing hydrological conditions and urban development. Such evaluations generally involve hydrological analysis to estimate the design rainfall and design flood discharge, followed by hydraulic analysis to determine whether the existing channel is capable of safely conveying the required flow. When the hydraulic capacity is found to be inadequate, channel rehabilitation or redesign becomes necessary to reduce flood risk and improve the reliability of the urban drainage system.

Although numerous studies have investigated urban drainage performance in rapidly developing cities, relatively few have focused on the hydraulic adequacy of secondary drainage channels in eastern Surabaya using an integrated hydrological and hydraulic approach. In particular, there is limited information regarding the extent to which existing channel dimensions can accommodate the design flood discharge under current land-use conditions. Therefore, a comprehensive evaluation of channel capacity is required to support evidence-based planning and infrastructure improvement.

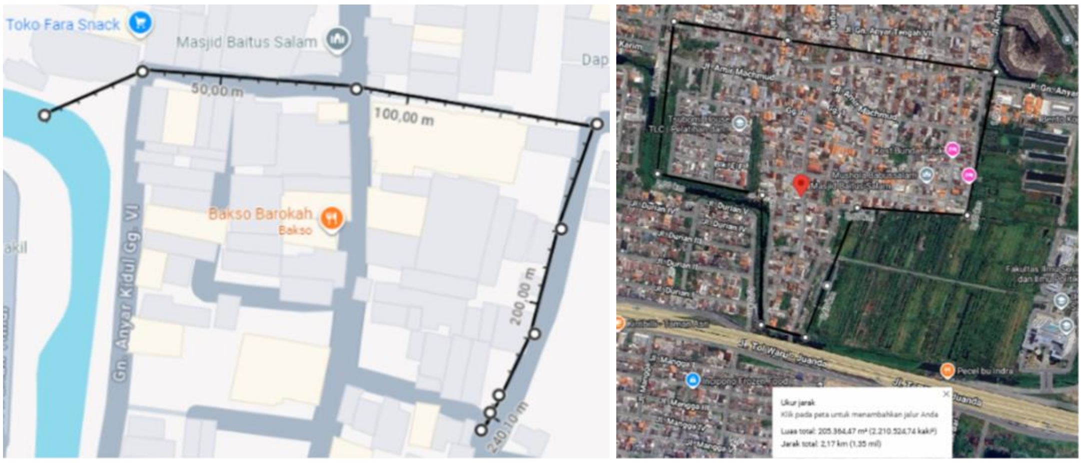
Accordingly, this study aims to evaluate the hydraulic performance of the secondary drainage channel in Gunung Anyar Kidul, Surabaya, by integrating hydrological and hydraulic analyses. Design rainfall was estimated using the Gumbel probability distribution based on annual maximum rainfall data, while the design flood discharge was calculated using the Rational Method in accordance with SNI 2415:2016 [4]. The hydraulic capacity of the existing channel was then evaluated using Manning's equation [5], and an optimized trapezoidal channel section was proposed when the existing capacity proved insufficient. The results of this study are expected to provide practical recommendations for improving drainage performance and contribute to sustainable urban flood management in rapidly developing residential areas.

2. Research Methodology

This study employed a quantitative descriptive approach supported by hydrological and hydraulic analyses to evaluate the capacity of the existing urban drainage system in Gunung Anyar Kidul, Surabaya. The research framework consisted of four main stages: problem identification, data collection, hydrological analysis, and hydraulic evaluation.

The study began with problem identification, which involved field observations and interviews with local residents to assess the existing condition of the drainage system and identify the factors contributing to recurring flooding. Particular attention was given to inundation characteristics, including the frequency, duration, and locations of flooding, as well as changes in population density and land use that potentially increased stormwater runoff. The interview results indicated that flooding commonly occurs during moderate to heavy rainfall and is generally associated with inadequate drainage capacity, sediment accumulation, poor channel maintenance, and the increasing extent of impervious surfaces. These findings were used to define the research scope and support the evaluation of the existing drainage system.

