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Spatial Mapping of Historical Flood Intensity Impacting Automotive Facilities in Jabodetabek

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ABSTRACT

Flooding is a recurring hydrometeorological disaster that has a significant impact on Jabodetabek, including the sustainability of the automotive industry as one of the country's strategic sectors. This study aims to map the historical flood intensity and analyze its implications for automotive supply chain facilities. Sentinel-1 imagery was applied to detect inundation, complemented by permanent water body and built-up area masking from Sentinel-2, as well as the integration of spatial data on road networks and automotive facilities. The results indicate that more than 53% of the affected area experienced recurrent flooding (>25 times), with Bogor City, Bekasi Regency, and Tangerang Regency being the most extensively inundated regions. A total of 61% of automotive facilities were exposed to flooding, and 47% of the road network in Jabodetabek was inundated at least once over the past five years. These findings highlight systemic vulnerabilities that threaten the continuity of the Just-in-Time supply chain, marked by potential production delays, increased logistics costs, and reduced efficiency. This study recommends integrating spatial risk analysis into facility planning, strengthening infrastructure, providing alternative distribution routes, and leveraging GIS-based digital technologies to enhance visibility and resilience of the automotive supply chain in Jabodetabek.

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1. INTRODUCTION

Flooding is one of the most critical hydrometeorological disasters in urban areas, particularly in large metropolitan regions [1]. In Indonesia, the Jakarta, Bogor, Depok, Tangerang, and Bekasi (Jabodetabek) metropolitan area plays a central role in the national economy, contributing approximately 22% to the national Gross Domestic Product and accommodating nearly 12% of the population [2]. However, this region faces recurrent flood disasters that cause annual economic losses estimated at IDR 2 trillion in Jakarta alone [3]. These floods are driven by a combination of upstream rainfall, local precipitation, and coastal tidal surges [2], [4], creating chronic environmental and economic challenges for the metropolitan area. Beyond threatening communities, flooding has severe implications for industrial continuity [5]. The automotive industry, as one of Indonesia's strategic sectors, depends on the reliability of production facilities, warehouses, and distribution networks [6].

Flood-induced disruptions can delay the supply of critical components, increase logistics costs, and undermine Just-in-Time (JIT) operations, which are central to efficiency in automotive manufacturing [7]. Conventional reactive measures, such as temporary relocation or production rescheduling, are no longer adequate to address systemic and recurring disruptions. Instead, floods impose complex impacts on infrastructure, transportation networks, and supply chains that extend from upstream suppliers to downstream distributors [8], [9].

Previous studies in Jabodetabek have widely employed Geographic Information System (GIS) and remote sensing to analyze residential vulnerability, flood-prone zones, and localized economic losses [10], [11]. Similarly, global research has demonstrated the value of integrating GIS with predictive analytics for disaster risk management [12]. However, these works predominantly focus on community-level vulnerability and land use planning, with limited attention to industrial facilities. To date, there remains a research gap in explicitly linking historical flood intensity mapping with the spatial distribution of automotive supply chain facilities in Jabodetabek, despite the region being one of the most important automotive production and distribution hubs in Southeast Asia. This gap is critical because recurring floods can significantly hinder industrial operations and weaken supply chain resilience. Therefore, this study aims to map the historical flood intensity in the Jabodetabek region and analyze its implications for automotive supply chain facilities. The expected benefits of this research are both theoretical and practical. From a theoretical perspective, it contributes to the literature on Supply Chain Resilience (SCR) by integrating geospatial analytics into resilience assessment. From a practical standpoint, it provides insights for policymakers, manufacturers, and logistics managers to design adaptive strategies such as facility relocation, redundancy planning, and resilient distribution networks in flood-prone urban areas.

The state of the art of this research lies in the integration of remote sensing-based flood detection with supply chain facility mapping. Unlike previous studies that primarily addressed socio-environmental vulnerabilities, this study applies the Score-Based Flood Detection (SBFD) method using Sentinel-1 radar data, combined with Sentinel-2-based masking and spatial overlay of automotive facilities and road networks. This approach enables a systematic evaluation of how recurrent flooding disrupts both infrastructure and supply chain operations. The main contribution of this research is twofold. First, it provides empirical evidence of the spatial extent and frequency of floods in Jabodetabek and their direct impact on automotive supply chain facilities and transportation infrastructure. Second, it offers a methodological contribution by integrating GIS and digital analytics into supply chain risk management, thereby supporting the development of adaptive and resilient strategies for the automotive industry in flood-prone metropolitan regions.

