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Hydrological modelling for urban drainage capacity assessment in a rapidly urbanizing commercial corridor: A case study from Pontianak, Indonesia

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Abstract

Background: Rapid urbanization has increased impervious surfaces in commercial areas, leading to higher surface runoff and reducing the performance of existing urban drainage systems during intense rainfall events. As a result, many drainage networks are no longer capable of conveying design runoff, increasing the risk of urban inundation and disrupting transportation and commercial activities.
Aims: This study aimed to assess the hydraulic capacity of the existing drainage system along Prof. M. Yamin Road, Pontianak, Indonesia, and to develop an optimal drainage design based on hydrological modelling.
Methods: A quantitative approach was employed using field measurements and annual maximum rainfall data collected over a ten-year period (2015–2024). Design rainfall was estimated using the Gumbel frequency distribution, rainfall intensity was calculated using the Mononobe equation, and peak runoff was determined through the Rational Method. The hydraulic performance of the existing drainage channels was subsequently evaluated using Manning's equation by comparing the channel capacity with the estimated design discharge.
Results: The estimated design rainfall was 255.13 mm, generating a rainfall intensity of 138.75 mm h^{-1} and a peak runoff discharge of 1.169 m^3 s^{-1}. The drainage channel toward Sutan Syahrir exhibited a capacity of 2.85 m^3 s^{-1} and was hydraulically adequate, whereas the channel toward Kota Baru provided only 0.375 m^3 s^{-1}, indicating insufficient capacity to accommodate the design discharge.
Conclusion: The integration of hydrological modelling and hydraulic analysis provides a reliable framework for assessing urban drainage capacity and supports evidence-based planning for effective stormwater management in rapidly urbanizing commercial corridors.

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INTRODUCTION

Urbanization has become one of the most influential factors driving hydrological changes in urban environments across the world. The continuous conversion of natural landscapes into impervious surfaces, including roads, commercial complexes, parking facilities, and residential areas, has significantly altered the natural hydrological cycle (Alhasaani et al., 2025; Fletcher et al., 2024; Moazzem et al., 2024; Ongaga et al., 2024). This transformation reduces the capacity of the soil to absorb rainfall and increases the proportion of precipitation that becomes surface runoff. As a consequence, runoff volumes and peak discharges increase substantially during rainfall events, placing additional pressure on urban drainage infrastructure. Many drainage systems that were originally designed to accommodate previous land-use conditions are no longer capable of conveying

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the increasing runoff generated by urban expansion (Alhasaani et al., 2025; Bibi & Kara, 2023; Panos et al., 2021). This condition highlights the necessity of continuously adapting urban infrastructure to changing spatial development patterns in order to enhance environmental sustainability and urban resilience, particularly in rapidly growing urban settlements (Panggabean et al., 2025). buatThese deficiencies frequently result in recurrent urban flooding, temporary waterlogging, traffic congestion, and damage to public infrastructure. The consequences of urban flooding extend beyond physical damage by disrupting economic activities, affecting public health, and reducing environmental quality. Effective drainage systems therefore play a fundamental role in maintaining urban functionality by safely conveying stormwater and minimizing flood-related hazards. The growing frequency of intense rainfall events combined with accelerated urban development has further increased the importance of evaluating drainage system performance. Consequently, improving the understanding of existing drainage capacity has become an essential component of sustainable urban water management and long-term urban resilience.

Commercial corridors represent one of the most challenging urban environments for stormwater management because they concentrate transportation networks, business activities, and densely developed infrastructure within relatively limited areas. The predominance of impervious surfaces in these corridors substantially increases runoff generation while simultaneously reducing opportunities for infiltration and temporary water storage. Continuous urban development often modifies natural drainage pathways and places additional hydraulic demands on existing drainage systems. Under such conditions, even rainfall events with moderate intensity may generate localized flooding when drainage facilities operate beyond their design capacity. Flooding within commercial districts has far-reaching consequences because it disrupts transportation services, interrupts commercial operations, damages public assets, and reduces urban accessibility (Kasmalkar et al., 2020; Yin et al., 2021). These impacts demonstrate that maintaining adequate drainage performance is not only an engineering concern but also an important requirement for supporting sustainable economic activities. Periodic assessment of drainage capacity is therefore necessary to determine whether existing infrastructure remains compatible with evolving hydrological conditions. Hydrological modelling provides an effective analytical framework for estimating design rainfall, runoff generation, and the hydraulic performance of drainage networks under specified design scenarios (Al-Ghadi et al., 2020a; Essien et al., 2024; Gomes et al., 2023). The integration of hydrological and hydraulic analyses enables engineers to identify capacity deficiencies and develop technically appropriate improvement strategies for existing drainage systems. Accordingly, comprehensive drainage capacity assessment has become an indispensable approach for reducing flood risk and improving the sustainability of urban infrastructure.

Pontianak City, located in West Kalimantan, Indonesia, has experienced considerable urban expansion driven by increasing commercial activities, transportation development, and population growth. One of the city's most strategic transportation corridors is Prof. M. Yamin Road, which serves as an important connection between the urban center and surrounding districts while supporting regional economic activities. The corridor is characterized by intensive commercial land use, extensive paved surfaces, and high traffic density throughout the day. These characteristics contribute to a relatively high runoff coefficient because rainfall is rapidly converted into surface flow rather than infiltrating into the ground. Although drainage channels have been constructed along the corridor, temporary inundation continues to occur during periods of intense rainfall, indicating potential inadequacies in the existing drainage system. Such flooding events interrupt traffic circulation, reduce commercial productivity, and negatively influence the overall quality of the urban environment (Beitelmal et al., 2024; Li et al., 2023; Marengo et al., 2020). Ongoing urban development is expected to further increase stormwater runoff and intensify the hydraulic demands imposed on the drainage network. Under these circumstances, evaluating the capacity of the existing drainage infrastructure has become increasingly important for determining its ability to accommodate present-day runoff conditions. Reliable assessment of drainage performance also provides valuable information for identifying critical sections that require engineering improvements and infrastructure upgrading. Therefore, systematic evaluation of the existing drainage system is essential for supporting effective stormwater management and promoting sustainable urban development within rapidly urbanizing commercial corridors.

Recent studies have substantially advanced the understanding of urban drainage systems through investigations on drainage capacity assessment, flood modelling, sustainable urban drainage systems (SuDS), stormwater management, and climate change adaptation using advanced modelling approaches such as SWMM, HEC-HMS, remote sensing, artificial intelligence, and machine learning (Afrin et al., 2020; Sahu et al., 2023; Singh et al., 2023; Y. Wang et al., 2022). Other studies have emphasized sustainable drainage strategies, resilience enhancement, and integrated stormwater management to improve the performance of urban drainage systems under changing environmental conditions (Bertrand-Krajewski, 2021; Grigg, 2024; Guptha et al., 2022; Zhang et al., 2020). Despite these developments, relatively limited attention has been given to the hydraulic evaluation of existing conventional drainage systems in rapidly urbanizing commercial corridors, particularly in medium-sized tropical cities where drainage performance is strongly influenced by increasing impervious surfaces and urban expansion (Dharmarathne et al., 2024; Le et al., 2024; M. Wang et al., 2023). Furthermore, previous studies have predominantly focused on flood simulation, optimization frameworks, or sustainable drainage concepts, whereas comparatively few have integrated rainfall frequency analysis, runoff estimation, and hydraulic capacity evaluation using practical engineering methods to assess existing drainage performance and formulate technically feasible channel improvement strategies. Therefore, this study addresses this research gap by integrating hydrological modelling and hydraulic analysis to evaluate the capacity of an existing urban drainage system and to develop evidence-based recommendations for improving stormwater conveyance in a rapidly urbanizing commercial corridor in Pontianak, Indonesia.

