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Research Article

Development of Early Warning Systems and Structural-Non-Structural Strategies for Flood Management in Urban Industrial Area.

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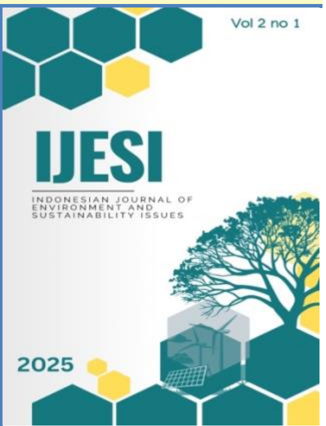
Abstract

This study aims to develop a holistic flood mitigation framework for the Jababeka Industrial Estate, a region increasingly affected by flooding due to accelerated land-use changes, diminished infiltration capacity, and insufficient drainage systems. The research integrates both structural and non-structural components, including the conceptualization of a real-time early warning system tailored for industrial urban environments. The methodology involved a detailed hydrological evaluation based on a decade of rainfall records collected from three meteorological stations. These data underwent consistency assessments using RAPS, trend analysis, and outlier detection, followed by the calculation of regional average rainfall through the Thiessen polygon method. Statistical distributions were applied to generate design rainfall values for return periods of 2 to 100 years, and flood discharges were estimated using four synthetic unit hydrograph (SUH) models: Snyder, Nakayasu, GAMA I, and ITB. Simulation of flood scenarios was conducted with the HEC-HMS platform, and field assessments were used to identify critical infrastructure deficiencies. The analysis revealed high-risk areas requiring structural upgrades such as river channel improvements, the addition of retention basins, and enhanced pumping systems. Additionally, the study proposes a sensor-integrated early warning mechanism capable of transmitting automatic alerts to stakeholders. The integrated strategy demonstrated here offers a scalable and transferable model for climate-resilient flood management, particularly relevant for rapidly urbanizing industrial zones facing intensifying hydrometeorological threats due to climate change and unregulated development.

Keywoards: *Integrated Flood, Urban Industrial, Hydrological, Early Warning System, Infrastructure*



INTRODUCTION

Flooding is a recurring and increasingly severe problem in many urban areas, particularly in regions undergoing rapid industrialization and land-use change [1], [2]. In Southeast Asia, and notably in Indonesia, industrial zones such as the Jababeka Industrial Estate have been facing heightened flood risks due to accelerated development that disrupts the natural hydrological cycle [3]. The expansion of impervious surfaces, reduction in natural infiltration zones, and the absence of sufficient green infrastructure contribute significantly to increased surface runoff [4], [5], [6], [7] . These factors are often compounded by outdated or undersized drainage systems, making urban industrial areas highly vulnerable to flash floods during extreme rainfall events [8], [9]. In such environments, even moderate rainfall can lead to localized inundation, disrupt transportation and logistics networks, and damage critical infrastructure. Improving the physical resilience of industrial road networks is therefore essential to minimize operational downtime during flooding events. One promising approach involves the use of modified asphalt mixtures with enhanced viscoelastic behavior, as demonstrated by Karami et al. (2020), who developed a resilient modulus master curve for Buton Rock Asphalt (BRA)-modified asphalt mixtures [10], [11] [12]. The risk is further amplified by climate change, which has led to shifts in rainfall intensity, frequency, and distribution [13], [14], [15], [16], [17]. This creates a complex challenge for planners and engineers who must now anticipate not only current risks but also future hydrometeorological scenarios [18]. As a result, urban flood management in industrial areas has become a multidisciplinary concern, requiring inputs from hydrology, spatial planning, infrastructure engineering, and disaster risk reduction [19], [20], [21]. Therefore, there is a critical need to conduct site-specific flood modeling and develop an integrated flood risk strategy for industrial urban zones like Jababeka, where economic assets and infrastructure are highly concentrated and vulnerable.