Data collection consisted of primary and secondary data. Primary data were obtained through field surveys to determine the geometric characteristics and physical condition of the existing drainage channel. The surveyed channel is a trapezoidal masonry-lined secondary drainage channel with an approximate length of 240 m, serving a drainage area of approximately 0.21 km² as shown in **Figure 1**. Field measurements included the channel cross-section, channel dimensions, longitudinal slope, and channel length, which were required for the hydraulic calculations. The existing cross-section was measured to determine the flow area, wetted perimeter, and hydraulic radius used in Manning's equation. Visual inspections further revealed sediment deposition, uncontrolled vegetation growth, solid waste accumulation, and localized deterioration of the channel lining, all of which reduce the effective flow area and consequently decrease the hydraulic capacity of the drainage system.



(a) **(b)**

Figure 1. Drainage map (a) and catchment area (b) of the Gunung Anyar Kidul canal

To complement the field survey, interviews were conducted with residents living near the drainage channel to obtain information regarding flood occurrence, including flood frequency, duration, water depth, and the locations most frequently affected by inundation. Residents reported that flooding generally occurs during moderate to heavy rainfall and may persist for several hours before the water gradually recedes. They also identified sediment accumulation, inadequate routine maintenance, and the limited capacity of the existing drainage channel as the primary causes of the recurring flooding. The interview findings were used to validate the field observations and strengthen the identification of drainage problems in the study area. **Figure 2** presents the existing condition of the canal, including the channel geometry, sediment deposition, vegetation growth, and solid waste accumulation observed during the survey.

(a) **(b)**

Figure 2. Existing condition of the Gunung Anyar Kidul drainage canal: (a) photograph of the existing drainage canal; (b) existing channel cross section.

Secondary data included annual maximum daily rainfall records obtained from the Juanda Meteorological Station (BMKG) for the period 2015–2024, drainage network maps, catchment boundary maps, and other supporting documents required for the hydrological and hydraulic analyses. These datasets were subsequently used to estimate the design rainfall, calculate the design flood discharge, evaluate the hydraulic performance of the existing drainage channel, and develop an improved channel design where the existing capacity was found to be insufficient.

The collected data were subsequently processed through hydrological and hydraulic analyses to determine the design flood discharge, evaluate the conveyance capacity of the existing channel, and propose an optimized channel section capable of safely conveying the design discharge while satisfying the applicable Indonesian drainage design standards. The overall research methodology adopted in this study is illustrated in the flowchart shown in **Figure 3**.