2. METHODS

2.1 Research Location

This study was conducted in Jakarta, Bogor, Depok, Tangerang, and Bekasi (Jabodetabek), the largest metropolitan area in Indonesia and the center of the national automotive industry. The region was selected due to its high flood vulnerability and the significant concentration of automotive industry and distribution facilities.

2.2 Research Data

The study utilized remote sensing and secondary spatial data as the basis of analysis. Sentinel-1 (SAR) and Sentinel-2 (optical) imagery from the Copernicus program served as the primary sources. Sentinel-1 was processed for historical flood detection, while Sentinel-2 was employed to analyze built-up areas and water bodies. Road network data were obtained from OpenStreetMap (OSM) to assess the exposure of transport infrastructure and to calculate the length of affected road segments. Automotive supply chain facilities, including factories, warehouses, and dealerships, were derived from MarkLines and Gaikindo databases to evaluate the exposure and vulnerability of facilities to historical inundation.

2.3 *Analytical Techniques*

The analysis was designed to map the frequency of historical floods by integrating radar, optical, and secondary spatial data. All processes were conducted on the Google Earth Engine (GEE) platform for the 2020–2025 period. The workflow consisted of satellite image preprocessing, flood index calculation, elimination of irrelevant areas, and flood frequency classification. The results were subsequently integrated with road network data and automotive supply chain facilities to identify the exposure of critical infrastructure. Systematically, the analytical procedure was divided into four main stages:

a. Data Preprocessing

The preprocessing stage combined ascending and descending orbit Sentinel-1 imagery for 2020–2025. Radar images were filtered using the Refined Lee Filter to reduce speckle, and topographic correction was applied based on radar incidence angles to produce more representative backscatter values [13]. A baseline of mean and standard deviation of backscatter during dry periods was established as a reference for flood detection. The dry period, identified from July to September between 2022 and 2024, was selected due to consistently low rainfall based on nine BMKG observation stations across Jabodetabek.

b. Historical Flood Detection using SBFD

The Score Based Flood Detection (SBFD) method was applied to each preprocessed Sentinel-1 image. SBFD was calculated from the difference between backscatter values and the established baseline, normalized by its standard deviation [14]. Pixels with SBFD values lower than −1,25 were classified as inundated [15]. All flood detections were temporally aggregated to generate a cumulative flood frequency map for the study period.

c. Water Body and Built-up Area Masking

To minimize classification errors, permanent water bodies were masked, as they are naturally irrelevant to temporary flood detection. Water bodies were identified using the Modified Normalized Difference Water Index (MNDWI) and the Flood Water Extraction Index (FWEI) from Sentinel-2 imagery. Urban areas were delineated using the Normalized Difference Built-up Index (NDBI) from Sentinel-2, where NDBI values greater than 0,05 were classified as built-up areas and subsequently masked to focus flood mapping on relevant urban contexts [16], [17].

d. Flood Frequency Classification

Flood frequency accumulation was performed by summing the number of inundation events per pixel, with each day of detected flooding contributing to the count. The final output was a raster map representing the total number of inundation occurrences for each location during the analysis period. To enhance spatial interpretation and facilitate infrastructure vulnerability assessment, the continuous flood frequency map was categorized into seven discrete classes based on event ranges. The classification captured flood dynamics from sporadic to chronic events, aligning with data distribution and managerial relevance for supply chain resilience planning. The classes were defined as 0 events (never flooded), 1 to 5 events, 6 to 10 events, 11 to 15 events, 16 to 25 events, 26 to 40 events, and more than 40 events.

