Integrating Urban Mobility Analysis and Flood Risk Mapping: A Case Study in Ho Chi Minh City

Syazwi Quthbi Al Azizi [1*], Nurjannah Nurdin[2]

[1]School of Architecture, Planning and Policy Development,

Bandung Institute of Technology (ITB), Bandung, Indonesia

[2]Research and Development Center for Marine, Coast and Small Islands, Hasanuddin University,

Makassar, 90245, Indonesia

cicisawi@gmail.com

Abstract: *Ho Chi Minh City, Vietnam, is increasingly exposed to urban flooding driven by rapid urbanization and climate change, causing severe disruptions to mobility. This study integrates urban mobility analysis and flood risk mapping to assess how inundation impacts transportation performance in key districts. Using Sentinel-1 Synthetic Aperture Radar (SAR) imagery from 2020–2022 and historical traffic datasets, flood extents and traffic dynamics were analyzed for Districts 1, 4, 5, 6, and 11—areas with dense traffic and frequent flooding. The annual flooded area ranged from 1,538 to 2,359 hectares, affecting up to 77,404 residents and reducing vehicle speeds to below 25 km/h during peak periods. Results indicate that flood-prone corridors correspond to major commuting routes, amplifying congestion and mobility inefficiencies. While Sentinel-1 SAR enables consistent flood monitoring, limitations remain due to spatial resolution and backscatter variability in dense urban settings. The study emphasizes the need for integrated flood-mobility management, combining improved drainage, real-time flood monitoring, and public transport enhancement. These findings contribute to spatially informed strategies that strengthen urban resilience and ensure sustainable mobility in flood-affected coastal cities.*

Keywords: Urban Flooding, Mobility Disruption, Sentinel 1-SAR, Spatial Analysis, Ho Chi Minh City, Climate Resilience

I. Introduction

Urban flooding has emerged as one of the most pressing challenges for rapidly growing cities under climate change, disrupting transportation networks, economic activity, and daily mobility (Dharmarathne et al., 2024). Mobility systems are particularly vulnerable, as flooding can significantly reduce accessibility and travel efficiency, especially in low-lying and densely populated cities (Moller-Jensen et al., 2023). At the same time, human mobility patterns themselves can exacerbate flood exposure when daily commuting flows concentrate in flood-prone urban corridors, amplifying risk distribution (Long & Duan, 2025).

While numerous studies have examined urban floods in terms of hazard mapping or infrastructure damage, relatively few have explicitly integrated spatial flood risk mapping with mobility analysis. For instance, studies in Wuhan, China combined high-resolution flood modeling with commute simulation under varying rainfall scenarios, revealing that short-distance commuters are less vulnerable to flood disruptions than long-distance ones, and that flood intensity (depth & duration) strongly correlates with drops in travel speed (Y. Liu et al., 2022). Similarly, research in Xi'an, China evaluated the impact of intense rainfall on the road network using road topology and elevation data, showing that heavy rain events significantly degrade network performance and travel reliability in flooded districts (J. Liu et al., 2023). Advances in Synthetic Aperture Radar (SAR)-based flood detection have made near-real-time mapping possible even under cloudy conditions, yet classification accuracy remains a challenge in complex urban environments due to radar backscatter variation and building orientation (Ghosh et al., 2024; Mason et al., 2023). Consequently, an integrated geospatial framework linking flood extent and mobility performance is still limited in current literature.

Ho Chi Minh City (HCMC), Vietnam, represents a critical case to investigate these interactions. As a rapidly urbanizing coastal metropolis within the Mekong Delta, over 45% of its land area lies below one meter above sea level, making it highly susceptible to rainfall-induced and tidal flooding (World Bank, 2019). Recent studies have emphasized that Southeast Asian coastal cities face increasing compound risks from intense precipitation and sea-level rise (Long & Duan, 2025). In HCMC, recurring inundation has already disrupted road transport and exacerbated chronic congestion, leading to substantial economic losses and mobility inefficiencies.

The growing availability of Sentinel-1 SAR imagery offers an opportunity to monitor flood dynamics consistently across time and weather conditions. Long-term radar observations have been used successfully to map flood extents globally, demonstrating the robustness of SAR for flood monitoring (Misra et al., 2025). In the Lower Ganges Basin, for example, the integration of multi-temporal Sentinel-1 data has provided reliable inundation mapping for flood management in tropical regions (Sajid et al., 2025). Building upon these advances, this study employs Sentinel-1 SAR data (2020–2022) and historical traffic datasets to analyze how inundation events influence transportation performance and congestion in key districts of HCMC.

By bridging geospatial flood risk mapping and urban mobility analysis, this research contributes to filling a methodological and empirical gap in flood resilience studies. It aims to quantify how flood exposure affects travel speed, congestion, and accessibility, while also providing actionable insights for integrated flood-mobility management. The findings are expected to inform sustainable and data-driven planning strategies that strengthen urban resilience in coastal Southeast Asian cities increasingly exposed to hydrometeorological hazards.

II. Literature Review

Recent advances in satellite remote sensing especially Sentinel-1 Synthetic Aperture Radar (SAR) have substantially improved the ability to detect and map inundation in all-weather conditions, making SAR a preferred data source for operational flood monitoring in cloudy or night-time situations. However, urban flood detection using SAR remains technically challenging: urban backscatter is spatially heterogeneous and sensitive to building orientation and double-scattering effects, which can complicate simple thresholding or change-detection approaches. Studies have therefore proposed combining SAR intensity and coherence, or using machine-learning segmentation, to improve urban inundation mapping accuracy (Mason et al., 2023).