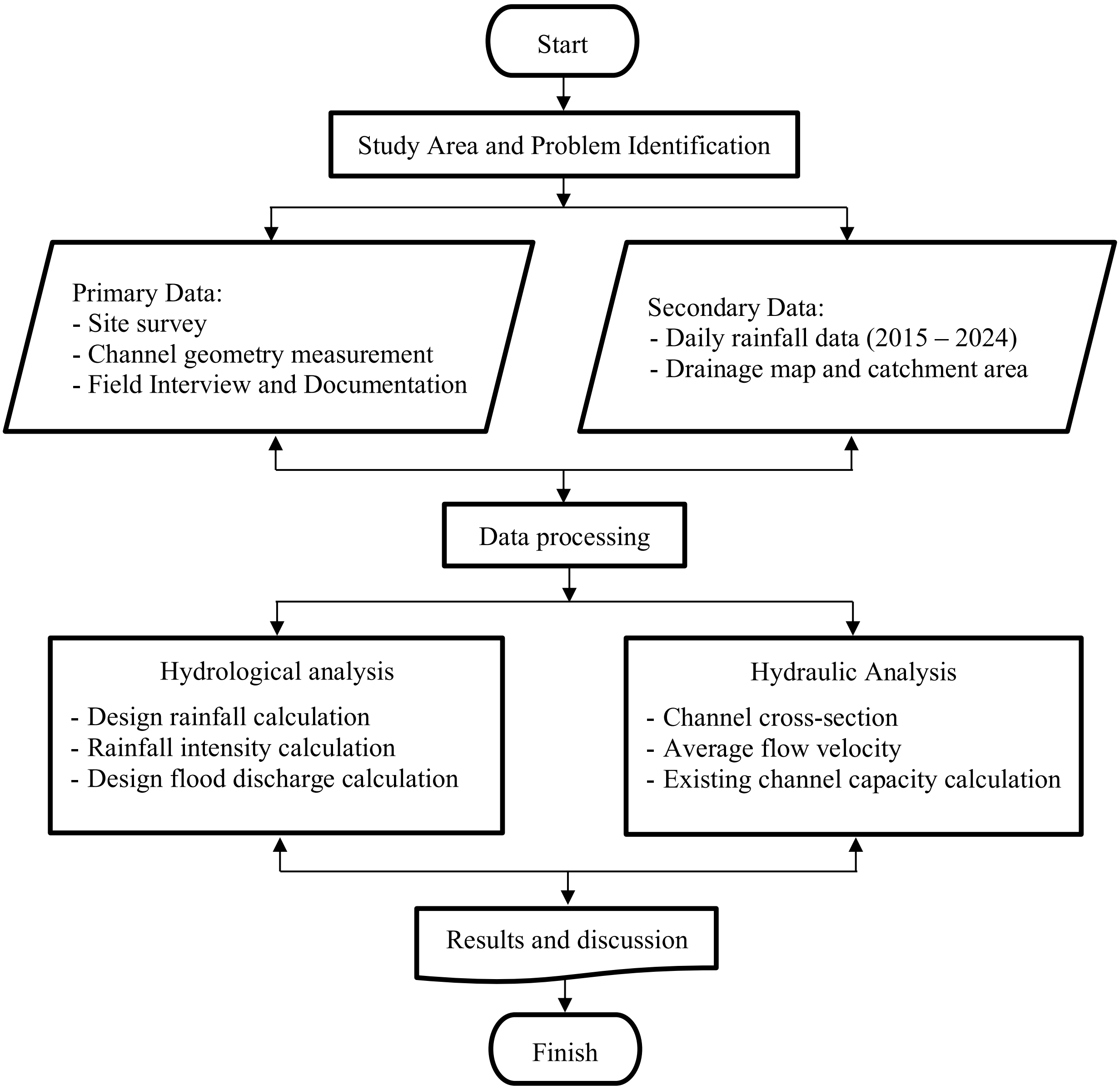


Figure 3. Research flowchart

3. Results and Discussion

This section presents the results of the hydrological and hydraulic analyses conducted to evaluate the performance of the existing drainage channel in Gunung Anyar Kidul, Surabaya. Annual maximum daily rainfall data recorded at the Juanda Meteorological Station (BMKG) for the period 2015–2024 were analyzed using the Gumbel probability distribution to estimate the design rainfall for the selected return period. The design rainfall was subsequently converted into rainfall intensity using the Mononobe equation, with the rainfall duration determined from the Kirpich equation for time of concentration. The Rational Method was then employed to calculate the design flood discharge, which served as the basis for evaluating the hydraulic capacity of the existing drainage channel using Manning's equation. The calculated channel capacity was compared with the design discharge to assess the adequacy of the existing channel and to develop an appropriate channel redesign where necessary.

3.1 Hydrological Analysis

The annual maximum daily rainfall data recorded at the Juanda Meteorological Station (BMKG) for the period 2015–2024 were used as the basis for the hydrological analysis. The data are summarized in **Table 1**.

Table 1. Annual maximum daily rainfall data at Juanda Meteorological Station (2015–2024) [6]

Year	Rainfall (mm)	Year	Rainfall (mm)
2015	65	2020	127.7
2016	87.5	2021	89.8
2017	106.5	2022	151.5
2018	88.5	2023	107.6
2019	156.6	2024	96.4

Before conducting the rainfall frequency analysis, the suitability of the Gumbel distribution was evaluated using the Kolmogorov–Smirnov goodness-of-fit test at a 5% significance level. The test yielded a maximum deviation of $D_{\max} = 0.128$, which is smaller than the critical value of $D_{\text{critical}} = 0.410$. Therefore, the null hypothesis was accepted, indicating that the Gumbel distribution adequately fits the annual maximum rainfall data and is suitable for design rainfall analysis.