3. RESULTS AND DISCUSSION

3.1 Sentinel-1 Flood Analysis using Score Based Flood Detection (SBFD)

The SBFD method leverages the unique characteristics of SAR imagery, where calm water surfaces reflect radar signals specularly, appearing as dark areas (Figure 1b) with much lower backscatter values compared to dry land surfaces (Figure 1a). The fundamental principle of SBFD is to detect anomalous decreases in backscatter by comparing radar images acquired during or after flood events with normal conditions (baseline). In this study, the baseline was constructed using Sentinel 1 imagery from the dry season (July to September between 2022 and 2024 based on BMKG data), which was considered to represent stable dry surface conditions. From this baseline image set, the mean and standard deviation of backscatter values were calculated for each pixel and subsequently used as statistical references. The SBFD computation produced a normalized score map, where negative values indicated a reduction in backscatter relative to normal conditions. The lower the SBFD value, the higher the likelihood that a pixel was inundated. A threshold value of −1,25 was applied to classify pixels as flooded areas. In other words, if the SBFD value of a pixel was lower than −1.25, the pixel was categorized as inundated.

In the Google Earth Engine (GEE) implementation, this process was performed by mapping the SBFD function across the entire preprocessed image collection. For each image, the SBFD value was calculated, followed by the creation of a binary mask with the condition lower than −1,25. The results of each daily flood detection were then temporally accumulated to produce a map of flood occurrence counts per pixel for the period January 2020 to June 2025. The SBFD approach offers several advantages compared to traditional flood detection methods. First, it does not require reference images from past flood events, as it relies solely on normal conditions from dry periods. Second, SBFD reduces spatial and temporal bias because the baseline is statistically calculated for each pixel, thus accounting for local variations due to topography or surface type. Third, the method can be fully automated within the Google Earth Engine platform, enabling efficient large scale time series analysis [14], [18].