This study aims to evaluate the hydraulic capacity of the existing drainage system along Prof. M. Yamin Road in Pontianak by applying an integrated hydrological modelling approach. The assessment combines rainfall frequency analysis, rainfall intensity estimation, runoff discharge calculation, and hydraulic capacity evaluation within a unified analytical framework. Annual maximum rainfall records are analyzed to determine the design rainfall associated with the selected return period. The resulting rainfall intensity is subsequently used to estimate peak runoff discharge generated within the drainage catchment. Hydraulic analysis is then performed to compare the conveyance capacity of the existing drainage channels with the estimated design discharge. The evaluation identifies sections of the drainage network that are potentially unable to accommodate present hydrological conditions. Based on the analytical results, appropriate drainage improvements are proposed to enhance hydraulic performance and reduce the likelihood of urban inundation. The study also examines the relationship between increasing urban development, runoff generation, and drainage system adequacy within a rapidly developing commercial corridor. The findings are expected to provide practical engineering recommendations for improving the effectiveness of urban drainage infrastructure under current development conditions. Ultimately, this research contributes to evidence-based stormwater management by providing a comprehensive assessment framework that supports sustainable urban infrastructure planning in Pontianak and other rapidly urbanizing cities with similar hydrological characteristics.

LITERATURE REVIEW

Urban drainage systems constitute one of the most fundamental components of urban infrastructure because they regulate the collection, conveyance, storage, and disposal of stormwater generated during rainfall events. Their primary objective is to maintain the hydraulic balance of urban environments by preventing excessive surface water accumulation that may lead to flooding, waterlogging, and deterioration of environmental quality (Wahid et al., 2026; Xu & Chen, 2022; Zhao et al., 2024). The effectiveness of a drainage system is closely associated with the hydrological characteristics of the contributing catchment, including land use, topography, soil conditions, and rainfall intensity (Liu et al., 2022; Rahayu et al., 2023). As cities continue to expand, natural landscapes are progressively transformed into impervious surfaces such as roads, commercial buildings, parking areas, and transportation facilities, substantially modifying the natural hydrological cycle (Alhasaani et al., 2025; Fletcher et al., 2024; Thien et al., 2026). These land-use changes reduce infiltration capacity while increasing runoff coefficients, causing larger runoff volumes and higher peak discharges during storm events. Consequently, existing drainage infrastructure frequently experiences hydraulic loading beyond its original design capacity, particularly in rapidly urbanizing commercial districts where impervious coverage is highly concentrated. Inadequate drainage performance not only increases the frequency of localized flooding but also affects transportation efficiency, commercial productivity, public safety, and environmental sustainability (Al-Ghadi et al., 2020b; Cea & Costabile, 2022; Kim et al., 2024). Urban drainage systems therefore perform multiple functions beyond stormwater conveyance by supporting socioeconomic activities, protecting public infrastructure, and maintaining environmental quality. Sustainable drainage management requires continuous evaluation of drainage performance to ensure that infrastructure remains compatible with evolving urban conditions and changing hydrological responses. Accordingly, understanding the interactions between urban development and drainage system performance provides an essential theoretical foundation for developing effective stormwater management strategies in rapidly growing cities.

Hydrological modelling has become one of the most widely adopted analytical approaches for evaluating urban drainage performance because it provides a quantitative representation of rainfall–runoff processes within a drainage catchment. The approach enables researchers and engineers to simulate the transformation of rainfall into surface runoff by considering rainfall characteristics, catchment geometry, land-use conditions, and hydrological parameters that influence runoff generation. Hydrological models are extensively applied to estimate design discharge, evaluate drainage adequacy, and support infrastructure planning under both existing and projected development scenarios. In urban environments, hydrological modelling commonly integrates several analytical components, including rainfall frequency analysis, rainfall intensity estimation, runoff calculation, and hydraulic evaluation of drainage channels (Cheng et al., 2020; Kumar et al., 2023; Natarajan & Radhakrishnan, 2020). The accuracy of each analytical component directly influences the reliability of the overall drainage assessment because uncertainties introduced during one stage may propagate throughout subsequent analyses. Appropriate hydrological modelling therefore requires careful selection of analytical methods that are consistent with the scale, characteristics, and objectives of the study area. Reliable runoff estimation enables engineers to evaluate whether existing drainage systems remain capable of accommodating stormwater generated under current land-use conditions. Furthermore, hydrological modelling facilitates the identification of critical drainage sections that require rehabilitation, upgrading, or redesign to improve hydraulic performance (Ghaffari et al., 2025; Mugume et al., 2024; Shrestha & Chini, 2025). The integration of hydrological analysis with engineering assessment also supports evidence-based decision-making by providing measurable indicators of drainage adequacy. Consequently, hydrological modelling has become an indispensable framework for evaluating urban drainage systems and developing sustainable stormwater management strategies in rapidly urbanizing regions.

Reliable estimation of design rainfall represents a critical stage in urban drainage analysis because hydraulic capacity calculations depend directly on the magnitude of rainfall adopted for engineering design. Design rainfall is generally determined through rainfall frequency analysis using historical precipitation records that represent long-term hydrological variability within a catchment (Banerjee et al., 2020; Williams & King, 2020). Statistical frequency analysis enables the estimation of rainfall associated with specified return periods that reflect the probability of extreme rainfall occurrence. Various probability distributions have been developed for hydrological applications, each possessing different assumptions regarding the statistical characteristics of rainfall data. The selection of an appropriate probability distribution should therefore consider data characteristics, sample size, and the intended engineering application. Return periods are selected according to the functional importance and acceptable risk level of the infrastructure under evaluation, with more critical facilities generally requiring larger design return periods. Following the estimation of design rainfall, rainfall intensity must be determined because runoff generation is strongly influenced by rainfall intensity rather than rainfall depth alone. Empirical rainfall intensity equations provide a practical means of relating rainfall duration to rainfall magnitude for engineering applications in urban drainage design. Accurate estimation of both design rainfall and rainfall intensity contributes substantially to reducing uncertainties in runoff prediction and hydraulic assessment. Therefore, rainfall frequency analysis constitutes an essential theoretical and analytical foundation for evaluating drainage capacity and developing reliable stormwater management strategies.