A total of 10 years of annual maximum daily rainfall data were analyzed, yielding a standard deviation of 29.36. Although this dataset satisfies the minimum data requirement for frequency analysis, a longer rainfall record (e.g., 20–30 years) is recommended to reduce estimation uncertainty and improve the reliability of the design. According to the Gumbel frequency distribution for n=10, the corresponding reduced standard deviation (σ_n) and reduced mean (Y_n) were 0.9496 and 0.4952, respectively [7]. The design maximum daily rainfall for a 5-year return period [8]was estimated using the Gumbel extreme value distribution with a 90% confidence level. The calculation involves determining the design maximum daily rainfall (R_t) and the confidence range (R_k). The final design rainfall is then obtained by combining these two parameters, as expressed in the following equations.

$$R_t = \bar{R} + \left(\frac{\sigma_R}{\sigma_n}\right)(Y_t - Y_n) \tag{1}$$

Where:
R_t = design maximum daily rainfall
$\bar{R}$ = mean of annual maximum daily rainfall
σ_R = standard deviation of rainfall data
σ_n = Gumbel reduced standard deviation
Y_t = Gumbel reduced variate (for return period T = 5 years)
Y_n = Gumbel reduced mean

$$R_k = \pm\, t(a)(S_e) \tag{2}$$

Where:
R_k = confidence range
$t(a)$ = critical value corresponding to the selected confidence level
S_e = standard error of estimation

The Gumbel analysis at a 90% confidence level yielded a design maximum daily rainfall of 169.29 mm. This value was used as the design rainfall for the subsequent analyses and represents a relatively frequent rainfall event. The estimated 90% confidence-level design rainfall was used to calculate the rainfall intensity (***I***) using the Mononobe equation and the design discharge ($\boldsymbol{Q_p}$) using the Rational Method. The rainfall intensity was calculated as follows:

$$S = \frac{H}{0.9 \times L} \tag{3}$$

Where:
S = average slope of the flow path or main channel (m/m)
H = elevation difference between the farthest point of the drainage area and the outlet point (km)
L = length of the main channel or drainage path (km)

$$t_c = \left(\frac{0.87 \times L^2}{1000 \times S}\right)^{0.385} \tag{4}$$

Where:
t_c = rainfall duration or time of concentration (hours)

$$I = \frac{R_{24}}{24}\left(\frac{24}{t_c}\right)^{\frac{2}{3}} \tag{5}$$

Where:
I = rainfall intensity (mm/hour)
R_{24} = maximum 24-hour daily rainfall (mm)

Using an elevation difference (***H***) of 0.0008 km and a main channel length (***L***) of 0.24 km, the Kirpich equation yielded a time of concentration ($\boldsymbol{t_c}$) of 0.1908 h. Based on the design maximum daily rainfall of 169.29 mm, the Mononobe equation produced a rainfall intensity of 177.09 mm/h. This rainfall intensity was subsequently used to calculate the design runoff discharge using the Rational Method [4], as shown in the following equation.

$$Q = 0.278\ C\ I\ A \tag{6}$$

Where:
Q = design discharge (m^3/s)
C = runoff coefficient
I = rainfall intensity (mm/h)
A = drainage area (km^2)

Based on field observations, the drainage catchment area was estimated at 0.21 km^2. A runoff coefficient (C) of 0.75 was adopted to represent the predominantly residential land use [9]. Using the calculated rainfall intensity, the Rational Method produced a design discharge of 7.58 m^3/s, which was used to evaluate the capacity of the existing drainage channel.