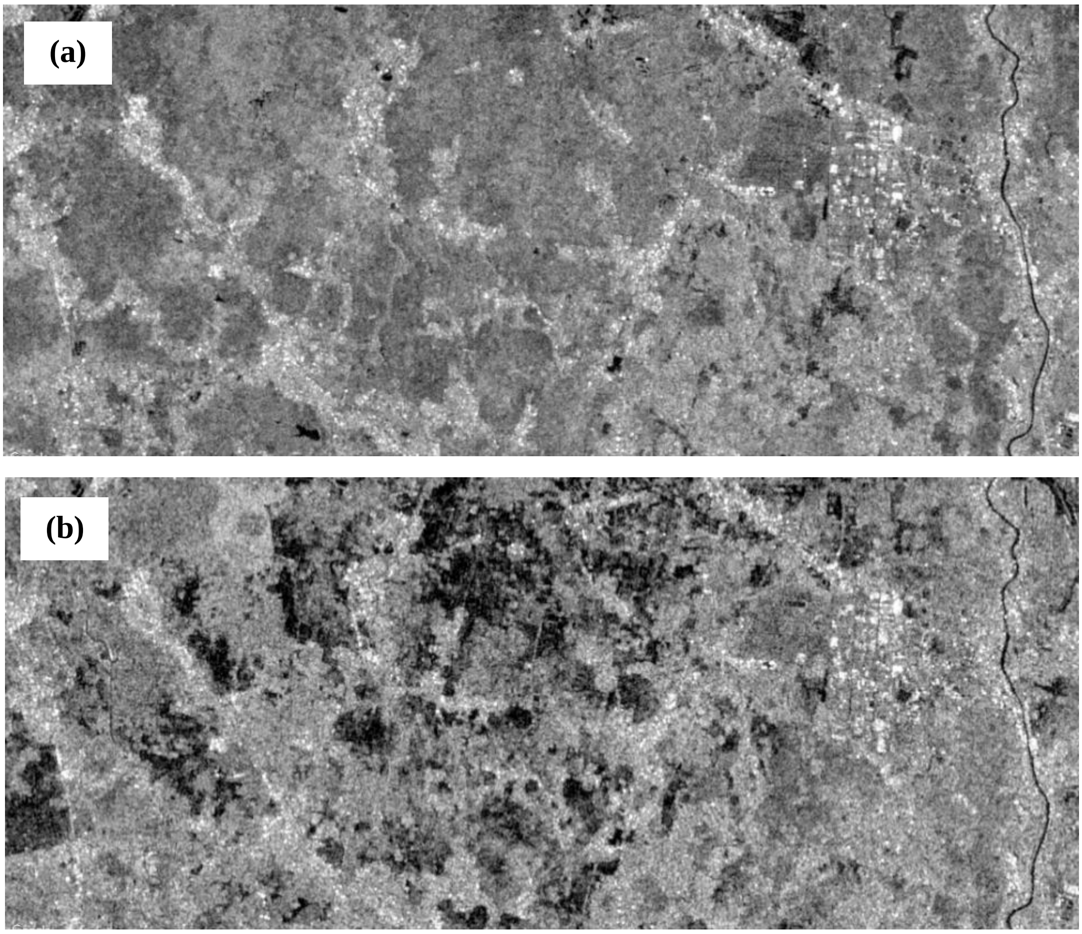


Figure 1. Sentinel-1 Imagery: (a) Before Flooding (Baseline); (b) During Flooding (30 Nov 2023)
(Source: Authors)

3.2 *Historical Flood Intensity in Jabodetabek*

The analysis of historical flood intensity was conducted using the SBFD method, which utilized Sentinel-1 radar data for automatic flood detection. Figure 2 illustrates the distribution of flood intensity in the Jabodetabek region, where colors represent the number of flood events per pixel. The locations of automotive facilities across Jabodetabek and permanent water bodies are also displayed on the map. Figure 3 presents the extent of affected area based on the frequency of flood events during the 2020–June 2025 period. This data was compiled for each district and municipality in Jabodetabek and reflects the spatial intensity of floods identified through Sentinel-1 image analysis. Overall, the largest flood affected area was recorded in Bogor City, with a total of 251,9 km^2, followed by Bekasi District (216,4 km^2) and Tangerang District (197,7 km^2). These three regions exhibit persistent and extensive inundation patterns, particularly in the higher frequency categories. For instance, Bogor City recorded more than 63 km^2 inundated between 26–40 times, and 66,8 km^2 inundated more than 40 times over the five year period, indicating high hydrological and topographical vulnerability. In DKI Jakarta, East Jakarta recorded the largest affected area (104,5 km^2), with widespread distribution in categories above 15 events, followed by South Jakarta (72,4 km^2) and West Jakarta (67,5 km^2). Although the absolute extent is smaller than in buffer regions, the high frequency of flooding in densely populated areas remains a major concern in terms of social and infrastructure risks.