Peak runoff discharge represents one of the most important hydraulic variables in drainage engineering because it determines the flow that must be accommodated by drainage channels during design storm events. Runoff generation is influenced by rainfall intensity, drainage area, land-use characteristics, surface permeability, and the proportion of impervious cover within the catchment (Kang et al., 2025; Mustafa et al., 2025). Urban catchments generally produce greater runoff than natural catchments because impervious surfaces reduce infiltration while accelerating surface flow toward drainage networks. As urbanization progresses, increases in impervious coverage are commonly accompanied by higher runoff coefficients and larger peak discharges. Estimation of runoff discharge therefore provides the basis for evaluating whether existing drainage infrastructure possesses sufficient hydraulic capacity under current hydrological conditions. Hydraulic capacity assessment involves analyzing channel dimensions, hydraulic radius, flow velocity, roughness characteristics, and discharge capacity to determine the adequacy of stormwater conveyance systems (Dagnachew Adinew et al., 2024; Mohamed & Katambara, 2025). Comparisons between estimated runoff discharge and available channel capacity enable the identification of hydraulic deficiencies that may contribute to localized flooding. Such assessments also provide valuable engineering information for determining whether channel rehabilitation, enlargement, or redesign is required to improve drainage performance. The integration of runoff estimation with hydraulic analysis establishes a comprehensive framework for evaluating the operational effectiveness of existing drainage systems. Consequently, combined hydrological and hydraulic assessments have become a standard engineering approach for supporting urban drainage planning and infrastructure improvement.

Flood resilience has emerged as an increasingly important concept in urban water management because cities are becoming more vulnerable to hydrological disturbances associated with rapid urbanization, infrastructure expansion, and changing rainfall patterns. Rather than emphasizing flood prevention alone, flood resilience focuses on improving the capacity of urban systems to anticipate, withstand, adapt to, and recover from flood events while maintaining essential urban functions (Cea & Costabile, 2022; Mabrouk et al., 2024; L. Wang et al., 2022). Urban drainage infrastructure plays a central role in achieving flood resilience because its hydraulic performance directly influences the effectiveness of stormwater conveyance during extreme rainfall events. Continuous urban growth frequently alters hydrological responses and gradually reduces the effectiveness of drainage systems that were designed under previous development conditions. Consequently, periodic evaluation of drainage capacity has become an essential component of resilient infrastructure management and sustainable urban planning. Hydrological modelling contributes to flood resilience by providing quantitative information regarding runoff generation, drainage adequacy, and potential hydraulic failures under various rainfall scenarios (Lameche et al., 2026; Osheen et al., 2023; Snikitha et al., 2024). The analytical results generated through hydrological modelling enable infrastructure managers to identify vulnerable drainage sections and prioritize engineering interventions based on objective technical evidence. Integrating hydrological modelling with hydraulic capacity assessment also supports adaptive stormwater management by allowing infrastructure improvements to be aligned with evolving urban development patterns. This integrated perspective is particularly important in rapidly urbanizing commercial corridors where economic activities, transportation functions, and impervious surface expansion continuously increase hydraulic pressures on existing drainage networks. Therefore, comprehensive hydrological modelling combined with hydraulic capacity evaluation provides a robust scientific foundation for improving drainage performance, strengthening flood resilience, and supporting sustainable urban infrastructure development in rapidly growing cities.

METHOD

Research Design

This study employed a quantitative engineering research design using an integrated hydrological modelling approach to evaluate the hydraulic performance of an existing urban drainage system within a rapidly urbanizing commercial corridor. The research was designed to assess whether the existing drainage infrastructure along Prof. M. Yamin Road in Pontianak City possesses sufficient hydraulic capacity to accommodate runoff generated during design rainfall events. A case-study approach was adopted because the selected corridor represents a strategic urban area characterized by intensive commercial development, high transportation activity, and recurring waterlogging during heavy rainfall. The analytical framework integrated rainfall frequency analysis, rainfall intensity estimation, runoff discharge calculation, and hydraulic capacity evaluation into a unified engineering assessment. Hydrological modelling was selected because it provides a systematic and scientifically accepted method for representing rainfall–runoff processes and evaluating drainage system performance under specified design conditions. Hydraulic analysis complemented the hydrological assessment by determining whether the existing drainage channels were capable of safely conveying the estimated design discharge. The integration of hydrological and hydraulic analyses enabled comprehensive evaluation of drainage adequacy under current land-use conditions. Both field observations and historical hydrological records were incorporated to ensure that the assessment reflected actual physical and environmental characteristics within the study area. The analytical framework also facilitated the identification of drainage sections exhibiting hydraulic deficiencies and requiring engineering improvements. Therefore, the adopted research design provides a reliable basis for evaluating drainage capacity and supporting evidence-based stormwater management in rapidly urbanizing urban environments.

Study Time and Location

The research was conducted during 2025 along Prof. M. Yamin Road, located in Pontianak City, West Kalimantan Province, Indonesia. The study corridor functions as one of the city's principal arterial roads connecting Pontianak with surrounding districts while supporting commercial, governmental, and transportation activities. Owing to its strategic role within the urban transportation network, the corridor has experienced continuous commercial expansion and increasing infrastructure development. Land use within the study area is dominated by commercial buildings, office complexes, transportation facilities, residential properties, and extensive paved surfaces. These characteristics have substantially increased impervious surface coverage and consequently intensified stormwater runoff during rainfall events. The drainage system consists primarily of open concrete channels constructed on both sides of the roadway to collect and convey stormwater toward downstream drainage networks. Existing drainage channels exhibit varying geometric dimensions, channel slopes, and hydraulic characteristics that may influence their overall conveyance capacity. Temporary inundation has frequently been observed during periods of intense rainfall, indicating potential hydraulic inadequacies within the existing drainage network. The study location was selected because it represents a typical rapidly urbanizing commercial corridor where urban expansion has significantly altered natural hydrological processes. Consequently, the study area provides an appropriate case for evaluating the adequacy of existing drainage infrastructure under present urban development conditions.

Figure 1. Location of the study area along Prof. M. Yamin Road, Pontianak City, West Kalimantan, Indonesia.

Material and Instruments

This research utilized both primary and secondary datasets supported by standard engineering measuring instruments to facilitate hydrological and hydraulic analyses. Primary data consisted of field measurements describing the physical characteristics of the drainage system and surrounding catchment area. Measured variables included road width, drainage channel width, channel depth, channel length, channel slope, flow direction, and catchment dimensions. Field measurements were performed using measuring tapes, leveling equipment, water level gauges (*peilschaal*), handheld GPS devices, and digital cameras to ensure accurate documentation of existing site conditions. Visual observations were additionally conducted to identify sediment accumulation, vegetation growth, structural deterioration, channel obstructions, and other physical conditions potentially affecting hydraulic performance. Secondary data consisted of annual maximum daily rainfall records obtained from the Meteorological, Climatological, and Geophysical Agency (BMKG) covering the observation period from 2015 to 2024. Supporting technical information, including drainage system layouts, land-use maps, and relevant national drainage design standards, was obtained from local government agencies and engineering references. Hydrological and hydraulic calculations were subsequently performed using Microsoft Excel to organize datasets, conduct statistical analyses, and compute design rainfall, runoff discharge, and channel capacity. Engineering design standards and hydraulic equations served as analytical references throughout the computational process. The combination of reliable field measurements, historical hydrological records, and engineering calculation tools ensured that the analytical process accurately represented existing drainage conditions within the study area.