A separate but growing literature documents how floods disrupt urban mobility and transportation networks. Network-oriented studies have shown that even relatively localized inundation can propagate large-scale failures in road connectivity and greatly increase travel times, with impacts that sometimes extend well beyond flooded segments due to rerouting and congestion effects. Percolation and network-failure analyses demonstrate that modest levels of direct inundation may trigger abrupt systemic degradation of connectivity. Empirical analyses of recent flood events likewise report persistent travel-time increases and spatially heterogeneous recovery patterns across urban road systems (Dong et al., 2022; Wang et al., 2019).

Case studies that explicitly link spatially-explicit flood extents and mobility outcomes are increasing but remain comparatively few. For example, Wuhan and Xi'an case studies (J. Liu et al., 2023; Y. Liu et al., 2022) combined flood or heavy-rain modeling with commute or road-topology analyses to quantify travel-time losses and identify vulnerable corridors, yet most of these works relied on hydrologic or rainfall proxies rather than on systematically derived SAR inundation products. Studies using high-resolution traffic records have revealed detailed patterns of network perturbation during flooding events, but integration with radar-derived flood maps is still not widespread

More recent work underscores the importance of accounting for dynamic human mobility when assessing flood exposure: dynamic population and mobility patterns can amplify compound flood risk in coastal cities, shifting temporal exposure between commercial and residential areas and altering where and when transport systems are most vulnerable (Long & Duan, 2025). More recent work underscores the importance of accounting for dynamic human mobility when assessing flood exposure: dynamic population and mobility patterns can amplify compound flood risk in coastal cities, shifting temporal exposure between commercial and residential areas and altering where and when transport systems are most vulnerable.

At the same time, large-scale SAR-based mapping efforts and open benchmark datasets (and associated deep-learning methods) now make it technically feasible to generate temporally consistent flood extents for multi-year analyses, creating an opportunity to more closely couple SAR-derived inundation maps with empirical traffic data for resilience assessment (Misra et al., 2025). Nevertheless, a clear methodological gap persists: relatively few studies have combined validated, multi-temporal SAR flood products with observed traffic performance metrics to quantify how inundation affects mobility in tropical coastal cities. This study addresses that gap by integrating Sentinel-1-based inundation mapping with historical traffic datasets to evaluate spatial coincidences between flood exposure and mobility degradation.

III. Materials and Methods

III.1 Study Area

Ho Chi Minh City (HCMC), located in southern Vietnam between 10°38′–10°50′N and 106°30′–106°50′E, is one of the largest and fastest-growing metropolitan areas in Southeast Asia. The city covers about 2,100 km² and is characterized by low-lying terrain, with nearly 45 % of its area less than one meter above mean sea level. HCMC experiences a tropical monsoon climate, with annual rainfall exceeding 1,800 mm concentrated between May and October.

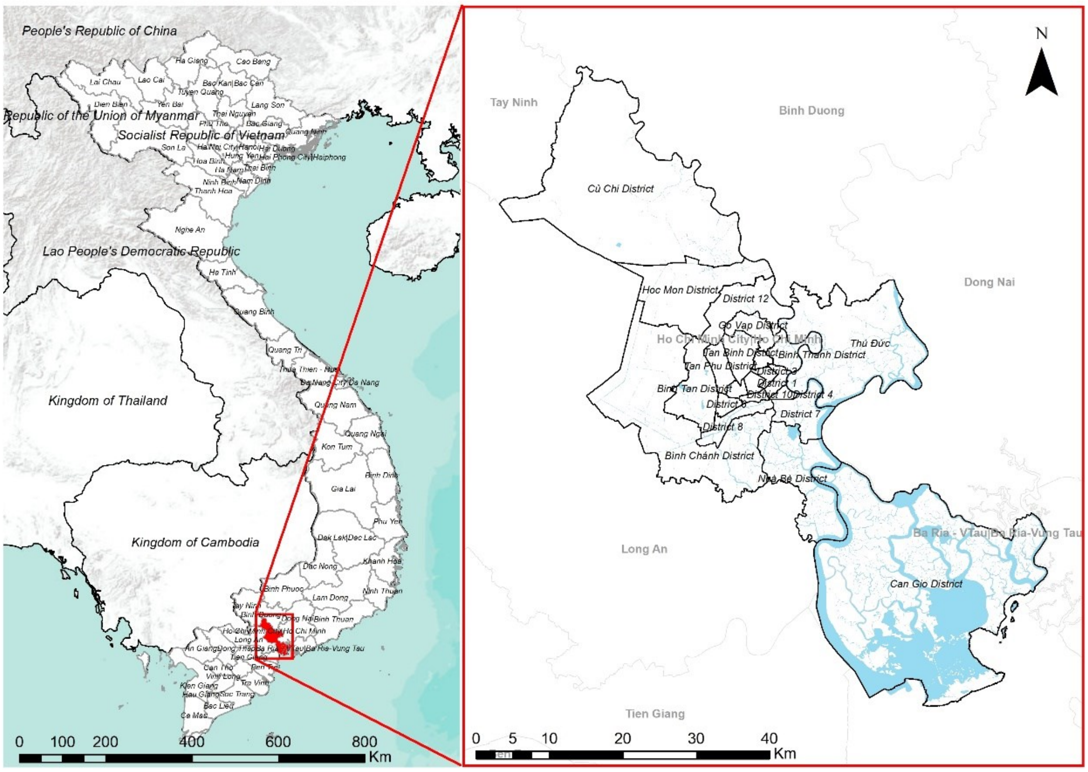

Figure 1: Study Area (Ho Chi Minh City, Vietnam)