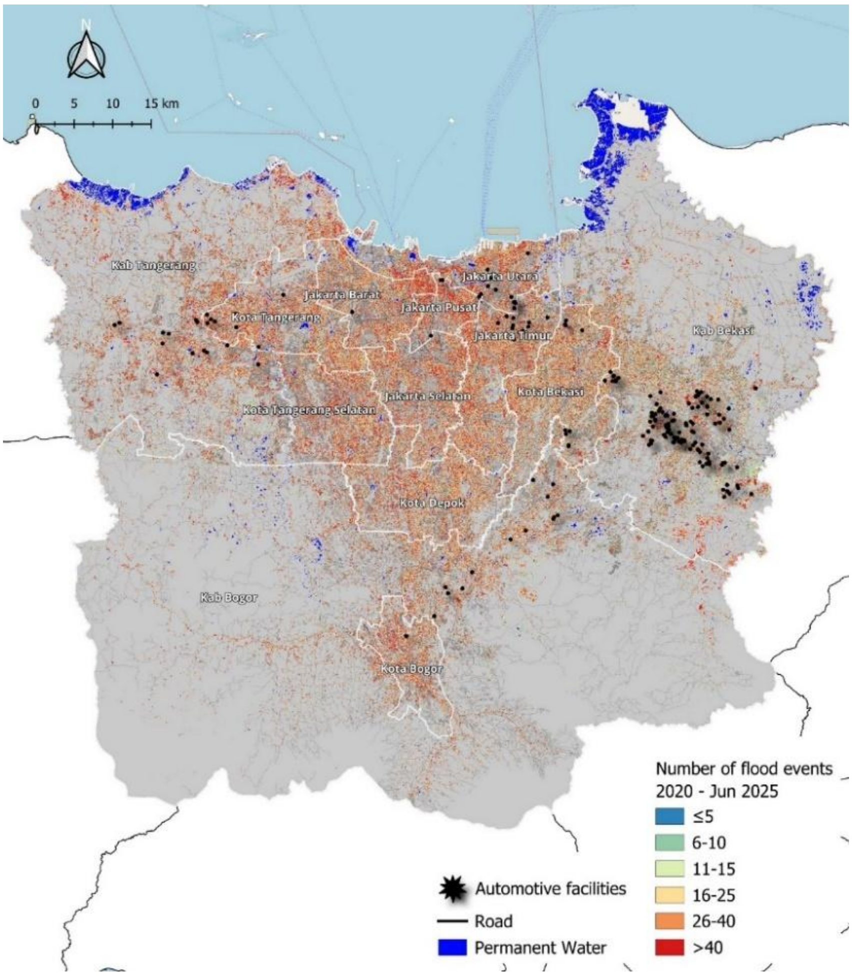
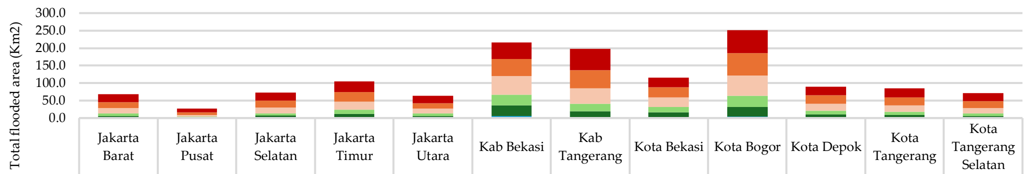


Figure 2. Flood Occurrence Frequency Map in Jabodetabek, 2020 – June 2025
(Source: Authors)

Conversely, Central Jakarta recorded the smallest flood affected area at 26,3 km². However, this represents more than 54% of the total area of Central Jakarta (47,9 km²), indicating that despite its small size, the relative exposure to floods is high. This phenomenon highlights that central urban areas remain vulnerable, particularly in locations with suboptimal drainage or high population density. Although Central Jakarta generally has higher topography and a better drainage system than surrounding areas, extreme rainfall and drainage stress due to urbanization continue to contribute to recurrent flooding [4]. These findings are consistent with [19], who emphasized that road drainage systems and flood frequency are among the most influential factors in spatial vulnerability. At the aggregate level, most flood events occurred in the high frequency class: categories above 25 events accounted for about 731 km² or more than 53,6% of the total affected area. This indicates that the majority of affected areas experienced recurrent rather than sporadic flooding, suggesting that risk reduction planning must focus on addressing chronic flooding.



	Jakarta Barat	Jakarta Pusat	Jakarta Selatan	Jakarta Timur	Jakarta Utara	Kab Bekasi	Kab Tangerang	Kota Bekasi	Kota Bogor	Kota Depok	Kota Tangerang	Kota Tangerang Selatan
> 40	21.9	10.1	23.1	30.6	21.8	46.9	61.0	27.9	66.8	25.1	24.9	23.6
26 - 40	17.8	6.8	19.7	26.9	16.2	50.0	52.1	28.1	63.4	23.8	22.9	19.6
16 - 25	14.6	5.0	15.6	23.6	13.5	52.1	44.1	27.8	58.1	20.7	18.9	15.5
11 - 15	6.9	2.3	7.4	11.9	6.5	30.9	21.3	15.4	31.3	10.4	9.2	6.9
6 - 10	5.5	1.9	5.8	10.0	5.5	31.0	16.7	14.1	27.8	8.6	7.2	5.1
≤ 5	0.9	0.3	0.8	1.5	0.9	5.5	2.5	2.4	4.4	1.4	1.2	0.7

Figure 3. Total Flooded Area by Flood Frequency Class in the Jabodetabek Area (Source: Authors)