To address these challenges, hydrological modeling has become an essential tool in flood risk assessment, helping decision-makers understand runoff dynamics and evaluate potential mitigation strategies [22]. Accurate hydrological models rely heavily on high-quality rainfall data and the ability to represent the physical characteristics of the watershed [23], [24]. In this context, the use of consistent and statistically validated rainfall data is crucial. Techniques such as the Rescaled Adjusted Partial Sums (RAPS) method, trend analysis, and stationarity testing are commonly employed to assess the reliability of historical rainfall records. In the case of the Jababeka catchment, rainfall data from three observation stations—Cilemah, Cikarang, and Cibogo—were analyzed and determined to be statistically reliable. These data were used to derive regional rainfall using the Thiessen polygon method, providing a robust design input of 178.93 mm. Subsequently, rainfall frequency analysis was conducted to determine design storms for return periods of 2, 5, 10, 25, 50, and 100 years. These inputs formed the basis for flood discharge estimation, a critical step in identifying infrastructure needs and prioritizing flood-prone areas.

To simulate flood behavior and runoff distribution, hydrological models require discharge estimates, typically derived from methods such as the Synthetic Unit Hydrograph (SUH). In this study, four SUH methods—Snyder, Nakayasu, GAMA I, and ITB—were employed to estimate peak discharge for various design storms. The results revealed that GAMA I consistently produced the highest discharge values, reflecting a more conservative modeling approach suited for high-risk environments. These discharge values were then input into the HEC-HMS (Hydrologic Engineering Center – Hydrologic Modeling System) software to simulate hydrographs and analyze flood propagation throughout the watershed [25], [26], [27]. Simulations highlighted several critical zones within the Jababeka area characterized by high imperviousness and insufficient drainage capacity. This modeling approach allows for the spatial identification of flood-prone zones, which is essential for effective infrastructure planning and prioritization. Moreover, flood modeling outputs serve as key references for designing both structural measures—such as river channel normalization and retention ponds—and non-structural strategies like early warning systems. Accordingly, this study is expected to provide practical insights that support data-driven flood management decisions and enhance disaster preparedness in complex industrial environments.

Although numerous studies have explored flood risk assessment from various perspectives ranging from uncertainty quantification [28], [29], climate-related impacts [30], and local-scale GIS-based. There remains a notable gap in integrated modeling approaches specifically tailored to industrial urban watersheds. Recent efforts have advanced discussions on resilience and urban governance, yet most studies do not incorporate real-time hydrological simulation tools such as HEC-HMS in conjunction with Synthetic Unit Hydrograph (SUH) methods, nor do they address the complexity of combining structural and non-structural flood mitigation strategies. Moreover, while national-scale frameworks have been proposed. These models often lack spatial resolution and contextual relevance for densely developed industrial zones. As such, there is a clear need for research that integrates multi-method hydrological modeling, real-time monitoring, and adaptive flood planning especially within the context of high-risk, infrastructure intensive areas like the Jababeka Industrial Estate.

This study aims to develop an integrated flood risk management strategy for the Jababeka Industrial Area by analyzing and validating peak discharge using multiple SUH models and HEC-HMS simulations. Additionally, it proposes a set of structural and non-structural mitigation strategies, including the conceptual design of a real-time early warning system (EWS), to support adaptive and sustainable flood control in complex urban-industrial environments.