Urban flooding is a recurrent problem in HCMC, caused by the combined effects of high rainfall intensity, tidal backflow from the Saigon River, and insufficient drainage capacity. Previous studies have shown that rainfall and tidal surges frequently inundate major arterial roads and intersections, severely affecting mobility and daily commuting (Long & Duan, 2025; World Bank, 2019). Given its rapid urbanization, exposure to compound flooding, and extensive transportation network, HCMC provides an ideal case study to examine how spatially explicit flood extent affects traffic speed, congestion, and overall mobility performance.

III.2 Data Collection

Multi-temporal Sentinel-1 Synthetic Aperture Radar (SAR) data were used to detect flood inundation across Ho Chi Minh City between 2020 and 2022. The imagery, acquired in Interferometric Wide (IW) mode with dual polarization (VV and VH), was accessed through the Copernicus Open Access Hub and processed in the Google Earth Engine (GEE) environment. The Sentinel-1 Ground Range Detected (GRD) product with 10 m spatial resolution was selected due to its suitability for flood mapping and consistent temporal coverage.

Digital Elevation Model (DEM) data were obtained from the Shuttle Radar Topography Mission (SRTM) at a spatial resolution of 30 m, used as a topographic reference for terrain-related analysis. Global Surface Water (GSW) data from the Joint Research Centre (JRC) were used to identify and exclude permanent water bodies from flood classification results.

The road network dataset was derived from OpenStreetMap (OSM), which provided the spatial framework for integrating flood extent and mobility datasets. Hourly traffic speed and congestion indices were obtained from a commercial mobility database covering the period 2020–2022, representing the spatial and temporal dynamics of urban mobility. Population data and density grids were obtained from WorldPop (2020) to estimate the number of exposed residents in inundated areas.

Historical traffic datasets were obtained from the Traffic Flow Data in Ho Chi Minh City, Vietnam project (Thành Nguyen, 2023) hosted on the Kaggle open-data platform. The dataset originates from the UTraffic Urban Traffic Estimation System, an urban traffic forecasting framework that integrates community-sourced data from mobile and web applications with big data analytics and machine learning to estimate real-time and historical traffic conditions. The dataset provides hourly traffic speed, congestion level, and level-of-service indicators for major roads in Ho Chi Minh City.

Although the dataset does not provide continuous two-year coverage, temporal samples coinciding with significant flood events between 2020 and 2021 were selected to ensure temporal alignment with Sentinel-1 SAR acquisition periods. This dataset was used to evaluate mobility performance and congestion patterns during flood events and to spatially link flood extent with transport disruption analysis.

Dataset	**Source / Provider**	**Resolution/ Coverage**	**Period**	**Purpose**
Sentinel-1 SAR (GRD, VV/VH)	Copernicus Open Access Hub (ESA); processed in Google Earth Engine (GEE)	10 m spatial resolution (IW mode)	2020–2022	Flood extent detection
SRTM DEM	NASA / USGS	30 m	Global	Terrain correction and slope masking

Dataset	Source / Provider	Resolution/ Coverage	Period	Purpose
Road Network	OpenStreetMap	Vector (1:10,000)	2024	Mobility Pattern Analysis
Population Density Grid	WorldPop Project (University of Southampton)	100 m resolution	2020	Estimation of population exposure in flooded areas
Traffic Flow and Speed Data	UTraffic Urban Traffic Estimation System, distributed via Kaggle (Thành Nguyen, 2023)	1-hour interval records for major urban roads	2020–2022 (samples around flood events)	Mobility performance and congestion assessment during floods

Table 1: Background Data

III.3 Methods

III.3.1 Mobility Assessment

Mobility assessment was conducted using the Traffic Flow Data in Ho Chi Minh City dataset (Thành Nguyen, 2023), derived from the UTraffic Urban Traffic Estimation System. This dataset consists of five main tables: (i) *train.csv*, which records the Level of Service (LOS) for each road segment at 30-minute intervals; (ii) *segment_status.csv*, containing real-time velocity updates; (iii) *segments.csv* and *nodes.csv*, defining the geometry of road segments; and (iv) *streets.csv*, providing road classification and maximum velocity.

For mobility analysis, the *train* and *segment_status* tables were joined via the *segment_id* field to obtain both categorical and numerical indicators of traffic performance. Average speed and LOS were computed for each segment before and during identified flood periods (2020–2022). Spatial overlay between flood extent and road network geometry (from *segments.csv* and *nodes.csv*) was then used to identify flooded segments. The total length of inundated roads, average velocity reduction, and change in LOS were calculated as indicators of flood-related mobility disruption.

Finally, results were aggregated at the district level to examine the relationship between flood exposure and traffic performance degradation. This integrated analysis provided a spatially explicit understanding of how flood events affect urban accessibility and road network efficiency.