Figure 2. Field measurement activities and existing drainage channel conditions along the study corridor.

Data Collection

Data collection was conducted through a combination of field surveys and secondary data acquisition to obtain comprehensive hydrological and hydraulic information. Field surveys were carried out to document the geometric characteristics of the drainage channels and surrounding catchment using direct engineering measurements. During the survey, channel width, channel depth, channel length, road dimensions, channel slope, and drainage flow direction were measured systematically at representative locations throughout the study corridor. Physical observations were simultaneously performed to record channel conditions, sediment deposition, vegetation, structural damage, and potential hydraulic constraints affecting stormwater conveyance. Catchment characteristics, including land use and surface conditions, were also documented to support the determination of runoff coefficients used in hydrological calculations. Secondary hydrological data were collected from BMKG in the form of annual maximum daily rainfall records covering ten consecutive years from 2015 to 2024. The rainfall dataset was selected because annual maximum rainfall data are widely used for estimating design rainfall in urban drainage engineering. Additional technical documents, including drainage layouts and supporting planning information, were collected from relevant governmental institutions to complement field observations. All datasets were carefully verified, organized, and screened for completeness, consistency, and suitability before being incorporated into subsequent analyses. The integration of primary observations with long-term hydrological records provided a comprehensive database for evaluating both runoff generation and drainage system performance.

Figure 3. presents the recommended cross-sectional design of the drainage channel based on the hydraulic analysis conducted in this study. The proposed reinforced concrete channel has a width (B) of 1.40 m, a flow depth (H) of 0.557 m, and a freeboard (W) of 0.528 m to safely convey the design runoff discharge of 1.1691 m^3/s. A 10 cm sand bedding layer is provided beneath the channel to

improve structural stability and foundation support. Overall, the proposed dimensions satisfy the hydraulic design requirements and are expected to improve the drainage capacity along Prof. M. Yamin Road.

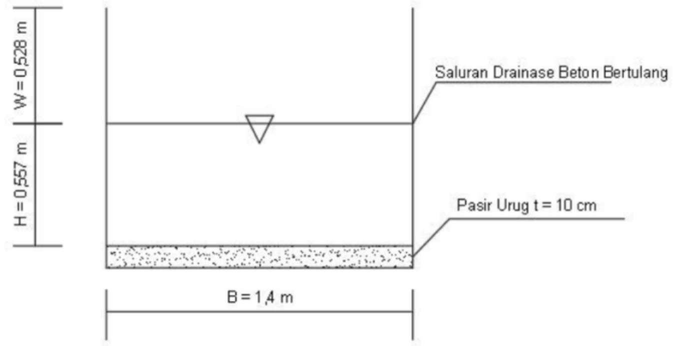

Figure 3. Cross-sectional geometry and measurement parameters of the existing drainage channel.

Data Analysis

The collected data were analyzed through sequential hydrological and hydraulic calculations to evaluate the adequacy of the existing drainage system. The analysis commenced with descriptive statistical evaluation of annual maximum rainfall records, including the calculation of the mean, standard deviation, coefficient of skewness, and coefficient of kurtosis to characterize rainfall variability. These statistical parameters were subsequently used to determine the suitability of probability distributions for estimating design rainfall. Based on statistical evaluation, the Gumbel distribution was selected to estimate design rainfall corresponding to a ten-year return period because it adequately represented the annual maximum rainfall characteristics within the study area. The estimated design rainfall was then converted into rainfall intensity using the Mononobe equation by incorporating the calculated time of concentration for the drainage catchment. Time of concentration was determined from both overland flow and channel flow travel times to represent the hydrological response of the watershed accurately. Peak runoff discharge was subsequently estimated using the Rational Method by integrating rainfall intensity, runoff coefficient, and drainage area. Hydraulic capacity of the existing drainage channels was calculated using Manning's equation by considering channel geometry, hydraulic radius, channel slope, roughness coefficient, flow velocity, and discharge capacity. Estimated runoff discharge was compared directly with calculated channel capacity to evaluate drainage adequacy and identify drainage sections susceptible to hydraulic failure during design storm events. Finally, engineering recommendations were developed by proposing revised channel dimensions capable of safely conveying the estimated design discharge while improving overall drainage system performance.

Research Procedure

The research procedure consisted of six sequential stages to ensure systematic implementation of hydrological and hydraulic analyses. The first stage involved identifying the study area, conducting preliminary observations, and reviewing relevant literature to establish the conceptual framework of the research. The second stage consisted of collecting primary field measurements describing the geometric characteristics of the drainage system together with secondary rainfall records obtained from BMKG. During the third stage, the collected datasets were verified, organized, and prepared for subsequent hydrological and hydraulic analyses. The fourth stage involved estimating design rainfall using the Gumbel probability distribution, followed by rainfall intensity calculation using the Mononobe equation and runoff estimation using the Rational

Method. The fifth stage consisted of hydraulic capacity assessment using Manning's equation by comparing the estimated design discharge with the conveyance capacity of each drainage channel section. Drainage segments exhibiting insufficient hydraulic capacity were identified as hydraulically inadequate and selected for engineering evaluation. Alternative channel dimensions were subsequently calculated to determine technically feasible improvements capable of accommodating projected runoff under the selected design rainfall conditions. The analytical results were interpreted to evaluate the influence of ongoing urbanization on drainage performance within the study corridor. Engineering recommendations were then formulated to improve stormwater conveyance and reduce flood susceptibility through appropriate drainage infrastructure enhancement. Finally, the overall findings were synthesized to provide an evidence-based framework supporting sustainable urban drainage planning and flood resilience in rapidly urbanizing commercial environments.