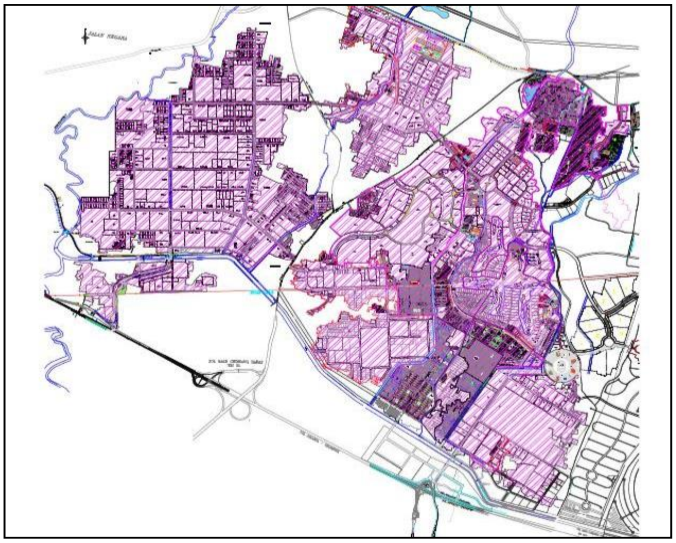
METHODS

Research Design

This research adopts a descriptive-quantitative framework to assess flood hazards within an industrial urban watershed using hydrological modeling tools. The study integrates long-term rainfall data analysis, peak discharge estimation through various synthetic unit hydrograph (SUH) methods, and flood simulation using HEC-HMS. The methodological approach also includes comparative evaluation with previously published flood control plans to verify model outputs and inform practical mitigation strategies. Furthermore, the results support the formulation of both physical infrastructure recommendations and non-structural flood management strategies, including early warning systems.

Time and Location of the Study

The research was conducted from June to November 2024, focusing on the Jababeka Industrial Estate located in West Java, Indonesia. This area was selected due to its high degree of urbanization, frequent flooding incidents, and the presence of critical economic infrastructure. The study site falls within the Cilemah Abang and Bekasi Lama watershed systems, both of which are prone to heavy runoff during peak rainfall. Meteorological data were gathered from three local rainfall monitoring stations: Cilemah, Cikarang, and Cibogo.



Picture 1. Research Location

Data Collection Methods

Rainfall data spanning a decade were obtained from three primary observation points. Prior to analysis, the datasets were subjected to multiple quality control procedures, including the Rescaled Adjusted Partial Sums (RAPS) for internal consistency, as well as statistical tests for trend detection, stationarity, and outlier identification. Additional spatial information—such as elevation, land use, and hydrological boundaries—was extracted from regional maps and planning documents. Historical flood management studies (2017 and 2020) were also reviewed to compare design discharges. Field reconnaissance was conducted to verify high-risk zones and assess the condition of drainage infrastructure.

Data Analysis Methods

Rainfall datasets were first evaluated for quality and consistency using the Rescaled Adjusted Partial Sums (RAPS) method. Additional statistical tests were applied to identify trends, test for stationarity, and detect outliers. The regional average rainfall was estimated through the Thiessen polygon method, which allocates spatial weight to each station based on its coverage within the watershed. Design rainfall values were calculated for return periods of 2, 5, 10, 25, 50, and 100 years using several probability distributions—Gumbel, Normal, Log-Normal, and Log-Pearson Type III. The best-fitting distribution was selected using Chi-Square and Kolmogorov–Smirnov tests.

Flood discharges were then estimated using four Synthetic Unit Hydrograph (SUH) models: Snyder, GAMA I, Nakayasu, and ITB. Peak discharge values obtained from these models were used as input in the HEC-HMS (Hydrologic Engineering Center – Hydrologic Modeling System) to simulate hydrographs and assess the spatial distribution of runoff. Calibration was carried out by comparing simulation outputs with historical discharge data. Based on the simulation results, structural mitigation strategies were formulated—including river normalization, construction of retention ponds, enhancement of pumping systems, and upgrading of existing weirs. In parallel, a non-structural framework was developed through the design of a real-time, technology-supported early warning system (EWS). The system concept integrates real-time rainfall and water level sensors, automated alert mechanisms, and institutional coordination protocols. The EWS was designed to improve the speed, reliability, and accessibility of flood warnings, with the ultimate goal of enhancing resilience in flood-vulnerable industrial zones and supporting long-term climate adaptation strategies.