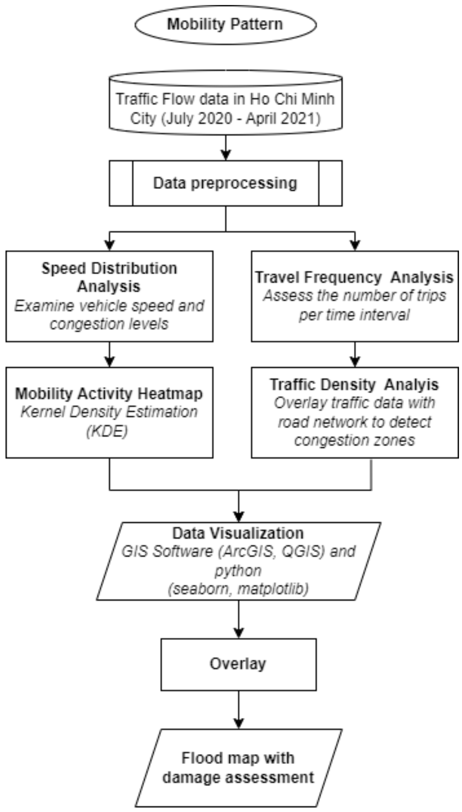

Figure 2: Exposure and Mobility Assessment Workflow (Utraffic-based)

III.3.1 Exposure and Flood Mapping Workflow

Population and mobility exposure to flooding were assessed by integrating the flood extent maps with demographic and traffic datasets. Population exposure was calculated by overlaying the binary flood map with WorldPop 2020 gridded population data. The number of residents within flooded pixels was then aggregated by administrative district to estimate spatial variations in human exposure.

Flood mapping was conducted using Sentinel-1 Ground Range Detected (GRD) imagery processed in Google Earth Engine (GEE). The workflow followed the UN-SPIDER Recommended Practice for Flood Mapping and Damage Assessment using Sentinel-1 SAR in GEE (UN-SPIDER, 2024), adapted for the study area. The method employs a change-detection approach based on the difference in radar backscatter intensity between pre- and post-flood conditions.

The area of interest (AOI) was defined using the administrative boundary of Ho Chi Minh City to restrict the processing extent. Sentinel-1 imagery was filtered by instrument mode (IW), polarization (VH or VV), orbit direction, and clipped to the AOI. The standard preprocessing pipeline in GEE—comprising orbit correction, thermal noise removal, radiometric calibration, terrain correction, and conversion to decibel (dB)—was automatically applied to all GRD scenes.

Pre-event and post-event image collections were defined for each flood episode and composited using the median reducer to minimize speckle and temporal noise. Change detection was performed by computing the ratio between post- and pre-flood mosaics (σ^0_post / σ^0_pre). A threshold ratio of 1.25, following UN-SPIDER guidelines, was used to identify flooded pixels; higher ratios indicate strong backscatter reduction due to water inundation.

Post-classification refinements included (1) masking slopes greater than 5 % using the SRTM DEM to avoid misclassification in hilly terrain, and (2) excluding permanent water bodies using the JRC Global Surface Water dataset. Morphological filtering was subsequently applied to remove isolated clusters smaller than four connected pixels. The resulting binary flood map (flooded/non-flooded) was cross-validated using daily rainfall and tidal data from the Vietnam Meteorological and Hydrological Administration (VMHA) to ensure temporal consistency with reported flood events. The final flood maps were exported as GeoTIFF layers for spatial overlay with exposure and mobility datasets.