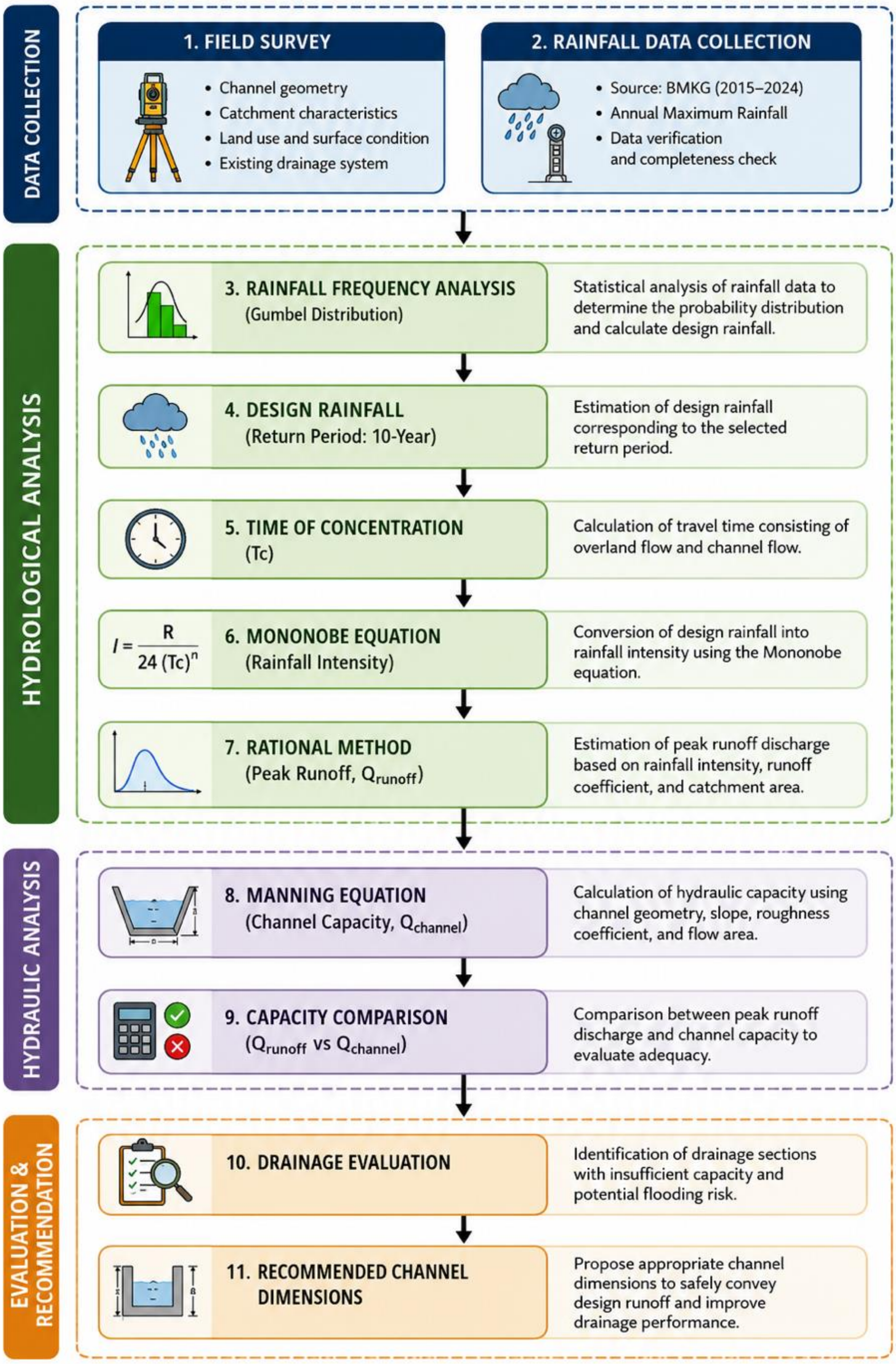

Figure 4. Research workflow for hydrological modelling and hydraulic capacity assessment.

RESULTS AND DISCUSSION

Results

Characteristics of the Study Area

The study was conducted along Prof. M. Yamin Road, one of the principal arterial roads in Pontianak City, West Kalimantan, Indonesia. The corridor functions as an important transportation route connecting Pontianak City with Kubu Raya Regency while simultaneously serving as one of the city's commercial and administrative centers. The surrounding area is dominated by commercial buildings, offices, and urban infrastructure, resulting in a high percentage of impervious surfaces that substantially reduce natural infiltration. Consequently, rainfall is rapidly converted into surface runoff, thereby increasing the hydraulic load imposed on the existing drainage network during storm events. Recurrent inundation observed along this corridor indicates that the drainage system requires a comprehensive hydraulic evaluation to determine whether its existing capacity remains adequate under current hydrological conditions.

A field investigation was conducted to obtain the geometric characteristics of the roadway and the existing drainage channels. Primary measurements included roadway dimensions, drainage channel geometry, and catchment characteristics. The surveyed road section extends approximately 2,500 m with a roadway width of 13 m. The shoulder width differs between both traffic directions, measuring 1.4 m toward Kota Baru and 2.9 m toward Sutan Syahrir. Meanwhile, the drainage channel dimensions also vary considerably between both sides of the roadway. The channel on the Kota Baru side has a width of 0.50 m and a depth of 0.50 m, whereas the channel toward Sutan Syahrir is considerably larger, measuring 1.91 m in width and 1.00 m in depth. These geometric variations indicate that the hydraulic capacity of the drainage system is not uniform throughout the study corridor.

Table 1. Physical characteristics of the study area

Parameter	Value
Road length	2,500 m
Road width	13.0 m
Shoulder width (Kota Baru)	1.4 m
Shoulder width (Sutan Syahrir)	2.9 m
Pavement type	Asphalt
Existing channel width (Kota Baru)	0.50 m
Existing channel depth (Kota Baru)	0.50 m
Existing channel width (Sutan Syahrir)	1.91 m
Existing channel depth (Sutan Syahrir)	1.00 m

The physical characteristics summarized in Table 1 provide the initial basis for subsequent hydrological and hydraulic analyses. Differences in channel dimensions are expected to influence the conveyance capacity of each drainage segment, particularly during high-intensity rainfall events.

Statistical Characteristics of Annual Maximum Rainfall

Hydrological evaluation was initiated by analyzing the annual maximum daily rainfall recorded at the BMKG Maritime Meteorological Station, Pontianak, over a ten-year observation period (2015–2024). Prior to estimating the design rainfall, the rainfall records were arranged in descending order and statistically evaluated to determine the principal descriptive parameters of the dataset. These statistical indicators were subsequently used to assess the suitability of several probability distributions commonly applied in hydrological frequency analysis. The statistical analysis included the computation of the arithmetic mean, standard deviation, skewness coefficient, and kurtosis coefficient, which collectively describe the variability and distributional characteristics of the rainfall data.

Table 2. Statistical characteristics of annual maximum rainfall using the Normal distribution

No	Year	Maximum Rainfall (mm)	$x - \bar{x}$	$(x - \bar{x})^2$	$(x - \bar{x})^3$	$(x - \bar{x})^4$
1	2022	256	103.4	10691.6	1105507.3	114309455.2
2	2021	200	47.4	2246.8	106496.4	5047930.5
3	2024	185	32.4	1049.8	34012.2	1101996.1
4	2023	175	22.4	501.8	11239.4	251763.1
5	2017	165	12.4	153.8	1906.6	23642.1
6	2020	154	1.4	2.0	2.7	3.8
7	2018	115	-37.6	1413.8	-53157.4	1998717.3
8	2019	112	-40.6	1648.4	-66923.4	2717090.7
9	2016	85	-67.6	4569.8	-308915.8	20882706.5
10	2015	79	-73.6	5417.0	-398688.3	29343455.6
	Total	**1526**		**27694.4**	**431479.9**	**175676761.0**
	Mean ($\bar{x}$)	**152.6**				
	Standard Deviation (Sx)			**55.4721151**		
	Skewness (Cs)				**0.351**	
	Kurtosis (Ck)					**3.681**

The statistical parameters presented in Table 2 indicate that the annual maximum rainfall exhibits considerable interannual variability. The average annual maximum rainfall reached 152.6 mm, with a standard deviation of 55.47 mm, indicating moderate dispersion around the mean. The calculated skewness coefficient (0.351) suggests a slightly positively skewed distribution, while the kurtosis coefficient (3.681) indicates a relatively peaked distribution compared with a perfectly normal dataset. Furthermore, the observed rainfall ranged from 79 mm to 256 mm, demonstrating substantial variability in annual rainfall extremes. These characteristics emphasize the necessity of selecting an appropriate probability distribution before estimating design rainfall for hydraulic design purposes.