RESULT AND DISCUSSIONS

Rainfall Data Quality and Consistency

A thorough evaluation of rainfall data quality was carried out prior to hydrological modeling to ensure data reliability. Rainfall records from three stations—Cilemah, Cikarang, and Cibogo—spanning a period of ten years were subjected to multiple statistical tests. These included the Rescaled Adjusted Partial Sums (RAPS) method for consistency, as well as homogeneity tests (absence of trend and stationarity), persistence testing, and outlier analysis. The results confirmed that all three stations produced consistent and statistically acceptable data, which were deemed suitable for use in rainfall–runoff modeling. A summary of these results is presented in Table 1.

Table 1. Summary of Rainfall Data tests at Observation Stations

No	**Rainfall Station**	**Test**				
		Consistency Test	**Homogeneity Test**		**Persistence Test**	**Outlier**
		RAPS	**Trend**	**Stasioner**		
1	STA Cilemah	Consistent Data	Ho accepted No Trend	Ho accepted Stationary/homogeneous variance	Ho diterima Random behavior	Within acceptable threshold
2	STA Cikarang	Consistent Data	Ho accepted No Trend	Ho accepted Stationary/homogeneous variance	Ho diterima Random behavior	Within acceptable threshold
3	STA Cibogo	Consistent Data	Ho accepted Ho accepted No Trend	Ho accepted Stationary/homogeneous variance	Ho diterima Random behavior	Within acceptable threshold

The hydrological analysis conducted in this study produced a detailed understanding of flood risks within the Jababeka Industrial Area. Ten years of rainfall data from three observation stations were validated using statistical tools including the Rescaled Adjusted Partial Sums (RAPS) method, trend and stationarity analysis, and outlier detection. These tests confirmed the quality and reliability of the rainfall dataset for hydrological modeling. Regional average rainfall was determined through the Thiessen polygon method, resulting in a design rainfall input of 178.93 mm.

Design Rainfall and Peak Discharge Estimation

Design rainfall values for return periods of 2, 5, 10, 25, 50, and 100 years were estimated using multiple probability distributions, with Log-Pearson Type III providing the best fit. The peak discharges for each return period were calculated using four Synthetic Unit Hydrograph (SUH) methods: Snyder, Nakayasu, GAMA I, and ITB.

Table 2. Comparison of Peak Discharge Estimates (Qp) from SUH Methods in Jababeka Watershed

Return Period (years)	Snyder (m3/s)	Nakayasu (m3/s)	GAMA I (m3/s)	ITB (m3/s)
2	71,82	82,21	94,39	87,64
5	103,38	118,83	136,46	125,83
10	126,65	145,66	167,39	154,34
25	152,76	175,79	202,11	186,27
50	171,15	197,01	226,48	208,90
100	186,07	213,93	247,51	228,32

To estimate flood discharge for various design return periods, four Synthetic Unit Hydrograph (SUH) methods were applied: Snyder, Nakayasu, GAMA I, and ITB. The calculated peak discharges (Qp) for each method and return period are presented in Table 1. Among all methods, GAMA I consistently produced the highest discharge estimates, indicating its conservative approach in flood prediction. For example, at a 100-year return period, the GAMA I method estimated a peak discharge of 247.51 m^3/s, compared to 186.07 m^3/s from Snyder and 213.93 m^3/s from Nakayasu. The flood discharge results were further used in HEC-HMS simulations to generate hydrographs and evaluate the spatial distribution of runoff across the watershed. The simulations identified areas with high flood potential, especially zones with limited drainage capacity and high impervious surface coverage. These critical zones inform the prioritization of mitigation efforts.

Based on these findings, a combination of structural and non-structural flood control strategies is recommended. Structural measures include river normalization, expansion of retention ponds, and improvement of pumping facilities to manage runoff volumes corresponding to peak design flows. In parallel, a non-structural approach is proposed through the development of a real-time early warning system (EWS), which incorporates rainfall and water level sensors, automated alert mechanisms, and communication protocols with local stakeholders.