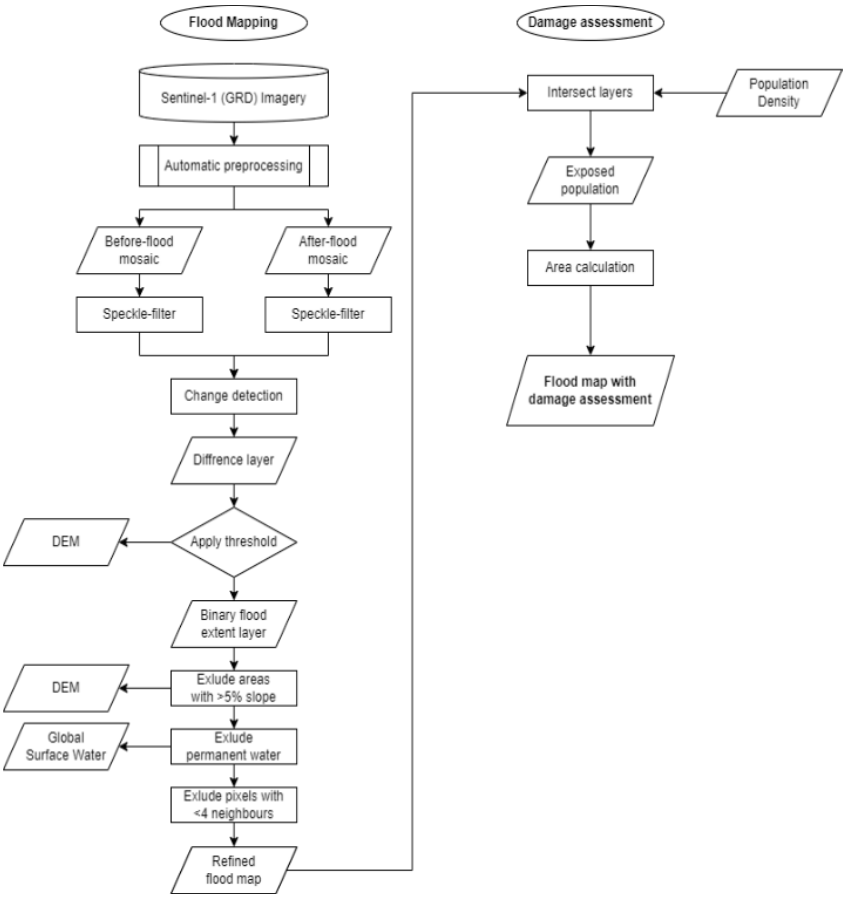

Figure 2: Workflow of flood mapping and exposure assessment adapted from the UN-SPIDER recommended practice (2024)

IV. Results

IV. 1 Average Speed Distribution

The analysis of speed distribution reveals a significant concentration of low-speed instances, indicating severe congestion in many areas. The dataset includes 179 speed variations, with recorded speeds ranging from 1 km/h to free-flow conditions. Notably, the lowest recorded speed of 1 km/h appears 33,341 times, suggesting a persistent pattern of gridlock, particularly in high-density urban areas. The speed distribution histogram (Figure 4) highlights the frequency of extreme congestion, emphasizing the need for enhanced traffic management in flood-prone districts. These findings confirm the presence of chronic congestion, likely caused by high vehicle density, inadequate road capacity, and inefficient traffic control systems.

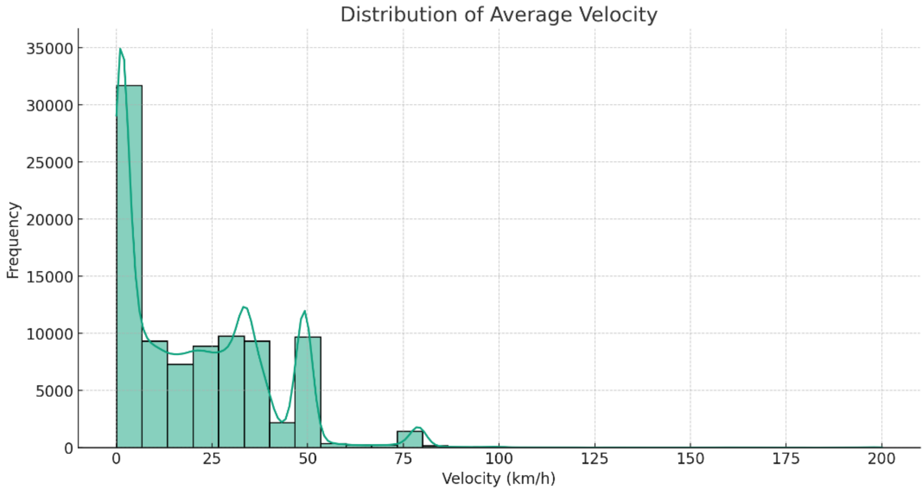

Figure 3: Distribution of Average Velocity

IV. 2 Travel Frequency

The temporal distribution of travel frequency (Figure 4) indicates that the highest number of trips occurs on Monday at 00:00, with 29,215 recorded trips. This suggests a significant movement of vehicles, potentially related to the transition from the weekend to the weekday. Peak travel activity is observed between 05:00–08:00 and 16:00–19:00, aligning with morning and evening commuting hours. During weekdays, traffic congestion is highly structured, driven by work and school commutes, whereas weekends exhibit a more even distribution of travel, though Sunday night records a notable surge in trips extending into early Monday morning. These patterns indicate that urban mobility demand varies significantly based on the day and time, with flood events likely intensifying delays in critical periods.