Table 1. Distribution of Automotive Facilities by Number of Flood Events

Area	No Flooding	Number of Flood Events					
		≤ 5	**6 - 10**	**11 - 15**	**16 - 25**	**26 - 40**	**> 40**
Jakarta Barat	1						
Jakarta Pusat	2						1
Jakarta Timur	2				1	3	4
Jakarta Utara	8			2	3	2	
Kab Bekasi	51	3	8	5	19	17	23
Kab Bogor	2		1		4	4	3
Kab Tangerang	6	1			1	3	2
Kota Bekasi	3				2	3	1
Kota Bogor				1			
Kota Tangerang	2		1	1		1	3
Total	**77**	**4**	**10**	**9**	**30**	**33**	**37**
Percentage	**39%**	**2%**	**5%**	**5%**	**15%**	**17%**	**19%**

Source: Authors

Table 1 shows the distribution of automotive facilities in Jabodetabek according to flood frequency during the 2020–June 2025 period. Out of the total, 77 facilities (39%) were never affected by flooding, indicating that almost half of the facilities remain in relatively safe zones. Most of these unaffected facilities were concentrated in Bekasi District (51 facilities) and North Jakarta (8 facilities). On the other hand, 37 facilities (19%) experienced very high flood frequency, exceeding 40 times over five years, representing the highest proportion among all frequency classes. This category was dominated by Bekasi District (23 facilities), followed by East Jakarta (4 facilities), Bogor District (3 facilities), and Tangerang City (3 facilities). This reflects significant flood exposure in industrial buffer zones around Jakarta, particularly in the east and south, which are generally characterized by lowlands, limited drainage systems, and rapid development. The frequency category of 16–40 times also demonstrated substantial exposure, with 63 facilities (32%) recorded in this range, consisting of 30 facilities in the 16–25 times category and 33 facilities in the 26–40 times category. Bekasi District again showed dominance, alongside Bogor District and Bekasi City. Facilities in this range are vulnerable to recurrent flooding, even if not yet at extreme chronic levels. Nonetheless, operational disruptions and risk of damage remain significant without planned mitigation. Meanwhile, 23 facilities were affected at lower frequencies of ≤15 times (combined categories of ≤5, 6–10, and 11–15), accounting for about 12% of the total. Although this frequency is relatively low, facilities in this category still face risks, particularly if located in dense or sensitive areas such as distribution centers, showrooms, or warehouse sites. Overall, the table indicates that 61% of mapped automotive facilities were affected by flooding at least once, with more than half (51%) experiencing intensive and recurrent flooding above 15 times. This underscores the importance of location based adaptation strategies, industrial area infrastructure reinforcement, and optimization of drainage systems. Regions such as Bekasi District, East Jakarta, and Bogor District should be prioritized in disaster risk reduction planning, as persistent flooding in these areas can reduce the resilience of the automotive sector as a key driver of the national economy.

Figure 4 presents the distribution of flood affected road lengths according to flood frequency across administrative regions in Jabodetabek during the 2020–June 2025 period. Out of a total road length of 59.234 km in Jabodetabek, 27.893 km (47%) were affected by flooding at least once in the past five years. This indicates that nearly half of the road infrastructure in the metropolitan area is exposed to inundation risks, potentially disrupting mobility, logistics distribution, and public accessibility. Bekasi District recorded the highest value with 3.655 km of flood affected roads, followed by Bogor District (3.508 km), Tangerang District (3.082 km), and Bekasi City (3.065 km). The large extent of affected roads in these regions is mainly due to their larger area size and complex hydrological conditions, particularly in lowland zones with rapid urban growth and insufficient drainage systems. In terms of proportion to total road length per region, Bekasi City had the highest ratio, with 64% of its roads affected by flooding, followed by East Jakarta (62%) and Depok City (58%). This ratio reflects the functional vulnerability of road infrastructure to flooding, influenced not only by absolute road length but also by drainage design, capacity, and surface flow patterns.