The results emphasize the value of an integrated modeling approach in informing both engineering design and emergency response planning. By comparing multiple SUH methods, the study ensures robustness in discharge estimation and offers a flexible, transferable strategy for managing urban industrial flood risks in other vulnerable regions. After presenting the discharge estimation results using synthetic unit hydrograph (SUH) methods and validating them through HEC-HMS simulations, a comparative analysis was conducted against two prior planning documents: the 2017 flood control design for Cilemah Abang and Bekasi Lama River (by PT. Supraharmonia Consultindo) and the 2020 flood mitigation plan for the Jababeka Area (by PT. Segoro Kidul). Table 3 presents peak discharge values (Q) for return periods of 2 to 100 years across major river sections based on these two references.

Table 3. Calibrated Discharge Recapitulation from Previous Studies and the Current Study

Return Period	**Flood Control Design Details for the Cilemah Abang River and Bekasi Lama River (2017) by PT Supraharmonia Consultindo**						**Flood/Waterlogging Mitigation Planning in the Jababeka Area (2020) by PT Segoro Kidul**		
(m^3/dt)	**Kali Bekasi Lama (Bawah CBL)**	**Bendung Cilemah Abang**	**Bendung Ciherang /Caringin**	**Kali Ciherang Muara**	**Kali Ulu**	**Kali Cipagadugan**	**Bendung Cilemah Abang**	**Kali Ulu**	**Kali Cipagadungan**
Q_{2th}	1.8	86.9	137.8	375.7	13.2	37.2	96.9	14.8	41.6
Q_{5th}	2.3	115.3	182.1	494.2	17.3	48.9	120.5	19.4	54.7
Q_{10th}	2.8	131.1	206.1	570.4	19.4	54.9	137.1	21.8	61.5
Q_{25th}	3.2	149.0	232.5	609.5	21.7	61.2	155.7	24.3	68.5
Q_{50th}	3.6	161.0	249.9	695.5	23.1	65.2	168.3	25.9	73
Q_{100th}	3.9	169.2	270.9	740	24.9	71.2	180	27.3	77

The comparison illustrates that there are notable differences in peak discharge estimates between the 2017 and 2020 planning documents. For instance, the estimated Q100th for Cilemah Abang increased from 169.2 m^3/s to 180.0 m^3/s, reflecting either updated hydrological inputs or revised design assumptions. Such variations support the need for continuous recalibration of flood design parameters and the adoption of more dynamic modeling frameworks—especially in fast-developing industrial areas such as Jababeka. These findings further justify the integrated modeling approach adopted in this study and highlight the necessity of aligning flood mitigation efforts with the most current and comprehensive data available. Based on simulation outputs and site assessments, a combination of structural and non-structural mitigation strategies was proposed. Structurally, the recommendations included river channel normalization, expansion of existing retention ponds, installation of modular storage tanks, enhancement of pump capacity at low-lying areas, and sediment control at intake points. These measures were designed to accommodate peak flows corresponding to up to a 100-year return period.

Non-structural measures focused on the development of an early warning system (EWS) tailored to industrial urban contexts. The conceptual design includes the deployment of real-time sensors for rainfall and water level monitoring, linked to a centralized data processing platform. Alert thresholds were established based on modeled flow predictions, with automated warning dissemination to local industries and emergency services. In parallel, institutional coordination mechanisms and stakeholder training programs were suggested to improve emergency responsiveness. The integrated approach demonstrated in this study underscores the limitations of relying solely on physical infrastructure to address flood risks in industrial urban areas. The findings confirm that hybrid strategies—merging engineered solutions with data-driven, community-oriented systems—can significantly enhance resilience. The proposed EWS model builds upon global best practices and adapts them to the spatial, hydrological, and economic characteristics of the Jababeka region. The implementation of such a system not only improves response time but also facilitates proactive risk reduction through informed decision-making.