Evaluation of Probability Distribution

To improve the reliability of the rainfall frequency analysis, the annual maximum rainfall dataset was further transformed into logarithmic values. The transformed dataset was subsequently analyzed to obtain the corresponding statistical descriptors. This procedure enables comparison between several probability distributions and facilitates identification of the most suitable statistical model for design rainfall estimation.

Table 3. Statistical characteristics of annual maximum rainfall using logarithmic transformation

No	Year	Max CH	Log X	$a = \log x - \log \bar{x}$	a^2	a^3	a^4
1	2022	256	2.408	0.252	0.063552	0.016021	0.004039
2	2021	200	2.301	0.145	0.020992	0.003041	0.000441
3	2024	185	2.267	0.111	0.012327	0.001369	0.000152
4	2023	175	2.243	0.087	0.007550	0.000656	0.000057
5	2017	165	2.217	0.061	0.003763	0.000231	0.000014
6	2020	154	2.188	0.031	0.000984	0.000031	0.000001
7	2018	115	2.061	-0.095	0.009110	-0.000870	0.000083
8	2019	112	2.049	-0.107	0.011433	-0.001223	0.000131
9	2016	85	1.929	-0.227	0.051405	-0.011655	0.002642

10	2015	79	1.898	-0.259	0.066831	-0.009675	0.004466
	Mean		**2.156**				
	Standard Deviation (Sx)			**0.16598**			
	Skewness (Cs)				**−0.294**		
	Kurtosis (Ck)						**3.144**

The logarithmic transformation reduced the variability of the rainfall observations, resulting in a standard deviation of 0.16598. Nevertheless, the transformed dataset remained slightly negatively skewed (Cs = −0.294) with a kurtosis coefficient of 3.144. Although the logarithmic transformation modified the statistical characteristics of the rainfall series, the resulting parameters did not fully satisfy the theoretical assumptions required for the Log-Normal distribution.

Selection of the Appropriate Probability Distribution

The statistical parameters obtained from both the original and logarithmically transformed datasets were subsequently compared with the acceptance criteria of four probability distributions commonly employed in hydrological frequency analysis. The comparison aimed to identify the probability model that most accurately represents the rainfall characteristics of the study area and provides reliable design rainfall estimates.

Table 4. Comparison of probability distributions

Distribution	Calculated Value	Acceptance Criterion	Decision
Normal	Cs = 0.351	Cs = 0	Not satisfied
	Ck = 3.681	Ck = 3	Not satisfied
Log-Normal	Cs = −0.294	Cs = 0	Not satisfied
	Ck = 3.144	Ck = 3	Not satisfied
Gumbel	**Cs = 0.351**	**Cs ≤ 1.139**	**Satisfied**
	Ck = 3.681	**Ck ≤ 5.402**	**Satisfied**
Log Pearson III	Cs = −0.294	Cs = 0–9	Not satisfied

The comparison summarized in Table 4 clearly demonstrates that the Normal and Log-Normal distributions do not satisfy the required statistical criteria because both the skewness and kurtosis coefficients deviate from their theoretical values. Similarly, the Log Pearson Type III distribution was not considered suitable for representing the rainfall characteristics of the study area. In contrast, the Gumbel distribution satisfied both statistical acceptance criteria and therefore provided the best representation of the annual maximum rainfall dataset. Consequently, the Gumbel distribution was adopted for estimating design rainfall and served as the basis for all subsequent hydrological and hydraulic analyses.

Recommended Hydraulic Design

The hydrological analysis was subsequently integrated with hydraulic calculations to determine the optimal dimensions of the drainage channel capable of conveying the design runoff discharge. The hydraulic design considered the peak runoff estimated using the Rational Method together with the channel geometry derived from Manning's equation.

Table 5. Summary of optimal drainage channel design

Parameter	Value
Design runoff discharge (Qr)	1.1691 m^3/s
Required flow area (A)	0.7794 m^2
Channel width (B)	1.40 m
Channel depth (H)	0.557 m
Freeboard (W)	0.528 m

The hydraulic design indicates that the optimal drainage channel should be capable of conveying a peak runoff discharge of 1.1691 m^3/s. Based on Manning's hydraulic analysis, the required cross-sectional flow area is 0.7794 m^2, corresponding to an optimal channel width of 1.40 m and a flow depth of 0.557 m. Additionally, a freeboard height of 0.528 m is recommended to provide an adequate safety margin during extreme rainfall events. These dimensions represent the proposed drainage configuration for improving the hydraulic performance of the existing drainage system along Prof. M. Yamin Road.

Discussion

The hydrological analysis demonstrated that the annual maximum rainfall observed in the study area exhibits considerable temporal variability, as reflected by the calculated mean rainfall of 152.6 mm, a standard deviation of 55.47 mm, a skewness coefficient of 0.351, and a kurtosis coefficient of 3.681. These statistical characteristics indicate that extreme rainfall events occur more frequently than would be expected under a perfectly normal distribution, thereby increasing uncertainty in urban drainage design. Such variability is typical of humid tropical regions, where convective rainfall often generates localized storms with relatively high intensities over short durations. Consequently, drainage systems designed solely on the basis of average rainfall conditions are unlikely to provide adequate hydraulic performance during extreme precipitation events. The statistical evaluation therefore provides an essential foundation for estimating representative design rainfall and minimizing the risk of underdesign. Similar rainfall variability has also been reported in studies conducted in urban areas of Indonesia, where annual maximum rainfall datasets exhibited noticeable deviations from normality because of the occurrence of extreme rainfall events (Mubarrok & Jang, 2022; Ramadhan et al., 2024; Siswanto et al., 2022). The similarity between the present study and previous investigations suggests that rainfall variability has become a common characteristic of rapidly urbanizing tropical cities. Nevertheless, the magnitude of rainfall variation identified along Prof. M. Yamin Road reflects local hydrometeorological conditions and should therefore be considered independently when designing drainage infrastructure. These findings reinforce the importance of employing statistical frequency analysis rather than relying solely on historical averages when evaluating urban drainage performance. Overall, the statistical characteristics identified in this study demonstrate that rainfall variability constitutes a fundamental consideration in the planning and evaluation of urban drainage infrastructure, particularly within rapidly developing tropical cities.