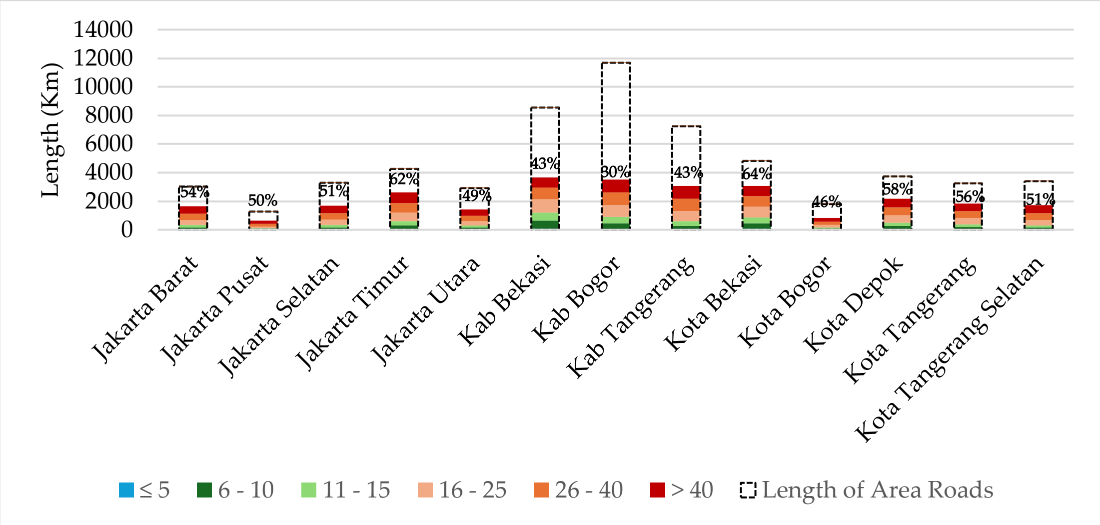


Figure 4. Total Road Length Affected by Flooding by Flood Frequency Class in the Jabodetabek Area
(Source: Authors)

Meanwhile, Bogor District recorded the lowest ratio, with only 30% of its roads affected, despite having the largest total road length in Jabodetabek, exceeding 11.666 km. This suggests that much of Bogor's road network is located at higher elevations or benefits from better natural runoff management [20], although the number of affected sites in the district remains significant. The distribution of flood frequency also shows that most affected road lengths fall into medium to high frequency categories. For instance, in the category of more than 40 flood events, the total affected road length reached 7.674 km, or about 28% of all affected roads, with the highest values recorded in Tangerang District, Bogor District, and East Jakarta. This indicates critical zones of chronic flooding where transport disruptions and infrastructure damage are highly likely to occur repeatedly. These findings highlight that flooding in Jabodetabek impacts not only residential and industrial areas but also severely disrupts the land transportation system. Therefore, adaptive road infrastructure planning is required to address climate change and increasing surface water runoff, including improved drainage systems, elevated road construction, and integration with green space planning as runoff buffer zones [21].

The spatial findings regarding flood distribution patterns in Jabodetabek carry profound strategic implications for supply chain management, particularly within the automotive industry which is highly dependent on timeliness, vertical integration, and precise logistics coordination. In an automotive supply chain system that applies the Just In Time (JIT) principle, any disruption to the flow of raw materials or components, even if temporary, may trigger production delays, efficiency losses, or even temporary shutdowns of assembly lines [22]. The finding that 27,893 km of logistics roads in Jabodetabek have been affected by floods indicates that the supporting infrastructure of the supply chain remains vulnerable, thereby threatening the continuity of reliable operations. From a managerial perspective, this reflects systemic vulnerability resulting from excessive reliance on short term operational efficiency without adequately considering long term resilience [10].

In the context of supply chain risk management, this finding confirms [8] argument that lean strategies which eliminate buffer stock improve efficiency but also increase exposure to external disruptions such as flooding. From a managerial standpoint, companies need to balance efficiency and resilience by adopting a risk adjusted supply chain design [23]. One strategic solution is to build capacity redundancy through strategic stockpiling of critical components in flood safe locations, or to develop alternate sourcing from suppliers located in non disaster prone regions [24]. Furthermore, the uneven spatial distribution of automotive facilities with high concentrations in flood prone areas such as Bekasi highlights the need to reformulate facility location planning strategies in supply chain management. Decisions on the location of factories and warehouses have so far been driven primarily by considerations of accessibility, land costs, and labor, but have insufficiently incorporated environmental risk. The integration of Geographic Information System (GIS) and digital analytics, as developed in this study, provides a strong managerial tool for data driven decision making in facility layout planning. By mapping flood risk points and simulating alternative distribution routes, supply chain managers can identify optimal locations for buffer warehouses, cross docking points, or supplier clustering in safe zones, thereby minimizing downtime during flood events [25].