Discussion

The results of this study underscore the necessity of combining statistically validated rainfall data with multi-method hydrological modeling to enhance flood risk assessment in rapidly urbanizing industrial areas. The regional design rainfall of 178.93 mm was consistent with patterns observed in similar tropical zones [31]. Who emphasized the importance of accurate spatial rainfall interpolation in urban watersheds. Among the four SUH methods applied, GAMA I produced the highest peak discharge values. Hydrological simulation using HEC-HMS revealed critical flood-prone zones due to high runoff and delayed recession. Field validation confirmed these results, with sediment accumulation and drainage obstruction observed in key areas, [30] that field-based calibration is essential for urban flood model reliability. When compared with previous planning studies. The current discharge estimates were significantly higher, reflecting the need for dynamic model. This study demonstrates the advantage of integrating structural planning with adaptive early warning systems, [28] to reduce flood vulnerability in complex urban systems. The relevance and alignment of this study with global best practices confirm its contribution to both methodological advancement and applied flood risk management in industrial environments.

Despite the comprehensive approach adopted in this study, several limitations must be acknowledged. First, the analysis relied primarily on secondary rainfall data from only three observation stations, which may limit spatial resolution and introduce interpolation uncertainty in areas with heterogeneous rainfall distribution. Additionally, while the use of multiple SUH models improved robustness in discharge estimation, the absence of high-resolution temporal rainfall data (e.g., sub-hourly intensity) restricted the ability to fully capture flash flood dynamics. Furthermore, the hydrological simulations using HEC-HMS were based on idealized land use and soil parameters, which may not fully reflect the micro-scale variability in industrial drainage infrastructure. Field verification was limited to select zones, and a more extensive survey could enhance calibration accuracy. Future studies are encouraged to integrate distributed hydrological models with remote sensing data and real-time hydrometeorological monitoring to improve spatial and temporal precision. Moreover, incorporating climate change scenarios and land use projections would allow for long-term flood risk forecasting. Expanding stakeholder involvement in the development of early warning systems may also provide valuable insights for community-based disaster risk reduction strategies in industrial regions.

CONCLUSION

Despite the comprehensive approach adopted in this study, several limitations must be acknowledged. First, the analysis relied primarily on secondary rainfall data from only three observation stations, which may limit spatial resolution and introduce interpolation uncertainty in areas with heterogeneous rainfall distribution. Additionally, while the use of multiple SUH models improved robustness in discharge estimation, the absence of high-resolution temporal rainfall data (e.g., sub-hourly intensity) restricted the ability to fully capture flash flood dynamics. Furthermore, the hydrological simulations using HEC-HMS were based on idealized land use and soil parameters, which may not fully reflect the micro-scale variability in industrial drainage infrastructure. Field verification was limited to select zones, and a more extensive survey could enhance calibration accuracy. Future studies are encouraged to integrate distributed hydrological models with remote sensing data and real-time hydrometeorological monitoring to improve spatial and temporal precision. Moreover, incorporating climate change scenarios and land use projections would allow for long-term flood risk forecasting. Expanding stakeholder involvement in the development of early warning systems may also provide valuable insights for community-based disaster risk reduction strategies in industrial regions.

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AUTHORS CONTIBUTIONS

Ashuri conceptualized the research framework, led the hydrological modeling design, and supervised the entire research process from initiation to completion. Tri Budi Wibowo contributed expert insights on regional flood mitigation planning and supported the comparative analysis with the 2020 flood planning data from PT. Segoro Kidul. M. Rizky Ismail conducted the rainfall data validation, performed the SUH-based discharge estimations, and executed the HEC-HMS simulations. Ahmad Zakaria was responsible for spatial analysis, field survey coordination, and contributed to the development of structural flood control recommendations. Muhammad Haviz provided technical expertise in early warning system (EWS) design, including sensor integration and real-time alert architecture. All authors participated in manuscript drafting, contributed to the interpretation of results, and reviewed and approved the final version of the manuscript.

CONFLICT OF INTEREST

The authors declare no conflict of interest. This research, including the selection of the research project, study design, data collection, analysis, interpretation, manuscript writing, and decision to publish, was conducted independently and without any external influence or funding sponsor involvement.

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