The selection of the Gumbel probability distribution constitutes one of the principal outcomes of this study because only this distribution satisfied both the skewness and kurtosis acceptance criteria. The Normal and Log-Normal distributions failed to satisfy the theoretical statistical assumptions, while the Log Pearson Type III distribution was also considered unsuitable for the available rainfall dataset. The suitability of the Gumbel distribution indicates that the observed rainfall characteristics are more appropriately represented by an extreme-value probability model than by distributions assuming symmetrical rainfall behavior. This finding is consistent with the engineering objective of estimating design rainfall associated with relatively infrequent but hydraulically significant storm events (Balacumaresan et al., 2025; Butcher et al., 2021). Comparable conclusions have been reported in several recent drainage studies conducted in Indonesia, where the Gumbel distribution provided reliable estimates of design rainfall before rainfall intensity was calculated using the Mononobe equation and runoff discharge was estimated using the Rational Method. The agreement between the present investigation and previous studies demonstrates that the Gumbel distribution remains an appropriate analytical approach for urban drainage assessment in tropical environments with limited long-term rainfall records (Lu & Qin, 2019; Mahato et al., 2026; Molino et al., 2026). Although some watershed-scale investigations have reported that Log Pearson Type III performs better under different hydrological settings, those studies generally involved larger river basins rather than relatively small urban catchments. Therefore, the statistical selection obtained in this study should be interpreted within the context of the drainage scale, land-use characteristics, and available rainfall observations. The consistency of the Gumbel distribution with the observed rainfall statistics also enhances confidence in the subsequent hydraulic analyses. Accordingly, the successful application of the Gumbel distribution in this research strengthens its relevance as a reliable statistical approach for estimating design rainfall in urban drainage studies undertaken in comparable tropical environments.

The hydraulic design adopted in this research integrates the Gumbel distribution, the Mononobe equation, the Rational Method, and Manning's equation into a sequential analytical framework for evaluating drainage performance. This methodological integration provides a practical engineering approach for assessing whether the existing drainage network can safely convey runoff generated during the selected design storm. Based on the analysis, the estimated design runoff reached 1.1691 m^3/s, requiring a minimum flow area of 0.7794 m^2 and an optimized rectangular channel with a width of 1.40 m, a water depth of 0.557 m, and a freeboard of 0.528 m. These dimensions indicate that the existing drainage configuration should be improved to achieve sufficient hydraulic capacity under design rainfall conditions. Similar conclusions have been reported in recent studies evaluating drainage performance in Denpasar, Lampung, Medan, and Jakarta, where the combination of rainfall frequency analysis, the Rational Method, and Manning's equation consistently identified hydraulically inadequate channels that required geometric redimensioning. Although the recommended dimensions differ among studies because of differences in catchment size, land use, rainfall intensity, and channel slope, the engineering principle remains the same: channel capacity must exceed the estimated peak runoff with an adequate safety margin. The close agreement between the present findings and previous investigations suggests that the adopted analytical framework is robust for evaluating urban drainage systems in rapidly developing cities (Osheen et al., 2023; Yang & Zhang, 2021). Consequently, the proposed channel dimensions represent a technically justified solution derived from both hydrological demand and hydraulic capacity considerations rather than from empirical assumptions alone. The hydraulic design produced in this study therefore provides practical guidance for infrastructure improvement while simultaneously confirming the applicability of conventional hydrological and hydraulic methods in supporting evidence-based urban drainage planning. This outcome demonstrates that engineering decisions supported by systematic hydrological analyses are more reliable than decisions based solely on empirical observations.

An important implication of the present findings concerns the relationship between rapid urbanization and increasing surface runoff. Prof. M. Yamin Road functions as one of the principal commercial corridors in Pontianak, where extensive asphalt pavement and dense building development substantially reduce infiltration opportunities. Such land-use characteristics increase runoff coefficients and shorten the time of concentration, resulting in higher peak discharges that place greater hydraulic stress on existing drainage infrastructure. Similar relationships between urban expansion, increasing impervious surfaces, and declining drainage performance have been documented in several contemporary urban drainage investigations. Furthermore, previous studies have demonstrated that inadequate drainage performance is not solely attributable to insufficient channel dimensions but may also be aggravated by sediment accumulation, solid waste deposition, structural deterioration, and inadequate maintenance practices (Alaneme et al., 2021). Although the present study primarily evaluates hydraulic capacity, these operational factors should also be considered during future drainage management because they may significantly reduce the effective conveyance capacity of drainage channels. Consequently, structural improvement alone may not completely eliminate localized flooding if routine maintenance is neglected. An integrated drainage management strategy combining hydraulic redesign, periodic maintenance, sediment removal, and land-use control is therefore likely to provide greater long-term effectiveness than infrastructure enlargement alone. Such an integrated perspective is increasingly recommended in contemporary urban drainage management to improve resilience against future hydrological extremes. Therefore, sustainable urban drainage management should integrate structural improvements with non-structural measures to ensure that drainage infrastructure remains effective under continuing urban development and changing climatic conditions.

The present study contributes to the growing body of knowledge on urban drainage evaluation by providing a site-specific hydraulic assessment for one of the most important commercial corridors in Pontianak City using a conventional yet well-established hydrological design framework. Unlike studies that rely exclusively on hydraulic simulation software, the analytical approach employed here remains relatively straightforward while producing engineering parameters directly applicable to drainage redesign and construction planning. Nevertheless, several limitations should be acknowledged. The rainfall analysis was based on a ten-year observation period, which satisfies many practical engineering applications but remains shorter than the datasets commonly recommended for long-term hydrological frequency analysis. Future investigations could improve design reliability by incorporating longer rainfall records, climate change projections, or physically based hydraulic models such as EPA SWMM for dynamic flow simulation. The integration of hydraulic modelling with real-time monitoring and high-resolution rainfall observations would also improve the understanding of drainage performance during extreme rainfall events. Despite these limitations, the findings provide a scientifically defensible basis for redesigning the drainage system along Prof. M. Yamin Road and offer a methodological reference for similar urban drainage evaluations in rapidly urbanizing tropical cities. The combination of rainfall frequency analysis, runoff estimation, and hydraulic capacity assessment presented in this study therefore has practical value for engineers, planners, and local governments seeking to improve urban flood resilience through evidence-based drainage infrastructure planning. The methodological framework developed in this research may also be adapted for evaluating drainage performance in other urban corridors exhibiting comparable hydrological and land-use characteristics. Future studies incorporating longer climatic records, advanced hydraulic simulations, and climate change scenarios are expected to further improve the robustness and applicability of urban drainage design recommendations.