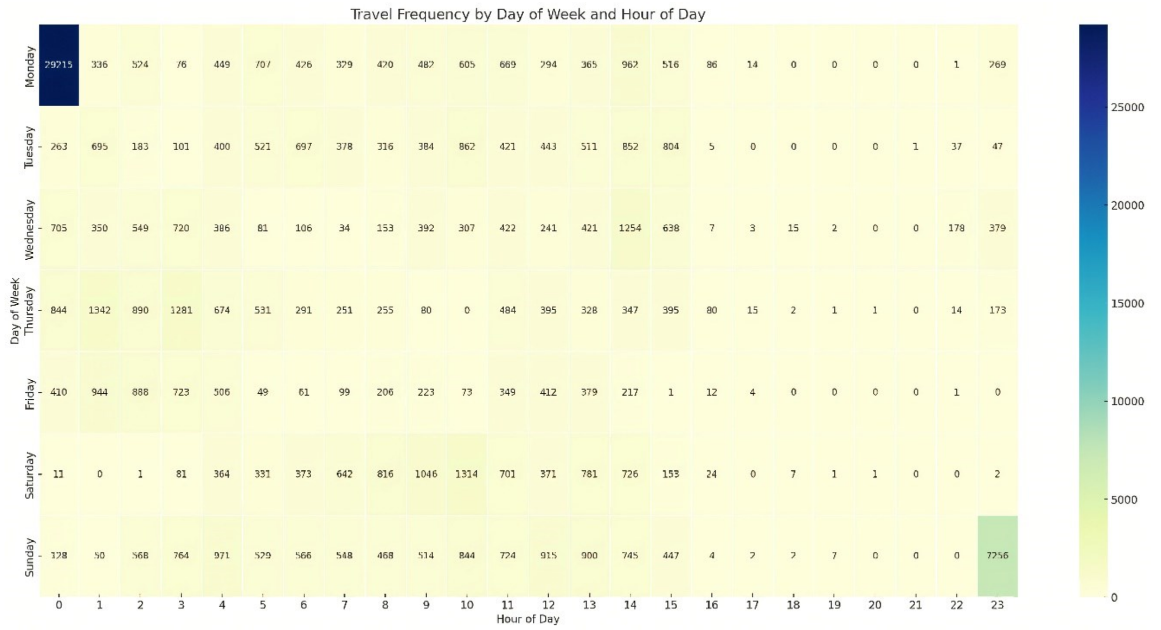

Figure 4: Travel Frequency

IV. 3 Mobility Activity Heatmap

The mobility activity heatmap (Figure 5) identifies Districts 1, 4, 5, 6, and 11 as the most active mobility zones. These areas correspond to Ho Chi Minh City's business, financial, and commercial hubs, explaining their high traffic intensity. Additional mobility concentrations are observed in Tan Binh District (near Tan Son Nhat International Airport) and Binh Thanh, though their densities are lower compared to the core districts.

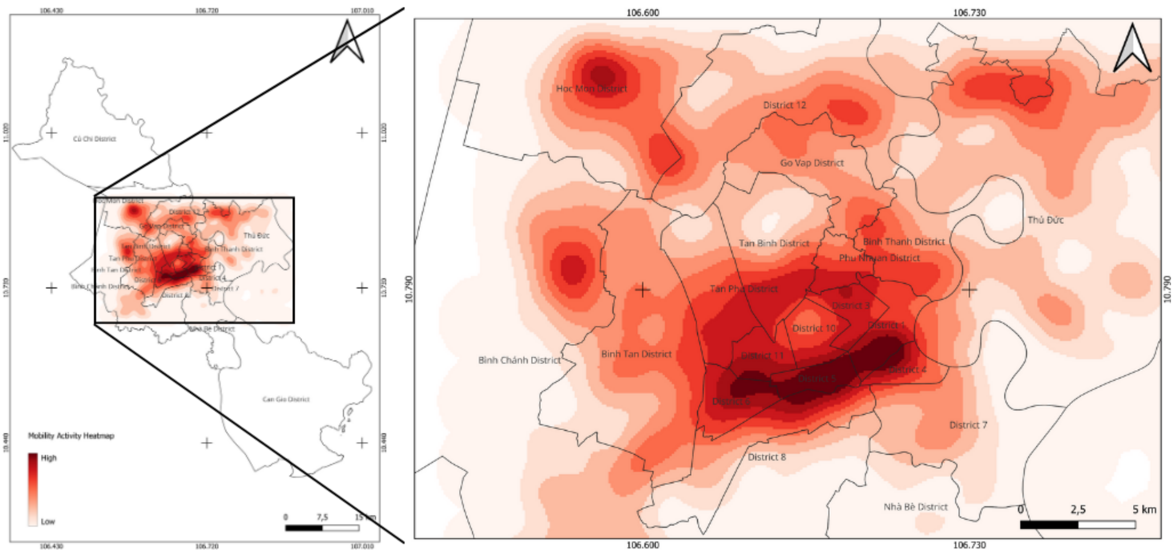

Figure 5: Mobility Activity Heatmap

The observed mobility patterns highlight the significance of these districts as central economic zones, with a constant influx of vehicles and pedestrians. This suggests that targeted interventions, such as optimizing public transport routes and improving pedestrian infrastructure, could alleviate congestion in these areas.

IV. 4 Traffic Density

The traffic density heatmap further confirms congestion patterns along key road corridors. Weekday traffic peaks during morning and evening rush hours, while weekend congestion is more evenly distributed but intensifies in the evenings. Specific roads, such as *Pham Van Dong Boulevard* and *Ly Thuong Kiet Street*, consistently experience high traffic volumes, reinforcing their role as primary commuting routes. The persistent congestion in these areas suggests that existing infrastructure struggles to accommodate traffic demand, necessitating improved road network management and potential expansion of alternative transport modes. Flood-prone intersections experience up to a 40% reduction in traffic flow, forcing vehicles onto alternative routes and worsening city-wide congestion.