From the perspective of coordination and visibility, these findings also emphasize the importance of end to end supply chain visibility as a key pillar of resilience [26]. Flood related disruptions are often exacerbated by information delays among supply chain partners, leading to bullwhip effects and miscommunication in production planning. The application of digital technologies such as IoT, cloud based platforms, and real time monitoring through GIS integration can enhance transparency in the flow of goods and information, enabling faster and more coordinated responses. For example, when a primary road is flooded, the system can automatically propose alternative routes based on actual road conditions or activate a supplier switching protocol if a main supplier becomes isolated by floods. Therefore, from a supply chain management perspective, the flood distribution pattern in Jabodetabek is not merely a technical or environmental issue but a strategic challenge that requires a transformation from reactive to proactive and adaptive supply chain management. Companies need to integrate spatial risk analysis into Supply Chain Management (SCM) strategies, build flexible redundancy capacity, strengthen collaboration with suppliers and government authorities, and leverage digital technologies to create systems that are not only efficient but also resilient to climate uncertainties [27].

4. CONCLUSION

This study successfully mapped the historical flood intensity in the Jabodetabek region during the 2020–2025 period using the Score-Based Flood Detection (SBFD) method based on Sentinel-1 radar imagery, combined with permanent masking (MNDWI, FWEI, and NDBI) derived from Sentinel-2. The integration of flood mapping results with data on automotive supply chain facilities and road networks shows that flooding in Jabodetabek is recurrent and chronic, with more than 53 percent of affected areas experiencing inundation more than 25 times over the past five years. The study presents three key findings. First, there is a high level of exposure of automotive facilities to floods, with 61 percent of facilities detected as being affected at least once, and more than half of them experiencing recurrent flooding exceeding 15 times. Bekasi, Bogor, and Tangerang are identified as the regions with the highest exposure, posing significant risks to the sustainability of the automotive industry. Second, land transportation infrastructure in Jabodetabek is highly vulnerable, with 47 percent of the total road length inundated at least once during the study period. This condition has serious implications for logistics mobility, higher distribution costs, and reduced efficiency of the Just-in-Time (JIT) system, which serves as the backbone of the automotive industry. Third, the distribution patterns of floods indicate that flooding is no longer a sporadic phenomenon but rather a chronic and recurrent issue in densely populated areas and strategic industrial zones.

The academic contribution of this study lies in the integration of geospatial analytics with the study of Supply Chain Resilience (SCR). This study explicitly links historical flood intensity with automotive supply chain facilities, thereby expanding the understanding of how hydrometeorological risks create systemic impacts on the sustainability of strategic national industries. From a practical perspective, this study offers several managerial recommendations. Automotive companies in flood-prone areas should implement redundancy and diversification strategies, such as placing buffer stock in safe locations and diversifying suppliers from non-flood-prone regions. A reformulation of facility location strategies is also needed by incorporating GIS-based flood risk data, so that location decisions are not solely based on cost and accessibility but also on long-term resilience. The integration of digital supply chain technologies such as IoT, cloud-based monitoring, and real-time GIS should be strengthened to enhance supply chain visibility and enable rapid and coordinated responses to flood disruptions. Collaboration among government, industry players, and spatial planning authorities is equally critical to developing adaptive logistics infrastructure, including improved drainage systems, the construction of alternative routes, and the integration of green open spaces as runoff buffers. In conclusion, this study emphasizes that the resilience of the automotive supply chain in Jabodetabek cannot be achieved solely through operational efficiency but requires a proactive approach that is spatial data-driven and adaptive to hydrometeorological risks. Chronic and recurrent floods in metropolitan areas demand a transformation from reactive supply chain systems to resilient systems that are robust against climate uncertainties.

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