Implications

The findings of this study have important practical and scientific implications for the planning and management of urban drainage systems in rapidly developing tropical cities. From a practical perspective, the identification of the Gumbel distribution as the most appropriate probability model and the determination of an optimal drainage channel geometry provide a technically sound basis for redesigning the existing drainage infrastructure along Prof. M. Yamin Road. The recommended channel dimensions can serve as an engineering reference for local authorities in prioritizing drainage rehabilitation projects aimed at reducing flood occurrence and improving stormwater conveyance capacity during extreme rainfall events. The results also demonstrate that the integration of rainfall frequency analysis, rainfall intensity estimation, runoff calculation using the Rational Method, and hydraulic evaluation based on Manning's equation constitutes a reliable framework for assessing drainage performance under existing urban conditions. Consequently, this analytical framework can be readily replicated in other urban corridors with comparable climatic conditions, catchment characteristics, and drainage configurations. The study further highlights that hydraulic inadequacy is closely associated with increasing urbanization and the expansion of impervious surfaces, indicating that drainage infrastructure planning should be continuously updated to accommodate future land-use changes rather than relying solely on historical design assumptions. These findings emphasize the necessity of integrating hydrological assessment into urban spatial planning to ensure that infrastructure development remains consistent with projected runoff characteristics. Beyond structural improvements, the study also suggests that sustainable drainage management should incorporate routine maintenance, sediment removal, and effective solid waste management to preserve the hydraulic capacity of drainage channels throughout their service life. From a scientific perspective, the research contributes empirical evidence supporting the continued applicability of conventional hydrological and hydraulic approaches for evaluating urban drainage performance in data-limited environments, particularly within developing regions. The proposed methodological framework provides a practical reference for future studies seeking to evaluate drainage capacity using readily available rainfall records and field-based geometric measurements without requiring complex numerical simulations. Furthermore, the outcomes of this research establish a baseline for subsequent investigations integrating climate change projections, high-resolution hydrological modelling, or smart urban drainage monitoring systems to enhance the resilience of drainage infrastructure against increasingly frequent extreme precipitation events. Overall, the study provides valuable insights for engineers, urban planners, and policymakers by demonstrating that evidence-based hydrological and hydraulic analyses are fundamental to developing resilient, efficient, and sustainable urban drainage systems capable of supporting long-term urban development.

Limitations and Suggestions for Future Research

This study has several limitations that should be acknowledged when interpreting the findings and considering their broader applicability. First, the hydrological analysis was conducted using annual maximum rainfall records covering a ten-year observation period, which provides a practical basis for engineering design but may not fully capture long-term climatic variability and the occurrence of rare extreme rainfall events. Second, the analysis relied on rainfall observations obtained from a single meteorological station, assuming that the recorded rainfall adequately represents the spatial distribution of precipitation across the entire study area, despite the potential influence of localized convective storms that frequently occur in tropical regions. Third, runoff estimation was performed using the Rational Method, which is widely accepted for relatively small urban catchments but does not explicitly account for temporal variations in rainfall intensity, flow routing processes, or dynamic storage effects within the drainage network. In addition, the hydraulic evaluation focused primarily on channel capacity derived from geometric characteristics and Manning's equation without explicitly incorporating operational factors such as sediment accumulation, vegetation growth, inlet blockage, or solid waste deposition that may significantly reduce the effective conveyance capacity of urban drainage systems under actual field conditions. The present investigation also evaluated the drainage system under existing land-use conditions and therefore did not consider future urban expansion or projected changes in impervious surface coverage that could substantially increase runoff generation over time. Likewise, the potential impacts of climate change on rainfall intensity, rainfall frequency, and extreme storm events were beyond the scope of the present analysis, although these factors are expected to influence the long-term performance of urban drainage infrastructure. Future research should therefore incorporate longer rainfall records obtained from multiple meteorological stations to improve the statistical reliability of rainfall frequency analysis and better represent the spatial variability of precipitation. Subsequent studies are also encouraged to integrate physically based hydrological and hydraulic simulation models, such as EPA SWMM or HEC-RAS, to evaluate flow dynamics, drainage network interactions, and flood propagation under a wider range of rainfall scenarios. Furthermore, incorporating geospatial analysis, high-resolution digital elevation models, and remote sensing data would improve the representation of catchment characteristics and facilitate more comprehensive assessments of urban runoff processes. Future investigations should additionally examine the influence of changing land use, urban growth, and climate change scenarios on drainage system performance to support adaptive infrastructure planning for rapidly developing cities. By addressing these limitations, subsequent studies are expected to generate more comprehensive scientific evidence and strengthen the development of resilient, sustainable, and climate-responsive urban drainage management strategies that can be effectively implemented in Pontianak and other tropical urban environments with similar hydrological characteristics.

CONCLUSION

This study successfully evaluated the hydraulic performance of the existing drainage system along Prof. M. Yamin Road in Pontianak City through the integration of hydrological frequency analysis and hydraulic capacity assessment. Statistical analysis of annual maximum rainfall demonstrated that the rainfall characteristics were most appropriately represented by the Gumbel probability distribution, which satisfied the required statistical criteria and therefore provided a reliable basis for estimating design rainfall. The resulting design rainfall was subsequently employed to determine rainfall intensity, estimate peak runoff discharge using the Rational Method, and evaluate the hydraulic capacity of the existing drainage channels using Manning's equation. The analysis revealed that the estimated peak runoff discharge reached 1.1691 m^3/s, indicating that several sections of the existing drainage system require hydraulic improvement to safely convey stormwater during design rainfall events. Hydraulic calculations further indicated that the recommended channel dimensions consist of a channel width of 1.40 m, a flow depth of 0.557 m, a required flow area of 0.7794 m^2, and a freeboard of 0.528 m, providing sufficient capacity to accommodate the projected runoff under the selected design conditions. These findings demonstrate that the application of a systematic hydrological and hydraulic evaluation framework provides a scientifically robust basis for identifying deficiencies in existing drainage infrastructure and developing technically justified improvement strategies. The study also confirms that conventional engineering approaches combining rainfall frequency analysis, the Mononobe equation, the Rational Method, and Manning's equation remain effective for evaluating urban drainage performance in relatively small tropical catchments with limited hydrological data. Furthermore, the results emphasize that continuous urban development and the expansion of impervious surfaces substantially increase runoff generation, thereby necessitating periodic reassessment of drainage capacity to maintain adequate levels of flood protection. Consequently, drainage planning should not rely solely on historical infrastructure conditions but should incorporate updated hydrological analyses that reflect evolving rainfall characteristics and urban growth patterns. Beyond supporting the redesign of the drainage system along Prof. M. Yamin Road, the methodological framework developed in this study provides a practical reference for evaluating urban drainage systems in other rapidly urbanizing areas with comparable climatic and land-use conditions. The outcomes of this research therefore contribute both to the scientific understanding of urban drainage assessment and to the practical implementation of evidence-based stormwater management strategies that enhance the resilience, efficiency, and sustainability of urban drainage infrastructure. Finally, the integration of statistically reliable hydrological analysis with hydraulic design evaluation demonstrates that data-driven engineering decision-making is essential for reducing urban flood risk and supporting sustainable infrastructure development in tropical cities experiencing rapid urban expansion.

AUTHOR CONTRIBUTIONS STATEMENT

Ikhwan Arif Purnama contributed to Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Visualization, and Writing original draft. Imanuel Kemenangenta Perangin Angin contributed to Conceptualization, Methodology, Validation, Supervision, Writing review and editing, and Project administration. Randy Setiawan contributed to Validation, Resources, Formal analysis, Visualization, and Writing review and editing. All authors have read and agreed to the published version of the manuscript.

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