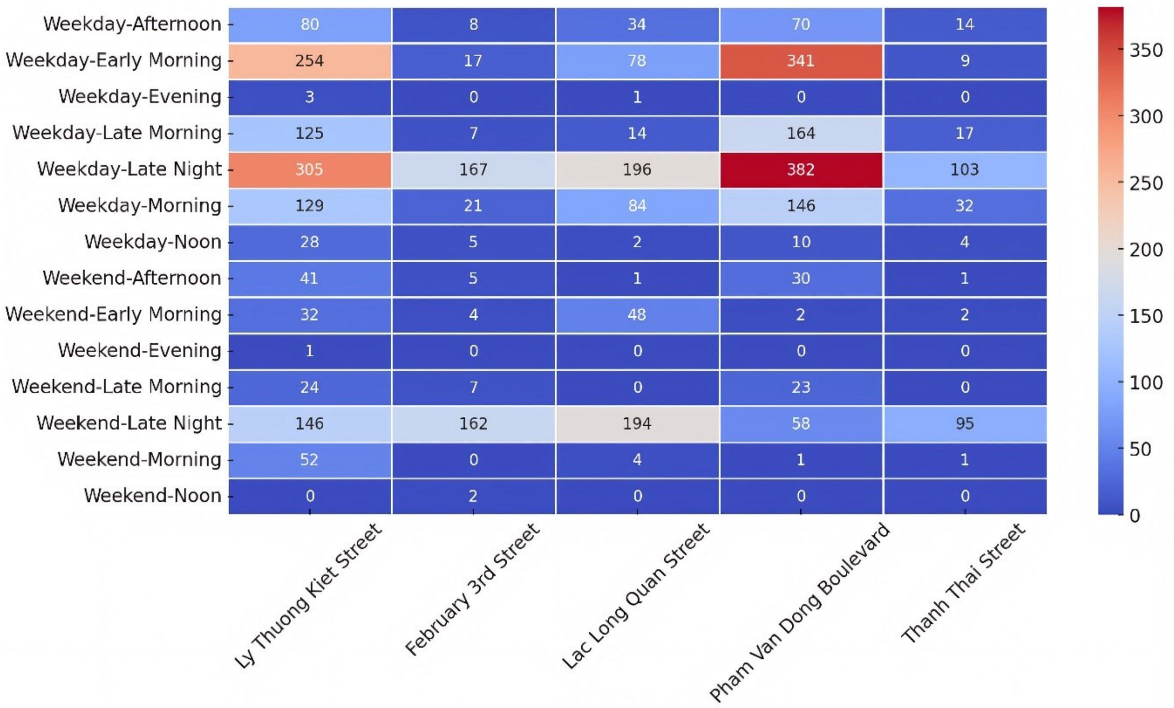

Figure 6: Heatmap of Traffic Density

IV. 5 Flood Exposure (2020, 2021, 2022)

Flood exposure analysis between 2020 and 2022 reveals clear temporal variations in the extent and intensity of inundation across Ho Chi Minh City.

In 2020 (Figure 7), floodwaters covered approximately 2,359 hectares, affecting about 77,404 residents. Inundation was concentrated along the Saigon River corridor and in densely built-up districts such as Binh Thanh, District 7, and Thu Duc, disrupting residential and commercial activities. The flood also affected around 2,590 hectares of urban land and 249 hectares of agricultural areas, highlighting the wide-ranging impact of prolonged rainfall and tidal influence on both infrastructure and local economies.

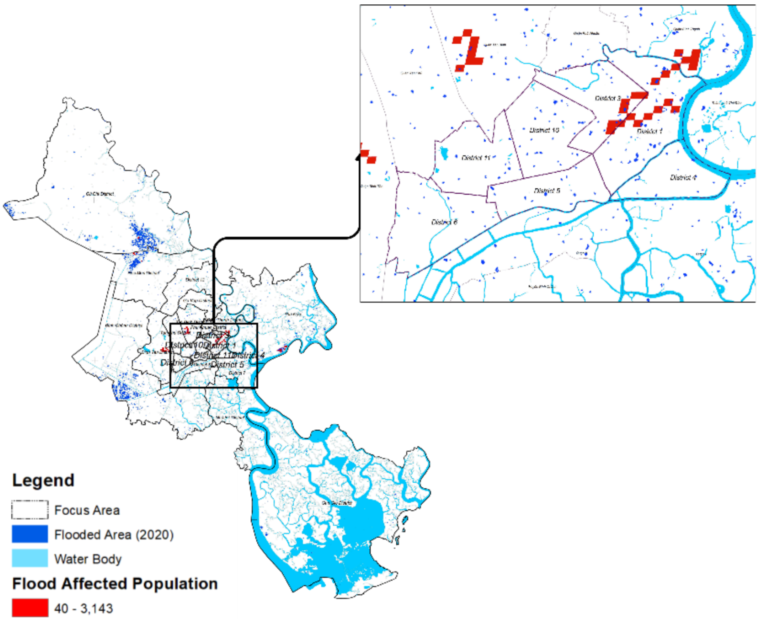

Figure 7: Flood Exposure Map (2020)

In 2021 (Figure 8), the inundated area decreased to roughly 1,925 hectares, with only 157 people directly affected. This sharp decline in exposure may be attributed to more localized rainfall patterns or improved drainage performance during that year, rather than the absence of flood events. Waterlogging persisted in several low-lying zones, indicating residual vulnerability despite the smaller inundation footprint.