3.2 Hydraulic Analysis

The hydraulic capacity of the existing drainage channel, illustrated in **Figure 2**, was evaluated using the continuity and Manning's equations [5] based on the measured channel geometry and hydraulic characteristics. The governing equations are presented below.

$$V = \frac{1}{n} R^{\frac{2}{3}} S^{\frac{1}{2}} \quad (7)$$

The discharge capacity was then calculated as :

$$Q = A\ V \quad (8)$$

Where:

Q = channel discharge (m³/s)
A = flow cross-sectional area (m²)
V = flow velocity (m/s)
n = Manning's roughness coefficient (dimensionless)
R = hydraulic radius (m), defined as the ratio of the flow area to the wetted perimeter (R=A/P)
S = channel bed slope (m/m or dimensionless)

The existing drainage channel has a hydraulic capacity of 2.79 m³/s, which is significantly lower than the design discharge of 7.58 m³/s. This indicates that the existing channel is *unable* to convey the design flow and therefore requires redesign. In accordance with urban drainage design standards, the proposed secondary drainage channel was designed for a 5-year return period.

The drainage channel was redesigned to accommodate the design discharge using the economic cross-section principle proposed by [7]. This method determines the channel dimensions based on a hydraulically efficient trapezoidal section, where the bottom width (b) is defined as $\frac{2}{3}h\sqrt{3}$. The proposed dimensions were calculated as a flow depth (h) of 1.50 m and a bottom width (b) of 1.80 m, providing sufficient hydraulic capacity while maintaining construction efficiency. The required freeboard was subsequently determined using the following equation.

$$w = \sqrt{0.5 \times h} \quad (9)$$

Where:

w = freeboard height (m)
h = design flow depth (m)

Based on SNI 03-3424-1994 [10], the minimum required freeboard for a design discharge of 7.58 m³/s is 0.60 m. The calculated freeboard of 0.87 m satisfies this requirement, confirming the adequacy of the proposed channel design. An illustration of the redesigned channel cross-section is presented in **Figure 4**.

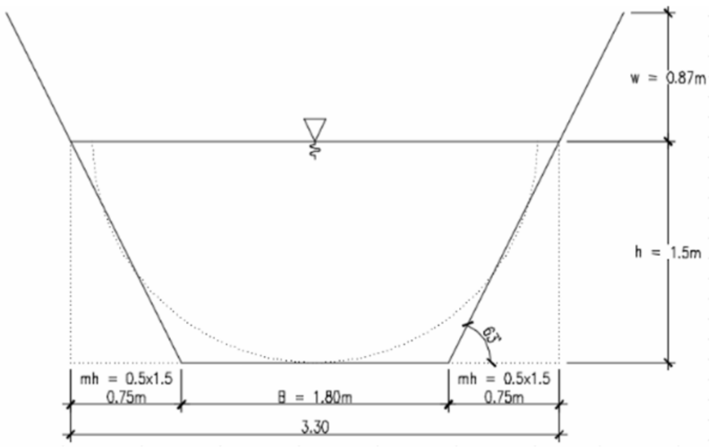


Figure 4. Redesigned drainage channel cross-section

4. Conclusion

This study evaluated the hydraulic performance of the existing drainage channel in Gunung Anyar Kidul, Surabaya, through integrated hydrological and hydraulic analyses. The results indicate that the existing channel capacity (2.79 m^3/s) is substantially lower than the estimated design discharge (7.58 m^3/s) for a 5-year return period, demonstrating that the existing drainage system is hydraulically inadequate. To address this limitation, the channel was *redesigned* using the economic trapezoidal cross-section method, resulting in a flow depth of 1.50 m and a bottom width of 1.80 m. The redesigned channel provides a hydraulic capacity of 7.83 m^3/s and complies with the minimum freeboard requirement specified in SNI 03-3424-1994, indicating its suitability for safely conveying the design flow. To maintain the long-term hydraulic performance and sustainability of the drainage system, periodic channel maintenance, including the removal of sediment, solid waste, and excessive vegetation, is recommended, particularly prior to the rainy season. These maintenance activities should be carried out under the responsibility of the relevant authority, such as the Public Works Department for Water Resources. In addition, future studies should evaluate the reconstruction cost of the redesigned drainage channel, estimate routine maintenance costs, and investigate alternative channel configurations, such as rectangular channels or box culverts, to optimize land use, particularly in densely populated residential areas such as Gunung Anyar Kidul. Although the proposed trapezoidal channel satisfies the required hydraulic capacity, the final channel configuration should be selected based on a comprehensive technical and economic feasibility assessment, as well as the availability of right-of-way along the roadway.

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