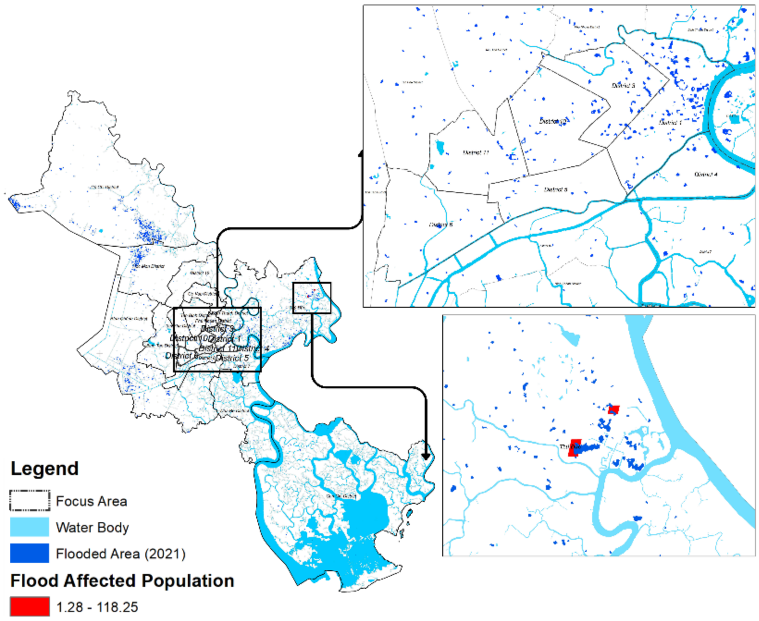

Figure 8: Flood Exposure Map (2021)

By 2022 (Figure 9), exposure increased again, with 1,538 hectares inundated and 18,125 residents affected. The renewed expansion of flood-prone zones occurred predominantly in transportation corridors and high-activity districts, implying that flood hazards not only threaten households but also disrupt urban accessibility and mobility. These temporal dynamics emphasize the need for continuous flood monitoring and adaptive planning that integrates both hydrological and transport resilience strategies.

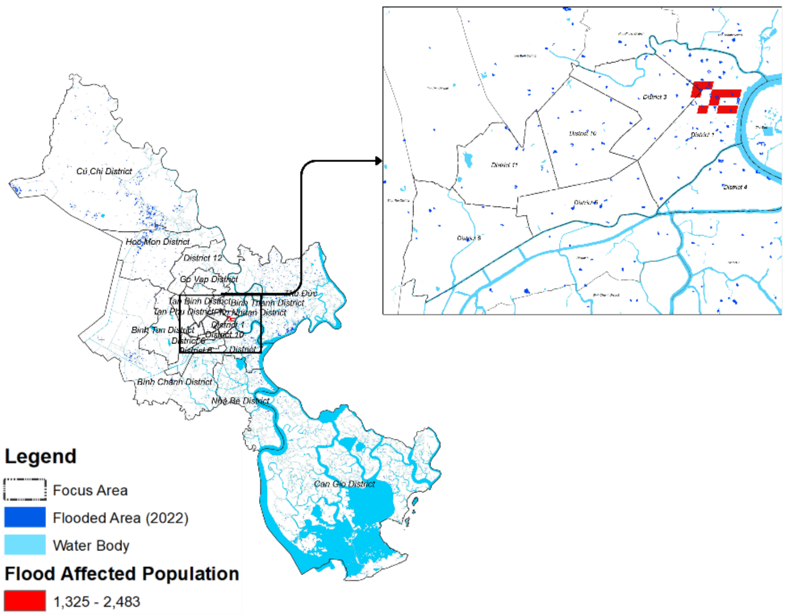

Figure 9: Flood Exposure Map (2022)

V. Discussions

The results reveal that urban flooding in Ho Chi Minh City is not a uniform phenomenon but a spatially and temporally dynamic process shaped by both hydrological and urban development factors. The substantial flood exposure in 2020 and the resurgence in 2022 demonstrate how rainfall intensity, tidal influence, and the city's rapid densification interact to amplify inundation risk in low-lying districts. These variations highlight the importance of continuous flood monitoring, especially as built-up expansion increasingly encroaches on natural drainage zones.

The integration of mobility analysis and flood mapping provides a more holistic understanding of flood consequences in dense tropical cities. The observed decline in traffic speed and Level of Service in flooded districts underscores how even short-term inundation can trigger cascading disruptions across the urban transport network. This coupling between hydrological processes and transport performance suggests that flood management cannot be addressed solely through drainage or structural solutions but must also involve mobility resilience strategies.

Furthermore, the spatial overlap between flood-prone areas and key mobility corridors points to an opportunity for co-benefit interventions. Nature-based Solutions (NbS), such as vegetated swales, permeable pavements, and urban retention zones, can reduce surface runoff while maintaining road accessibility. Embedding such measures within existing transport infrastructure planning can enhance both hydraulic performance and network functionality. Overall, this study demonstrates the value of integrating geospatial analysis of flood exposure and mobility patterns to support data-driven, climate-resilient urban planning in fast-growing coastal megacities.

VI. Conclusion and Recommendation

This study demonstrates the significance of integrating flood exposure mapping and urban mobility analysis to better understand the cascading impacts of flooding in Ho Chi Minh City. The results show that flood exposure varied considerably from 2020 to 2022, with the most extensive inundation occurring in densely populated and low-lying districts. The spatial coupling between flooded zones and key mobility corridors revealed that short-term inundation can substantially degrade traffic performance and accessibility. These findings highlight that urban flood impacts extend beyond physical damage, affecting socio-economic connectivity across the city.

Based on these insights, future planning should emphasize cross-sectoral strategies that combine hydrological management with transport resilience. Nature-based Solutions (NbS)—such as vegetated swales, retention ponds, and permeable pavements—can simultaneously enhance flood mitigation and maintain network functionality. Establishing a continuous geospatial monitoring framework using Sentinel-1 and community-based traffic data is recommended to support adaptive, data-driven decision-making. Expanding this integrated approach to other Southeast Asian coastal cities could strengthen regional strategies for climate-resilient urban mobility.

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